Status and challenegs of neutrino physics

Journée annuelle de P2I,
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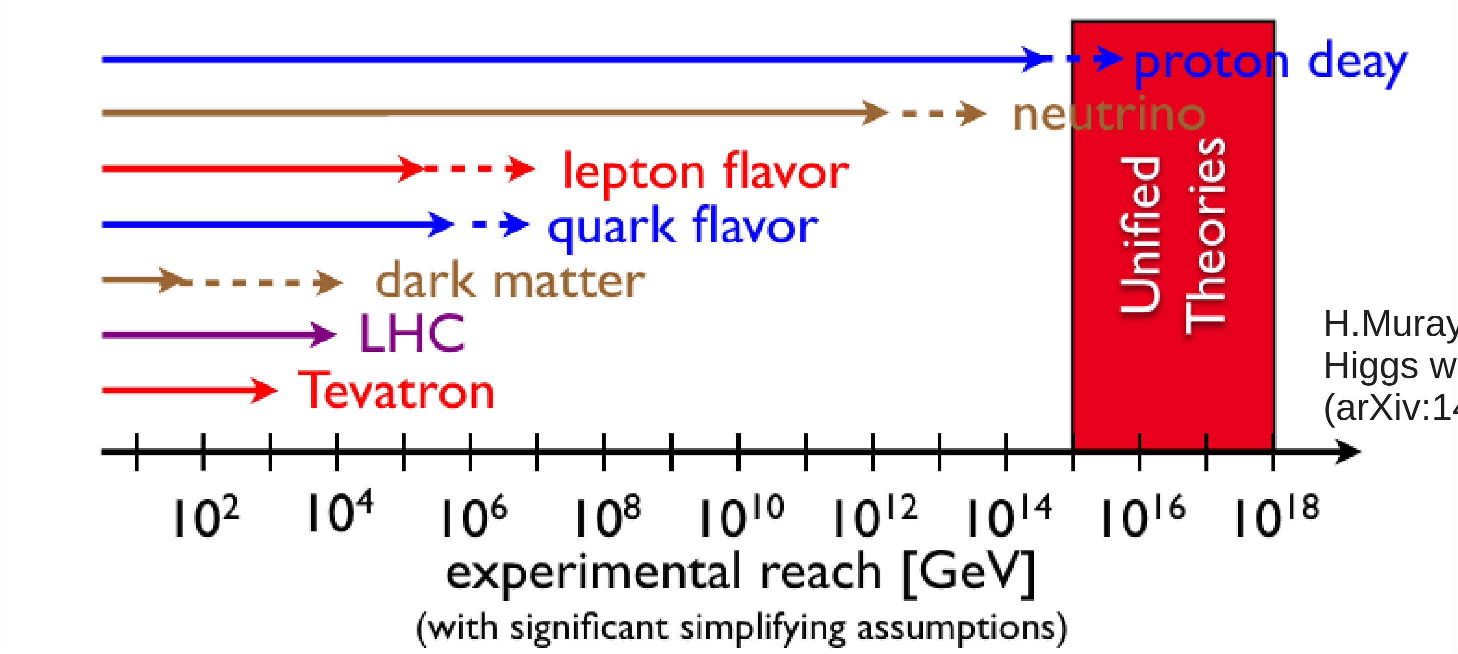
S.Bolognesi (IRFU, CEA)

Neutrinos as probe to very high energy

- **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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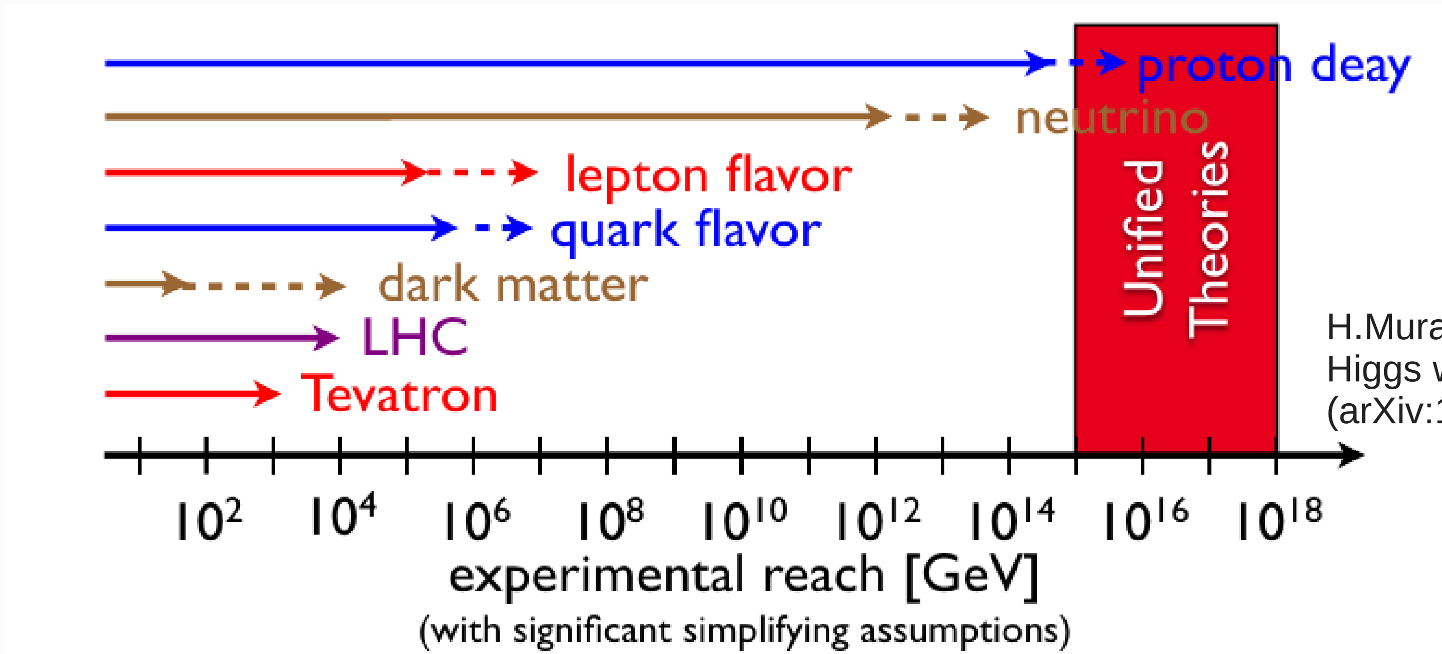

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- Sensitive to very tiny effects thanks to interferometry (i.e neutrino oscillations)!
  Unique tool to study very high energy scale (today $\Lambda \sim 10^{14}$GeV)

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

  → What is the **New Symmetry hidden behind the mass and flavour mixing?**

  → **Why neutrinos do have mass?**

Neutrinos as door to New Physics

- **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

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

$$\frac{246^2}{10^{15}} GeV \approx 10^{-2} eV$$

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

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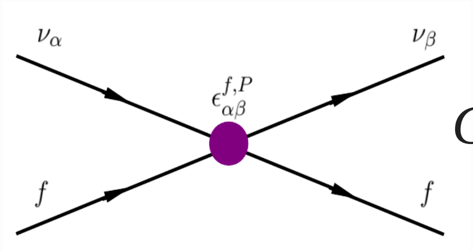
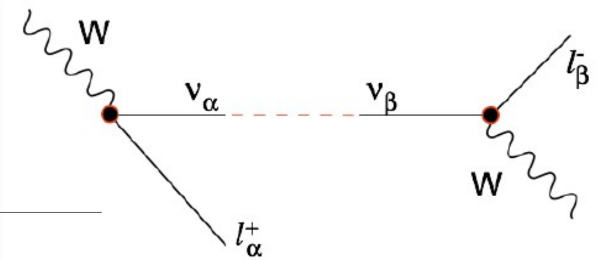
- Peculiar nature of ν and being in direct contact with Λ_{UV}: natural to expect new type of interactions for neutrinos: Non Standard Interactions



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

Neutrino oscillations



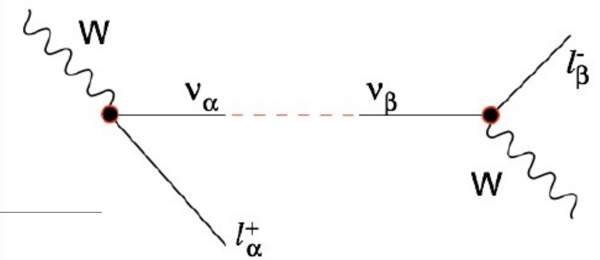
- Oscillation discovered with atmospheric and solar neutrinos by SuperKamiokande and SNO
Since then, accelerator (and reactor) neutrinos provided a controlled source

- **Oscillation probability estimated by comparing ν (and $\bar{\nu}$) rate by flavor between source (near detectors) and far detectors:**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\textbf{amplitude}} \sin^2\underbrace{\left(1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)}_{\textbf{frequency}}$$

(simplified 2-flavors approximation)

Neutrino oscillations



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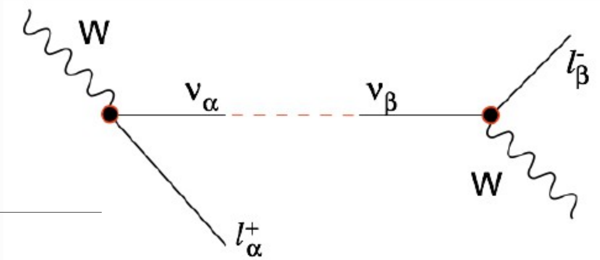
- Full 3-flavors formalism: PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

$U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}

Neutrino oscillations



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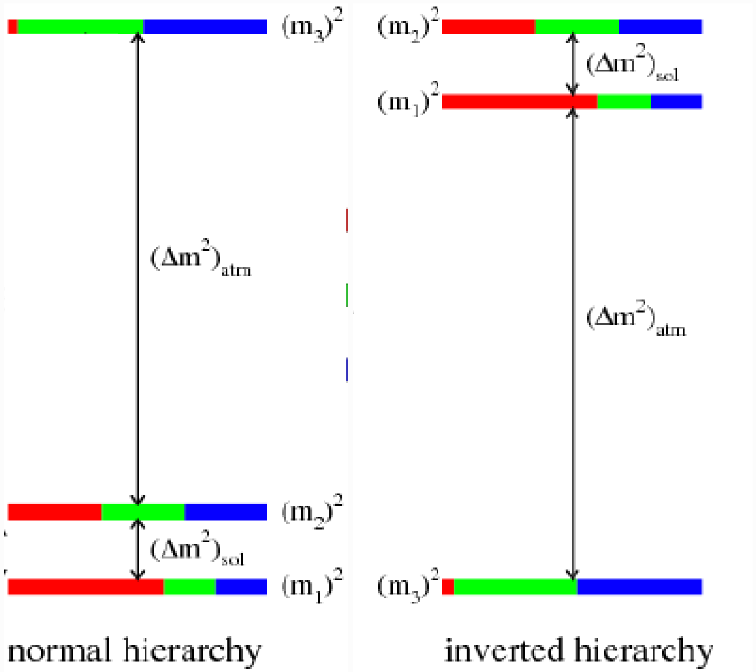


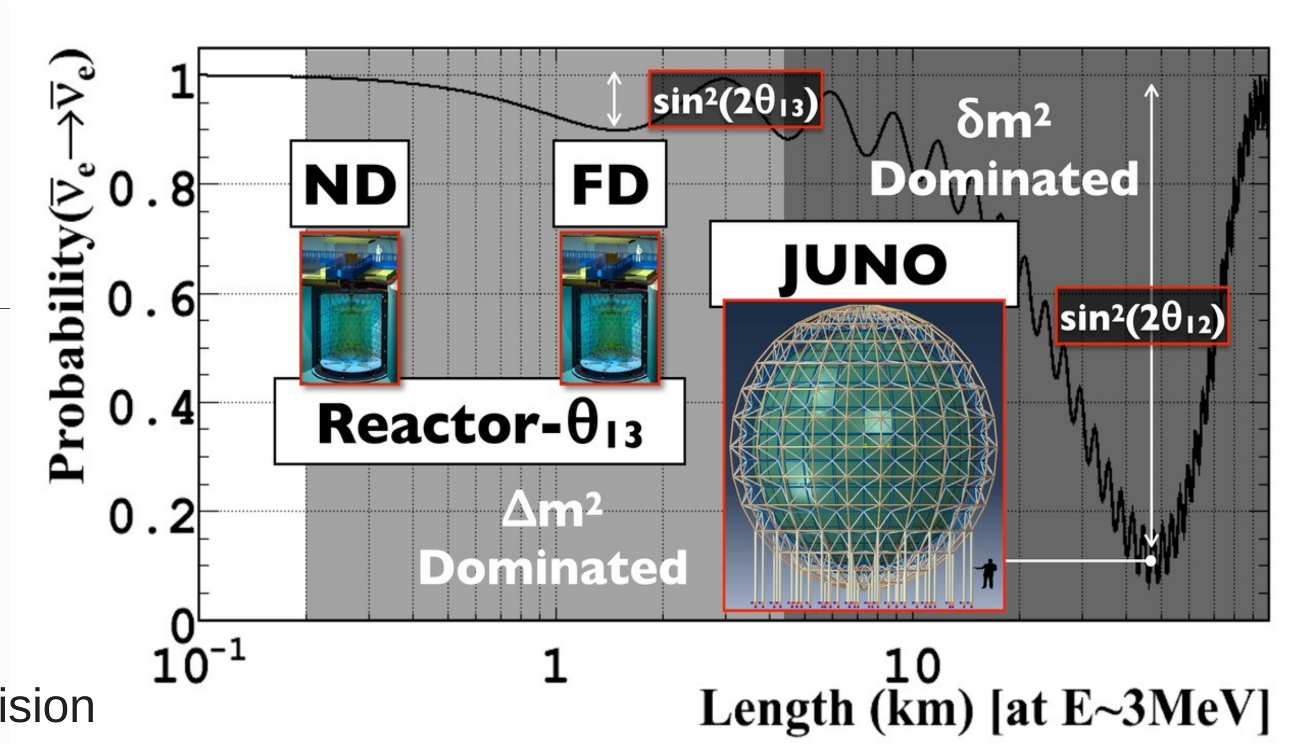
- 3 mass states → two Δm^2: solar (small) and atm (large)
  $\Delta m^2_{21} \sim 8\times10^{-5}$ eV $\Delta m^2_{31(32)} \sim (-)2.5\times10^{-3}$eV
  → mass ordering unknown (normal = same as lepton ordering)

Oscillation measurements

- **Neutrinos from reactors:** disappearance of $\bar{\nu}_e$

~few MeV, L~1 km

$\sin^2\theta_{13} = 2.18 \pm 0.07$ (Daya-Bay, Double Chooz, RENO)



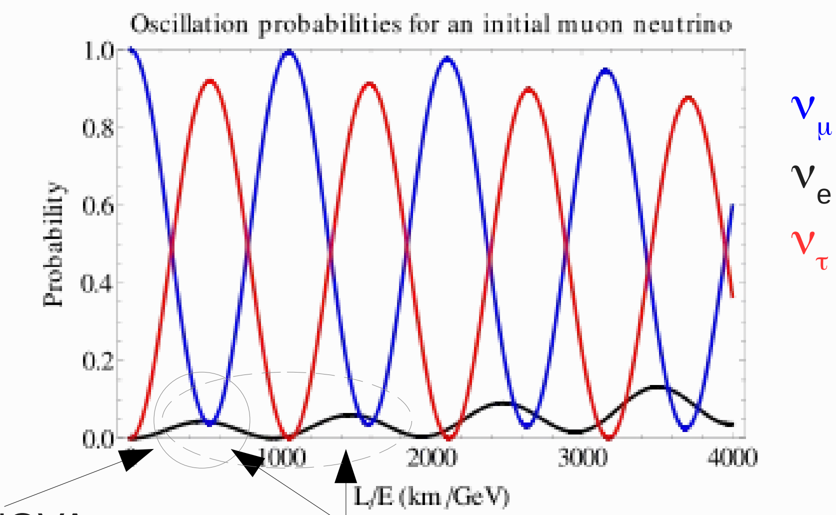
- JUNO: 50km baseline → precision measurement θ_{12} and MH sensitivity

- **Neutrino from accelerator**: flux of ν_μ ($\bar{\nu}_\mu$) → ν_μ ($\bar{\nu}_\mu$) disappearance, ν_e ($\bar{\nu}_e$) appearance

Experiment	Energy	Baseline
T2K (T2HK)	0.6 GeV	295 km
Nova	2 GeV	810 km
DUNE	1-3 GeV	1300 km

(to exploit ν_τ need $E_\nu > m_\tau$ 1.78 GeV)

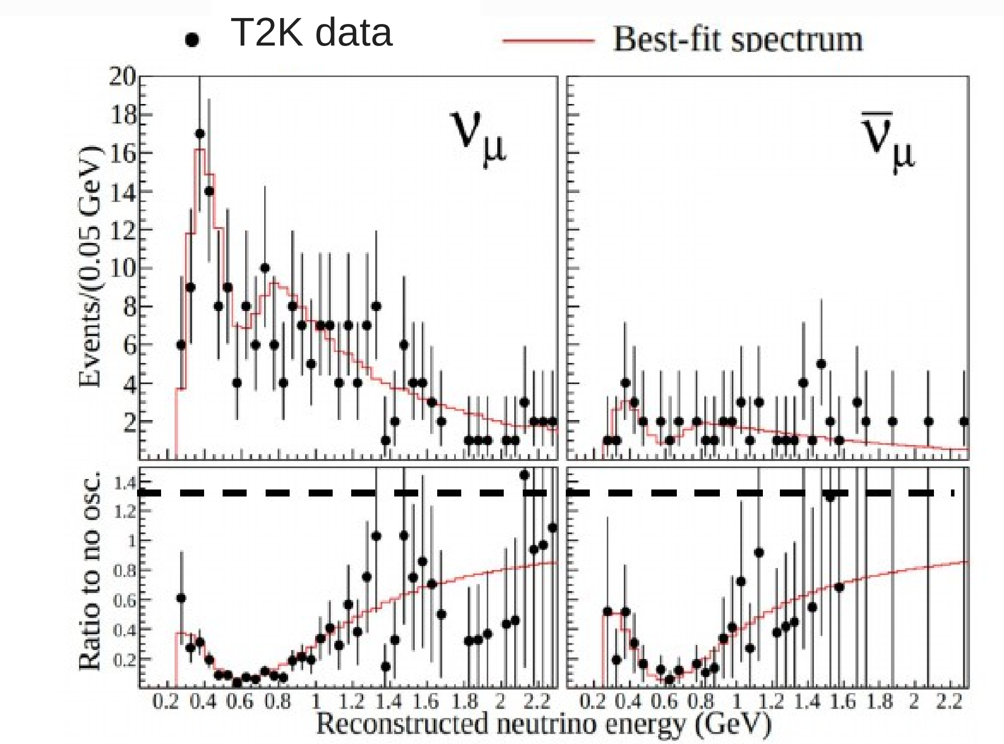
In the atmospheric sector $\Delta m^2_{32} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

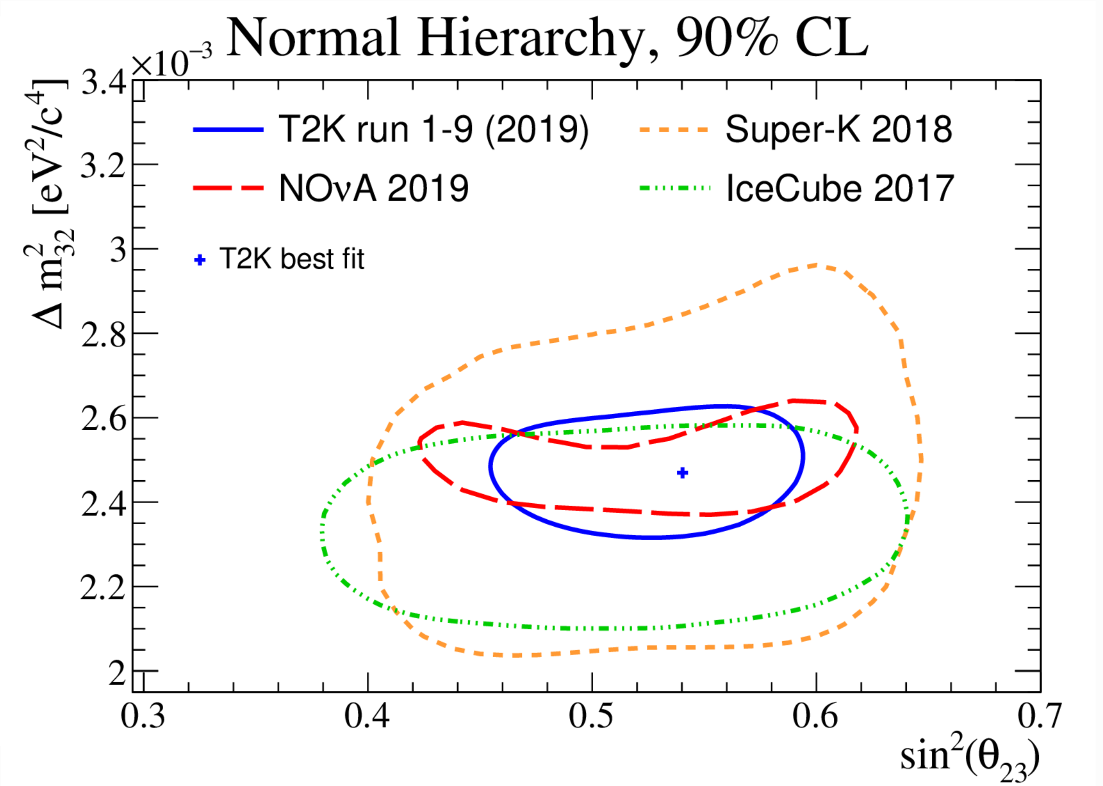


T2K (T2HK) and NOVA working point

DUNE wideband beam covers (at low energy) also the second oscillation maximum

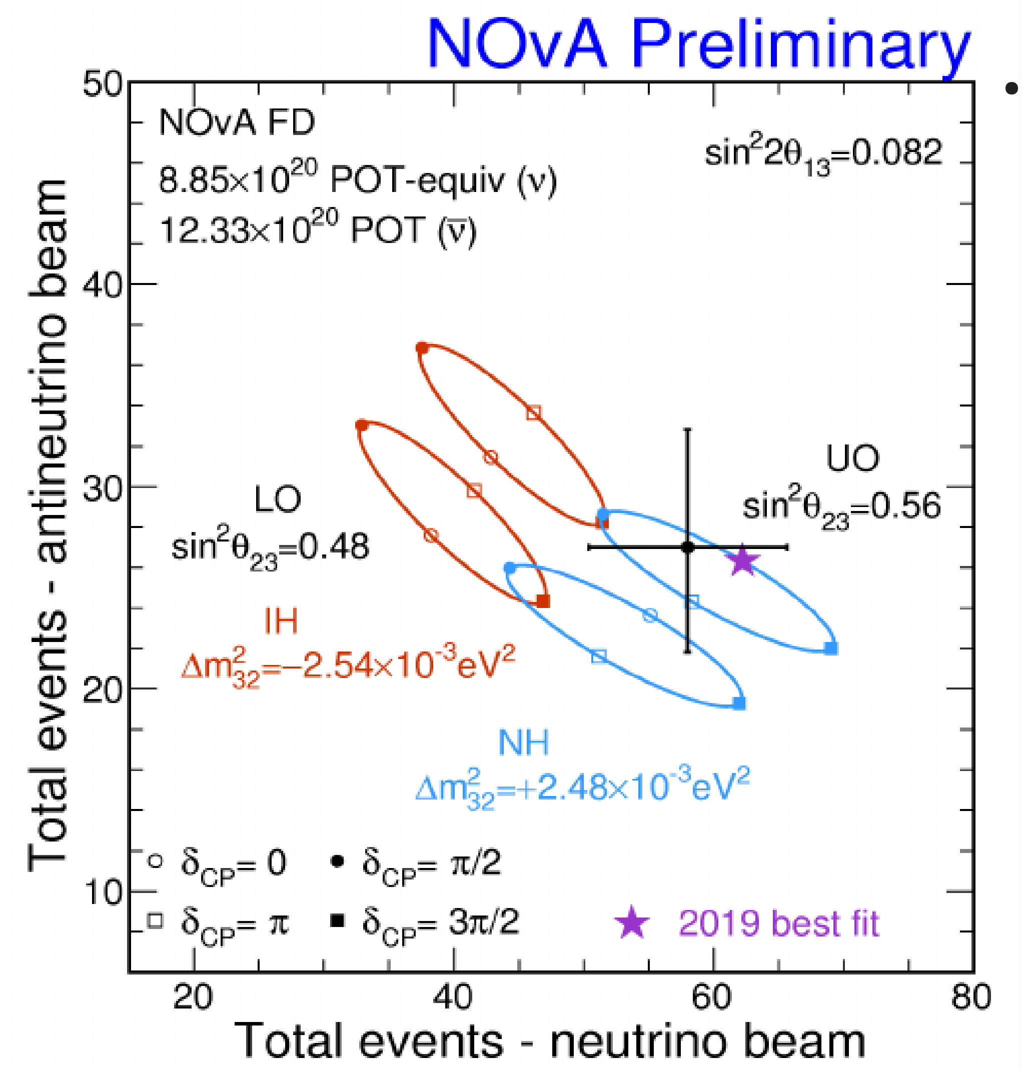
Latest results: $\sin\theta_{23}$, Δm^2_{32}





- **$\sin\theta_{23}$ ~ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance**
- **$\Delta m^2_{31(32)}$ ~ frequency of the disappearance (position of the minima)**

Latest results: mass hierarchy



- **MH through matter effects (long baseline) by comparing ν_μ vs $\bar{\nu}_\mu$ disappearance**

NOVA: NH preferred at 1.9σ

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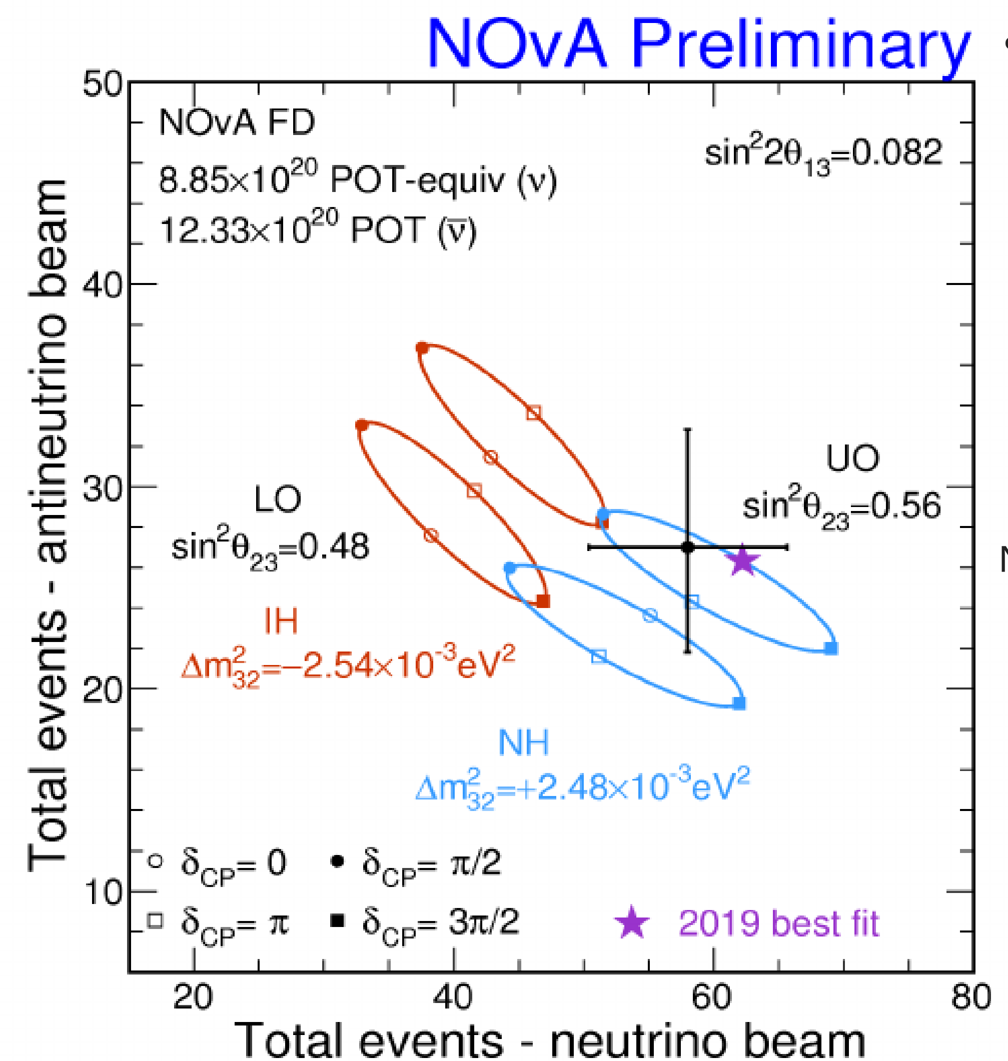

- **MH through matter effects (long baseline) by comparing ν_μ vs $\bar{\nu}_\mu$ disappearance**

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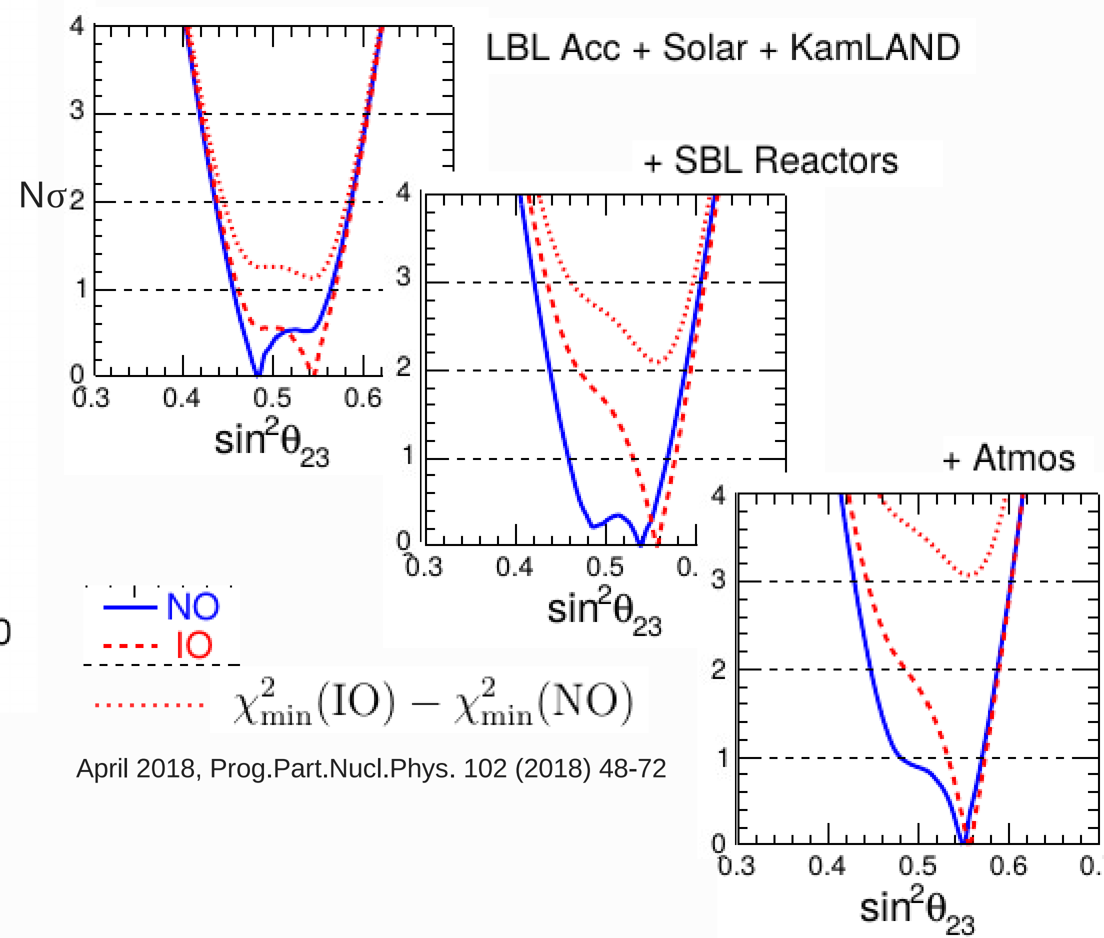
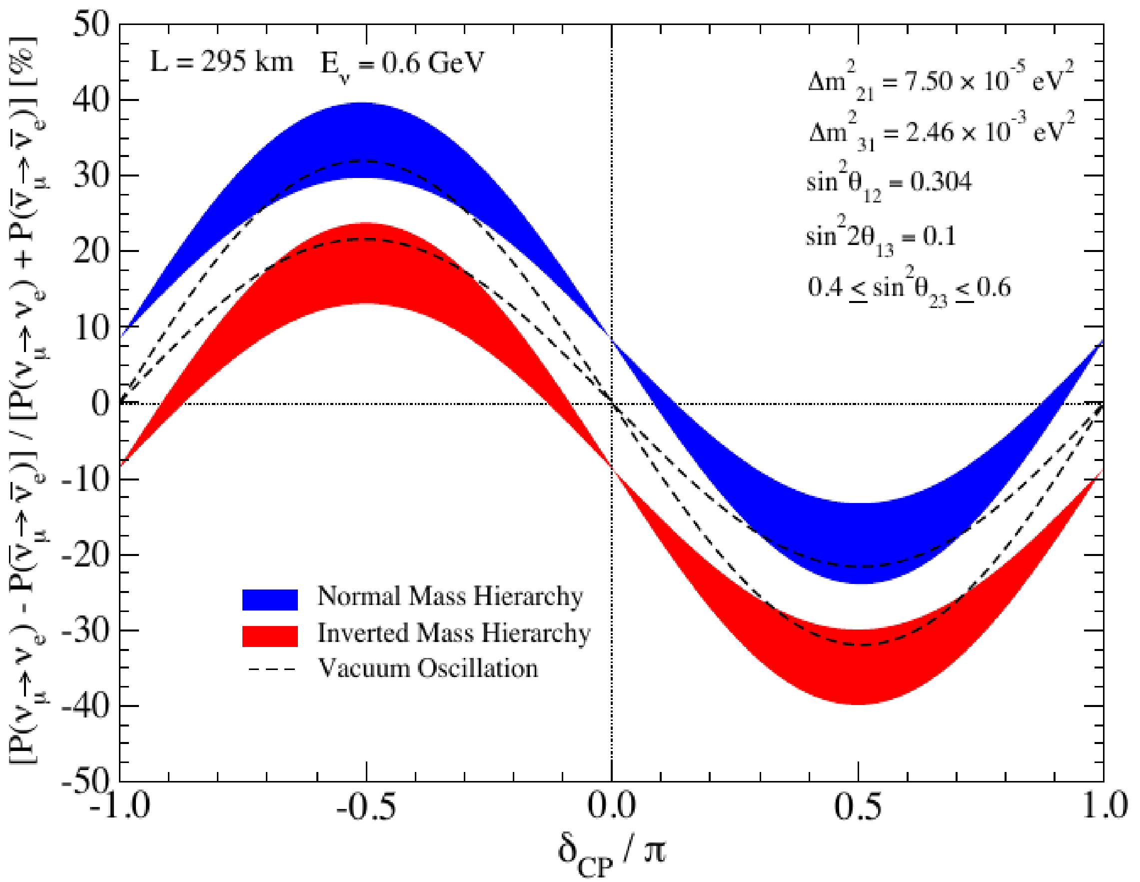
- **IH disfavored at 3σ** by combining with SK atmospheric data



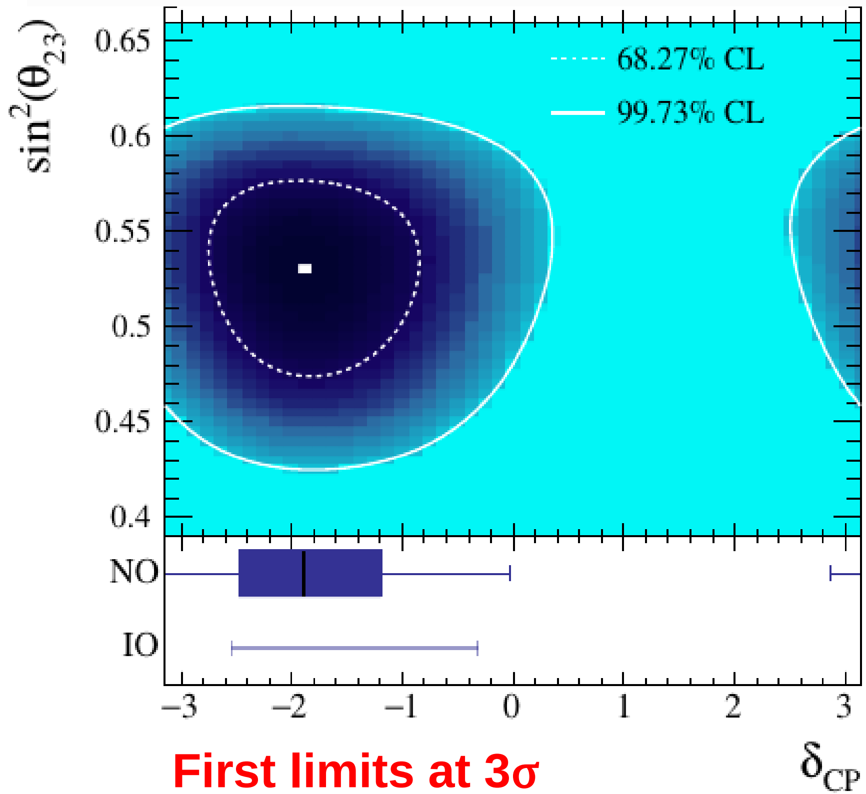
April 2018, Prog.Part.Nucl.Phys. 102 (2018) 48-72

Latest results: δ_{CP}

- δ_{CP} from ν_e vs $\bar{\nu}_e$ appearance



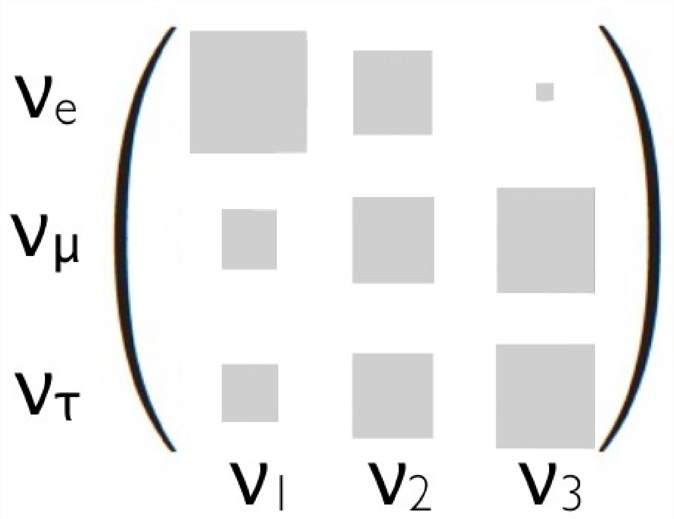
T2K run 1-9
+ θ_{13} constraints from reactors



First limits at 3σ

(arxiv 1910.03887 submitted to Nature)

PMNS characterization



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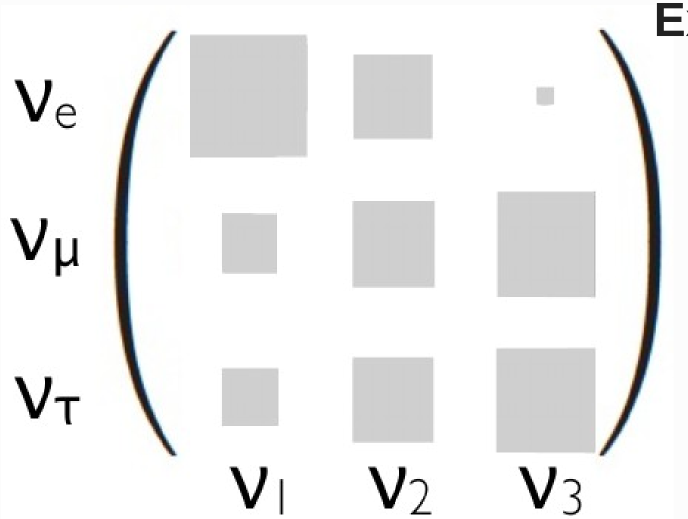


Exploring unitarity from different rows:

⇒ **best precision**

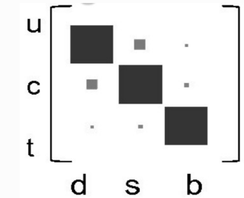
⇒ **OK precision**

⇒ **poorest precision**

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

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

→ best limit expected from **electron top row**: θ_{13} from reactors and θ_{12} from JUNO



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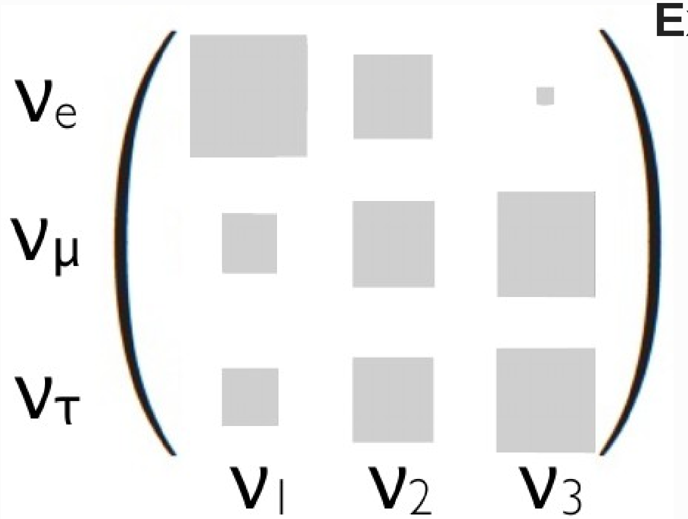

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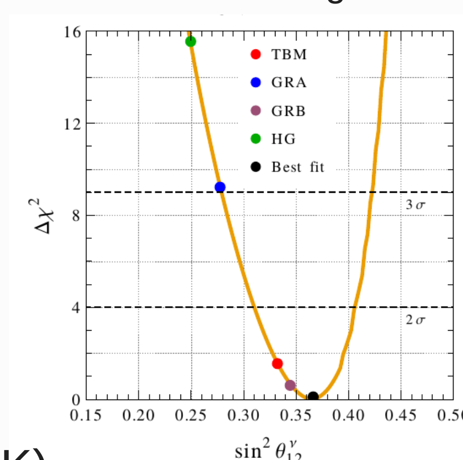
→ best limit expected from **electron top row**: θ_{13} from reactors and θ_{12} from JUNO

Why such (unexpected) shape? (e.g compared to CKM) → constrain of NP standing behind flavour mixing pattern

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

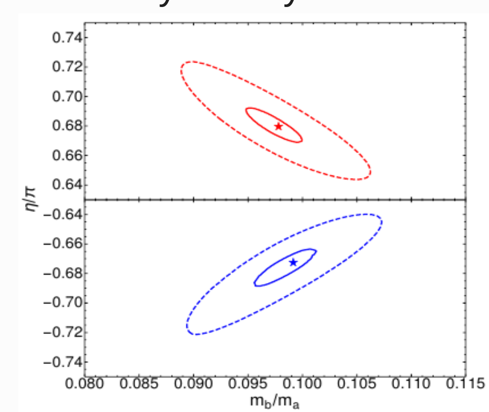
Examples of model predictions:

Discrete flavour symmetries → neutrino mixing sum-rules



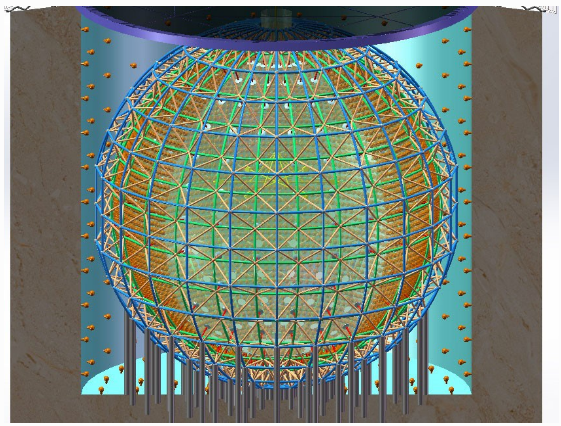
Eur.Phys.J. C78 (2018) no.4, 286

Littlest Seesaw model with flavour symmetry

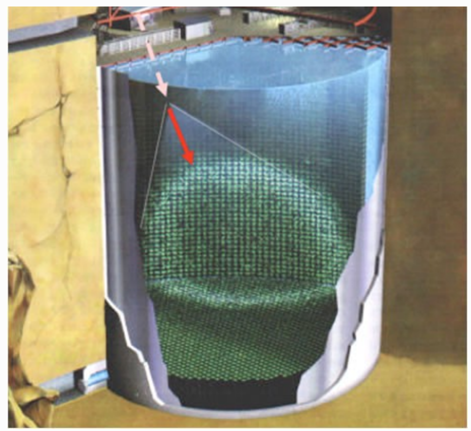


Plausible scenario of oscillation precision measurements

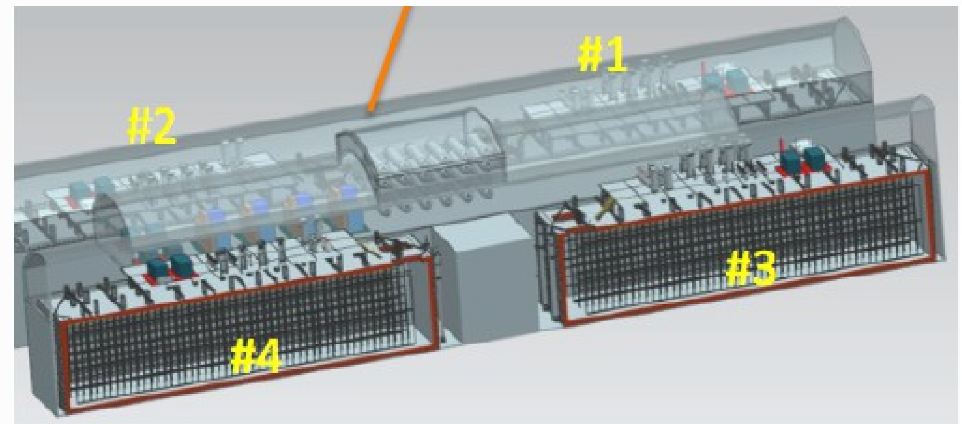
JUNO
20kt liquid scintillator (LAB)



HyperKamiokande
260kTon water Cherencov



DUNE
40kTon LAr TPC

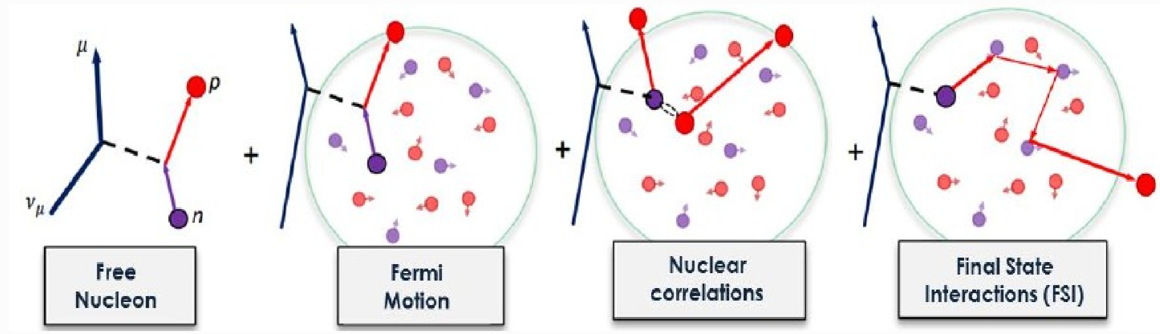


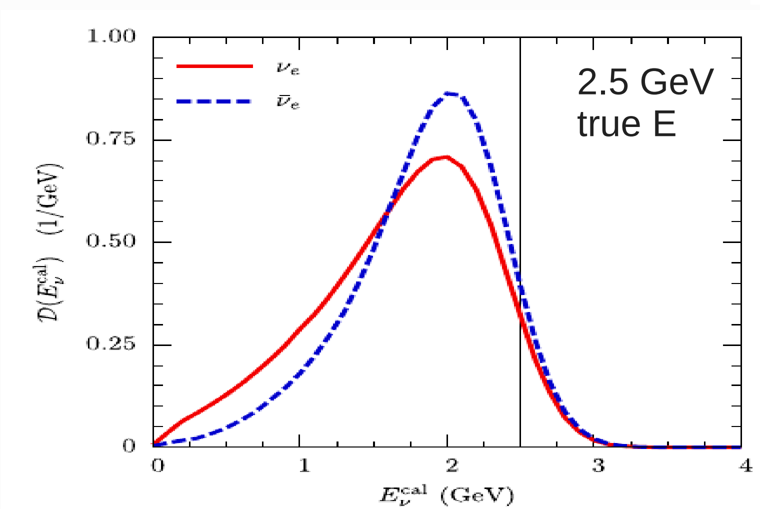
Mass hierarchy:
Today 3σ from combination (+NOVA) → JUNO 3-4σ in 6y (from solar-sector oscillation in vacuum) → DUNE 5σ in 1-2y (with beam matter-effects) → Hyperkamiokande 5σ in 10y (with atm)

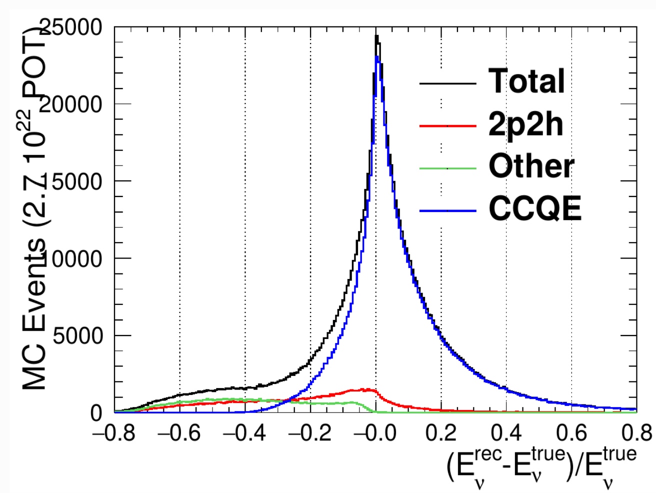
CP-violation discovery
3σ at T2K-II (+3σ T2K+NOVA) → 5σ in 2030 HK, DUNE →
δ_{CP} precision measurement: ~10 degrees in 5-10y DUNE (wide beam)

The challenge to the oscillation precision measurements

- **Measurements systematics-dominated** (thousands of neutrino interactions)
  - JUNO: 3% energy resolution and a factor of 6 better energy scale than previous experiments
  - HyperKamiokande, DUNE: improvement of a factor 2-5 in the systematics due modeling of neutrino-nucleus scattering





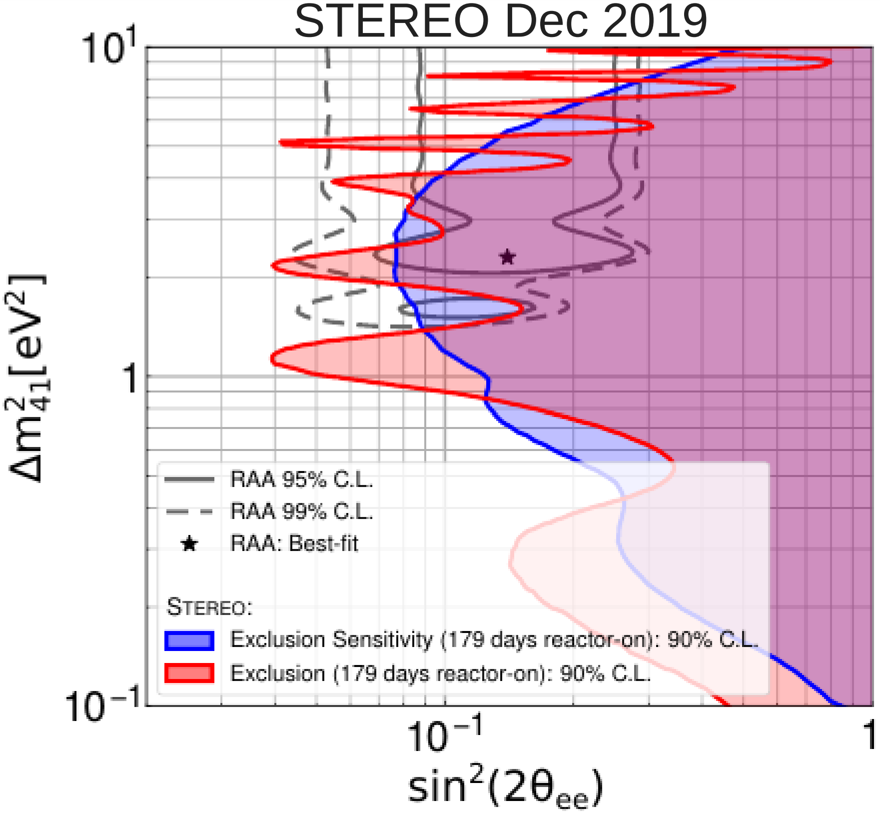


→ **Crucial role of Near Detectors: more and more sophisticated**

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: detectors near to reactors/accelerators or large masses**
  - **Search for Majorana neutrino nature with 0νββ**
  - **Phenomenology behind non-unitarity: NSI or sterile neutrinos**

STEREO Dec 2019



complete program of:
+ similar experiments at reactors
+ short baseline at accelerator
(eg MicroBoone, SBL at FNAL)
+ pion DAR neutrinos from neutron source
(eg JSNS^2 at JPARC)

→ Reactor anomaly plagued by uncertainties on reactor flux measurement
→ other hints (MiniBoone, LSND) difficult to reconcile in a 'natural' scenario
→ indirect constraints from cosmology for ANY relativistic particle at early stage of universe (model-dependent)

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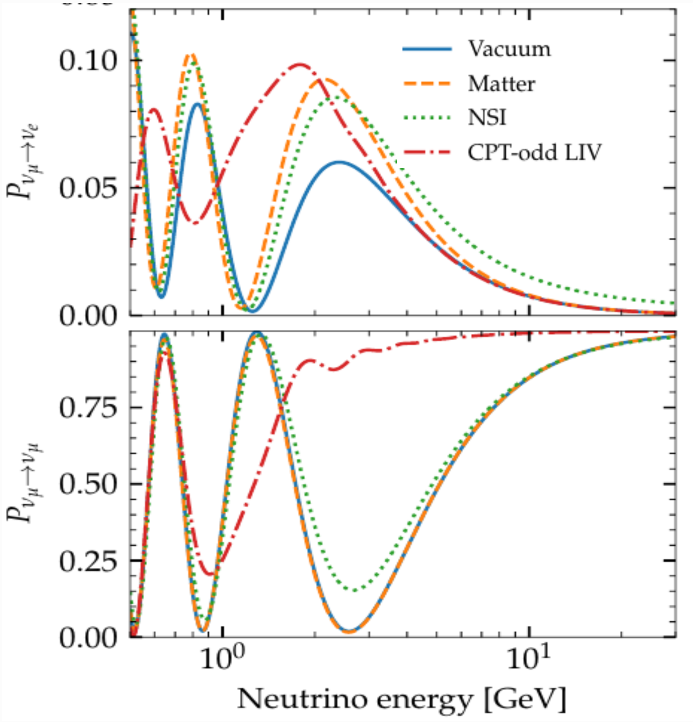
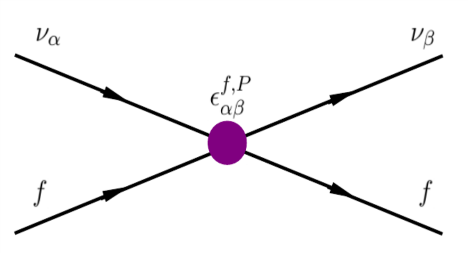
Degeneracy of NSI with standard PMNS signatures of MH and δ_{CP}

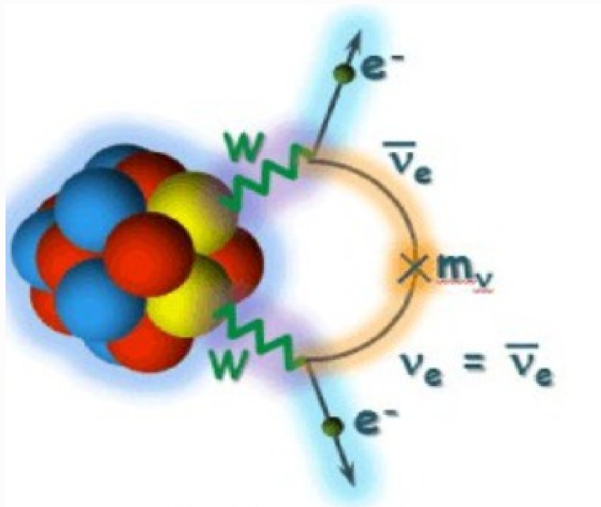


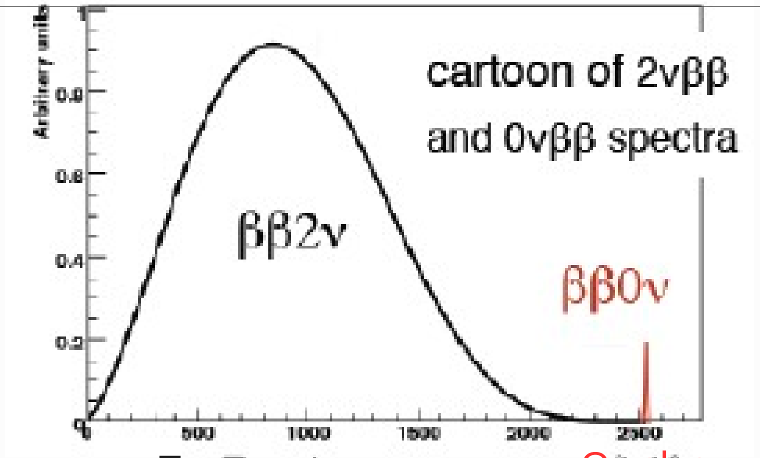


$$G_F \epsilon_{NSI} (\bar{\nu} \nu)(\bar{f} f)$$

- NSI in Charged Current: affecting oscillation results at production and detection point → can be constrained with near detector measurements at LBL
- NSI in Neutral Current: affecting LBL results through matter effects: → can be constrained with combination of multiple baselines/energies and with dedicated experiments of Coherent Elastic Neutrino-Nucleus Scattering at reactors

Neutrino-less double beta decay





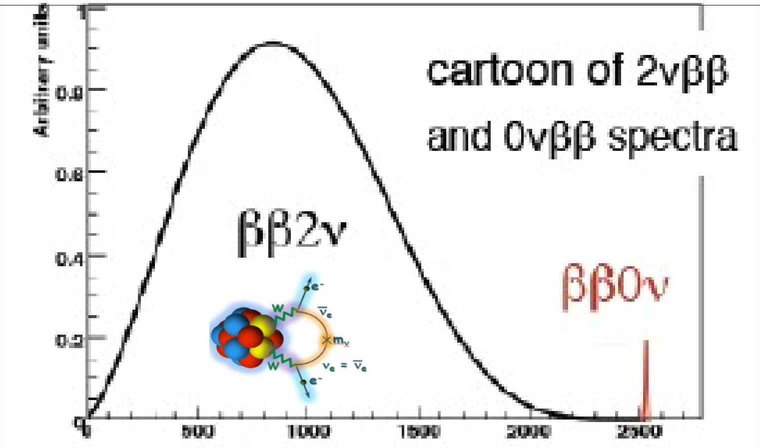
Two e- energy Q value

Neutrino-less double beta decay

- **0νββ rate:**

phase space — nuclear matrix element — effective majorana mass

$$\frac{1}{\tau} = \underbrace{G(Q,Z)}_{\text{phase space}} \underbrace{|M|^2}_{\text{nuclear matrix element}} \underbrace{\langle m_{\beta\beta} \rangle}_{\text{effective majorana mass}}$$



Two e- energy

Q value

- $\langle m_{\beta\beta} \rangle = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$
- large and not well known **uncertainties on nuclear matrix element (g_A)**
- phase space: large Q gives higher sensitivity to $m_{\beta\beta}$ for the same experimental half life sensitivity

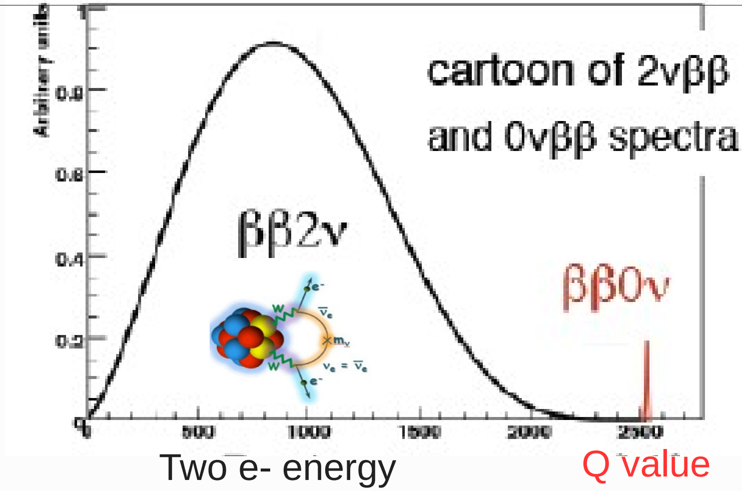
Neutrino-less double beta decay

- **$0\nu\beta\beta$ rate:**

phase space — nuclear matrix element

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

effective majorana mass

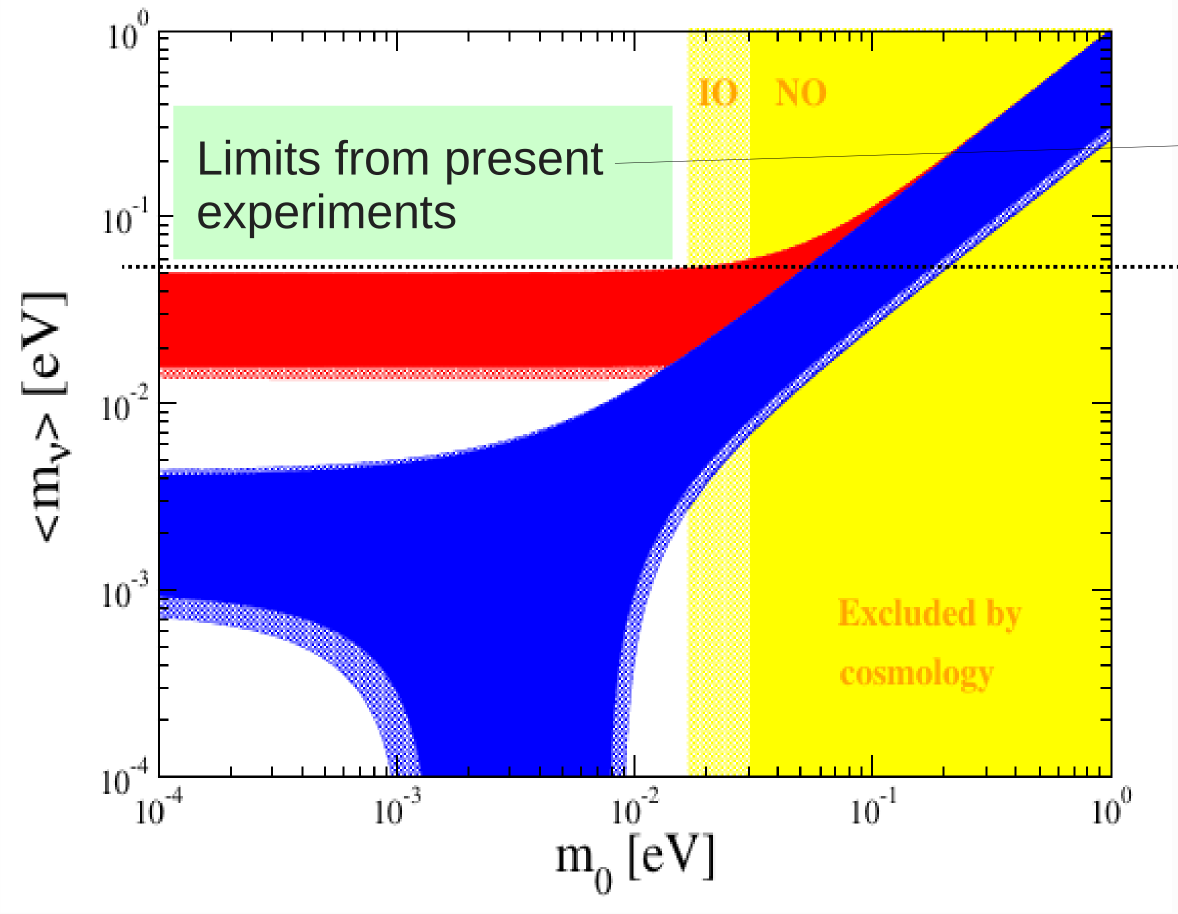


- $\langle m_{\beta\beta}\rangle = \left|\,|U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3\right|$
- large and not well known **uncertainties on nuclear matrix element (g_A)**
- phase space: large Q gives higher sensitivity to $m_{\beta\beta}$ for the same experimental half life sensitivity

- **Sensitivity:** $S_{\langle 1/\tau\rangle} \propto \left(\frac{M\cdot t_{live}}{\delta E\cdot B}\right)^{\frac{1}{2}}$ need for **experimental technique** with excellent radiopurity and resolution

	FWHM	Backgr. (cts/y/ton)	$T_{1/2}$ [10^{26} y] for $m_{\beta\beta}$=0.1eV	
GERDA	~3.5	4	1 - 10	Ge detectors
Kamland-Zen	270	120	~0.5	Liquid Xenon baloon
EXO-200	170	71	~0.5	Liquid Xenon TPC
Cupid-Mo	5	few	0.1 - 1	Scintillating bolometers

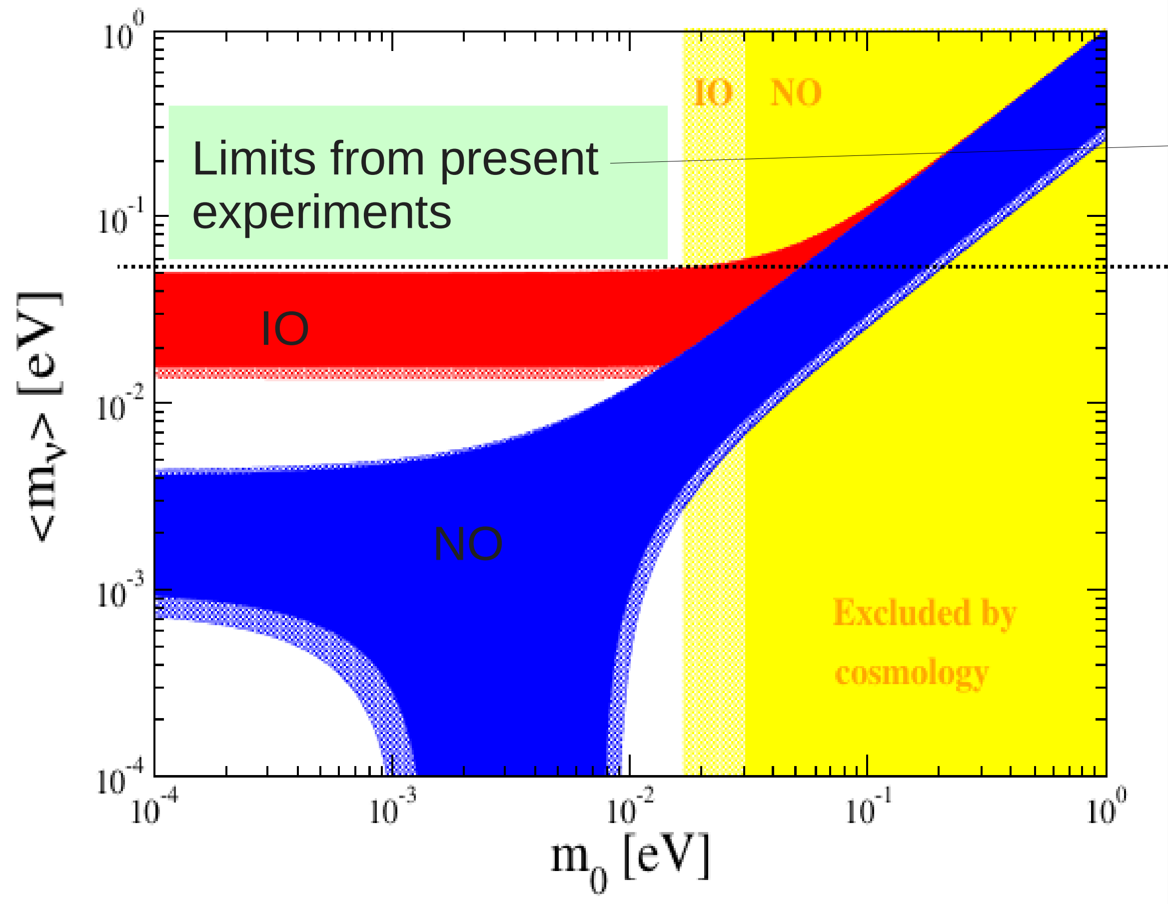
$0\nu\beta\beta$ prospects



	Results on $m_{\beta\beta}$ upper limit
CUORE	75-350 meV
GERDA	100-230 meV
Kaml-Zen	61-165 meV
EXO-200	93-286 meV

5 - 50 counts/ y ton

0νββ prospects



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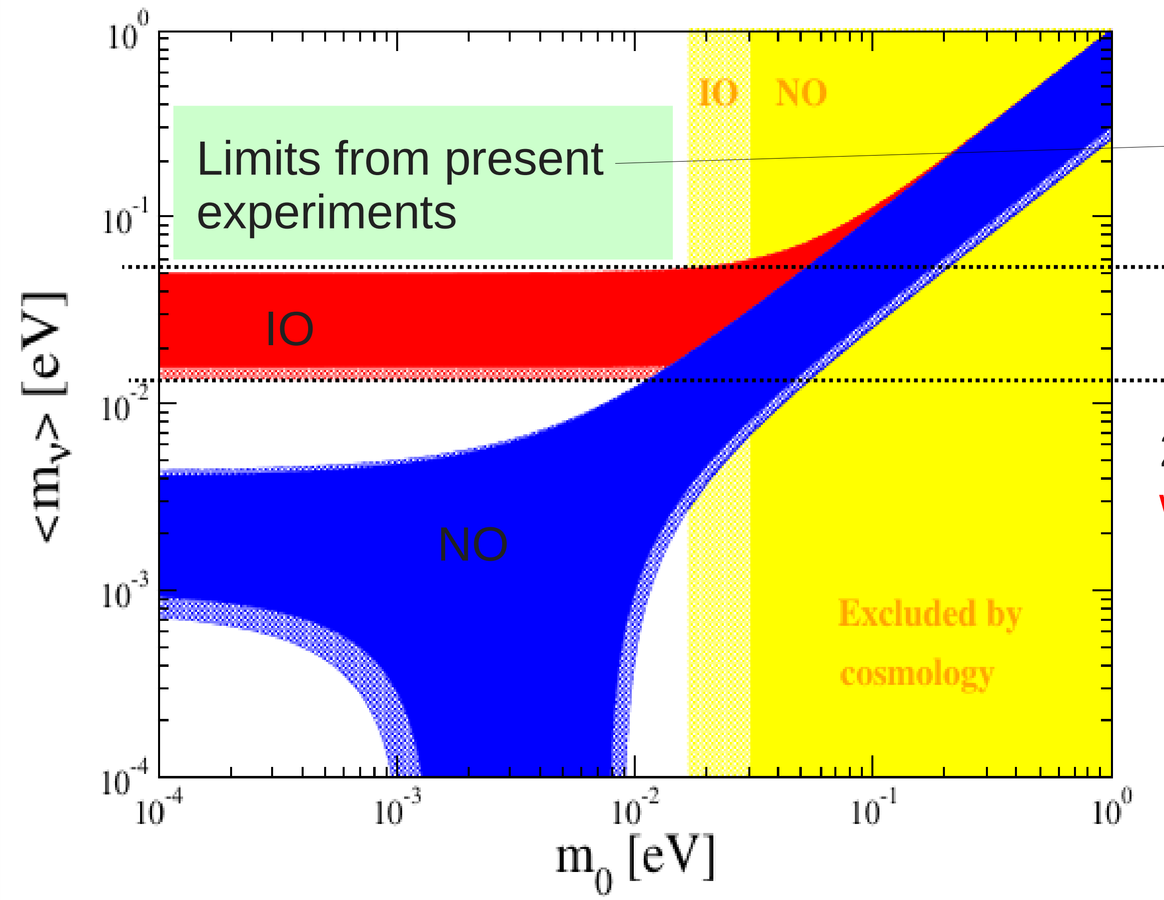
- As long as expected signal is large enough, the largest mass wins... **for very low rates the technological challenges are resolution and background:**
  - Liquid Xenon resolution >1% due to intrinsic diffusion in liquid
  - R&D with Xenon gas using topology for background discrimination: TPC precision to be demonstrated on very large volumes (Panda-X, NEXT)

0νββ prospects

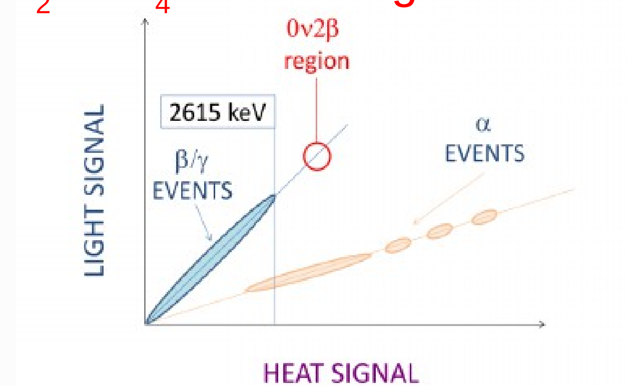
	Results on $m_{\beta\beta}$ upper limit
CUORE	75-350 meV
GERDA	100-230 meV
Kaml-Zen	61-165 meV
EXO-200	93-286 meV



5 - 50 counts/ y ton

0.5 - 5 counts/ y ton

20-30meV baseline sensitivity of CUPID with Li_2MoO_4 scintillating bolometers



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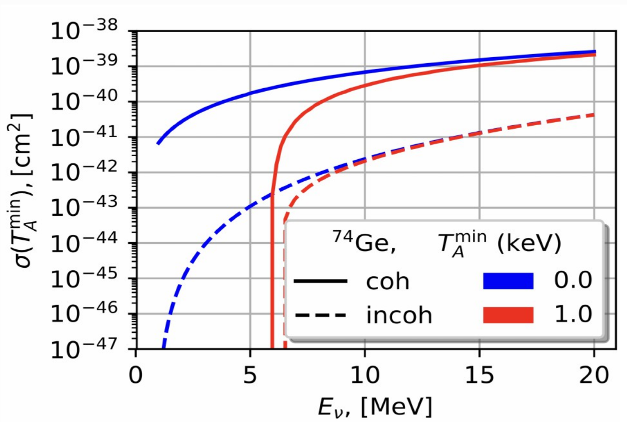
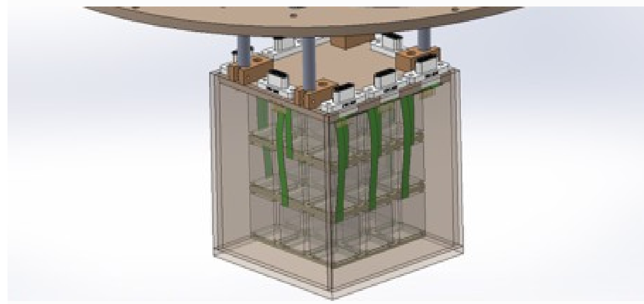
Coherent ν-nucleus scattering (CEνNS)

Bolometric technology applied to neutrinos from reactors:

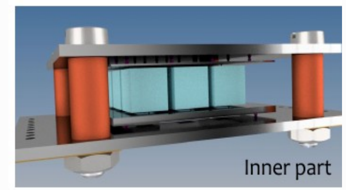


Ricochet (@ILL)



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

NUCLEUS (@Chooz)

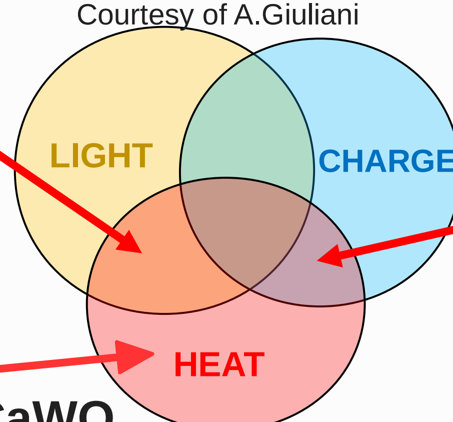


- Neutrino magnetic moment
- New massive weak-interaction mediator
- Non-standard interactions
- Active-to-sterile neutrino oscillations
- In applications, nuclear reactor monitoring

CUPID – 0νββ

Li_2MoO_4 scintillating bolometers (Future: **TeO_2** Cherenkov bolometer)

Courtesy of A.Giuliani



RICOCHET - CENNS

Ge bolometers with heat and ionization readout

NUCLEUS - CENNS

- Pure heat bolometers based on **$CaWO_4$**

Bolometric technology

0νββ

Very low signal rate:

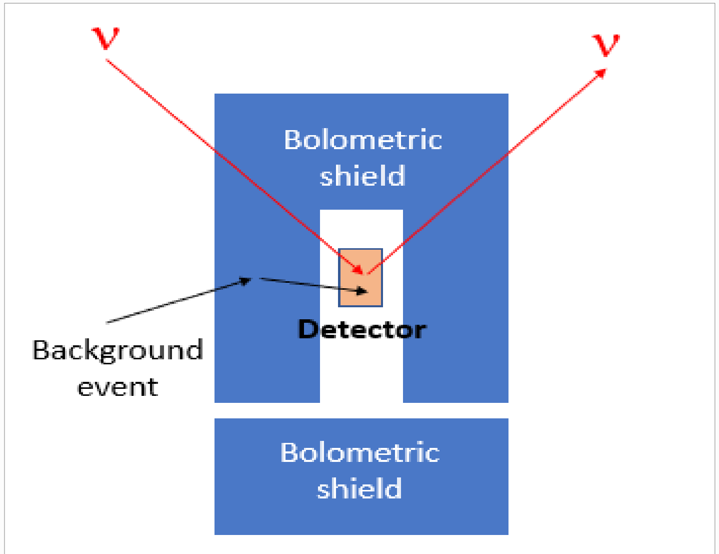
- **large mass:** growing of large crystals to minimize external background and number of electronics channel
- **radiopurity of the infrastructure + shielding**

CEνNS

Very low threshold and on surface

- slow detectors → array of **small detectors**
- **shielding** against cosmics

- Common needs/developments:
  - internal active bolometric shields
  - low threshold innovative phonon sensors (NTD, TES, KID) for heat/light/ionization signals



Courtesy of A.Giuliani

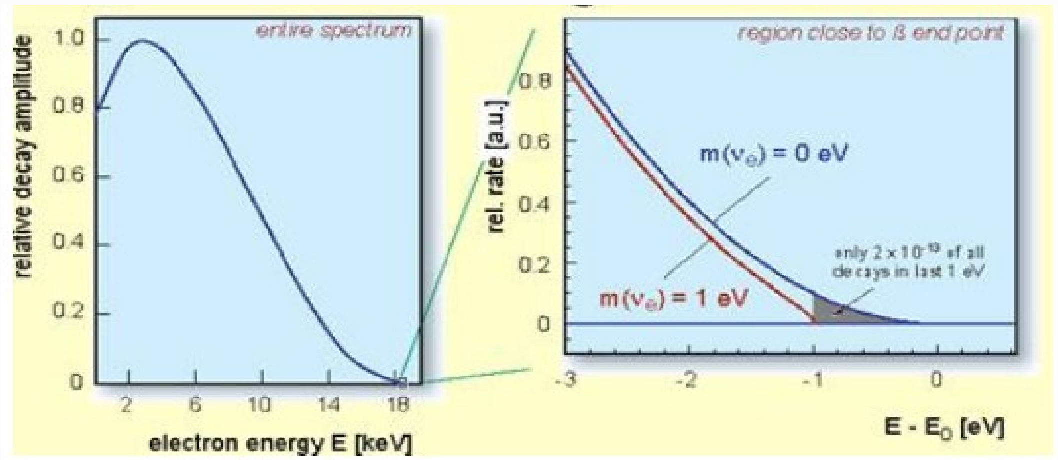
Mass measurement

- **Direct measurement:**
KATRIN <0.9eV @95% (FC limits)
→ ultimate sensitivity 0.2eV

$$dN/dE = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

($m_{\beta\beta}$ in 0νββ is also a direct mass measurement <~100meV if we think that neutrino is Majorana)

Electron energy spectrum in β decay

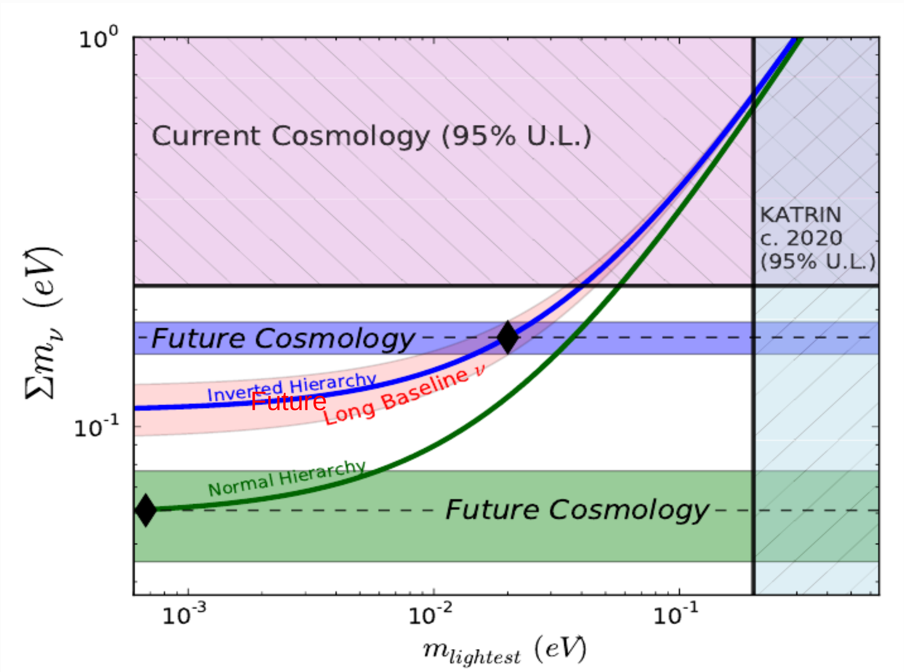


- **Cosmology** (Σm): impact of ν free streaming in matter clustering (captured by Galaxy surveys, BAO, CMB lensing) ~< 150 meV @95%

- Lower bound on mass sum depends on mass ordering from oscillation experiments

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$

→ indirect way to exclude IH



Conclusions

- **Will the next major HEP discovery be in the neutrino sector?**

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

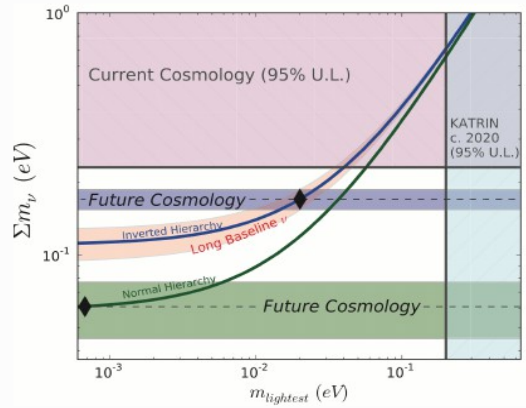
  - PMNS characterization to high precision, mass hierarchy determination and CP violation in leptons
  - $0\nu\beta\beta$ and NSI search: establishing limits to NP models and defining the road to future discovery
  - R&D of highly capable detectors

- **The neutrino community musts increase and work coherently to face such challenges:**
  - The size and complexity of next generation of experiments (JUNO, DUNE, T2HK, CUPID) **requires critical mass to reach visibility**
  - In order to exploit neutrinos as door to NP, we need a **coherent and complete understanding of the neutrino sector**

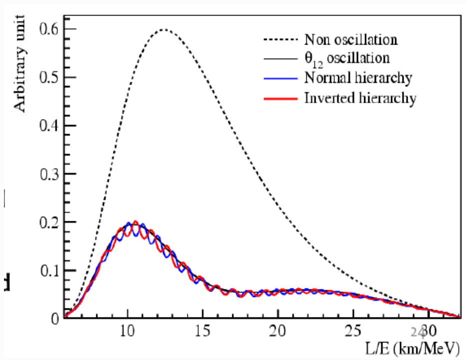
BACK-UP

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

Fundamental parameter to establish the absolute neutrino mass scale

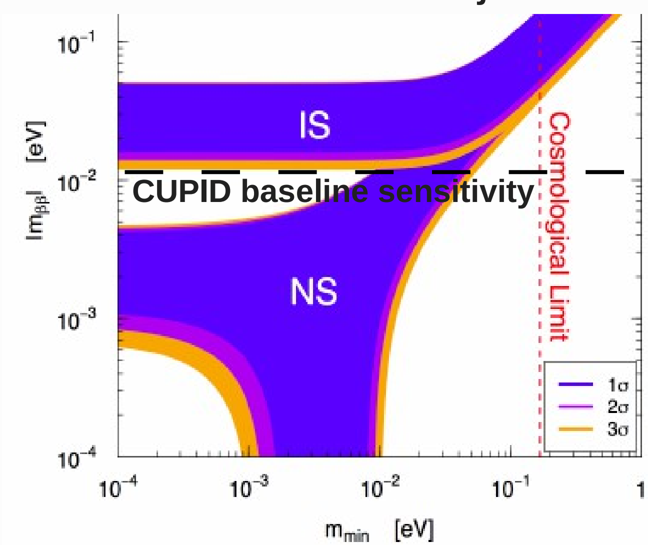


JUNO 4σ sensitivity: solar-sector oscillation in vacuum (systematic on energy scale)



An example: MH

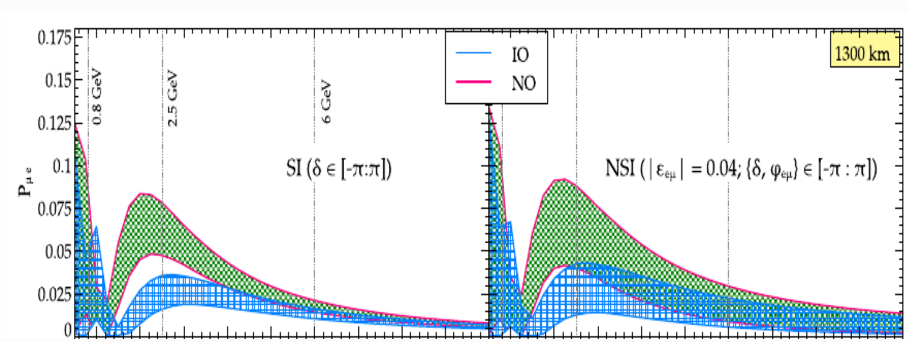
0νββ: related with $m_{\beta\beta}$ parameter space: can exclude IO if Majorana



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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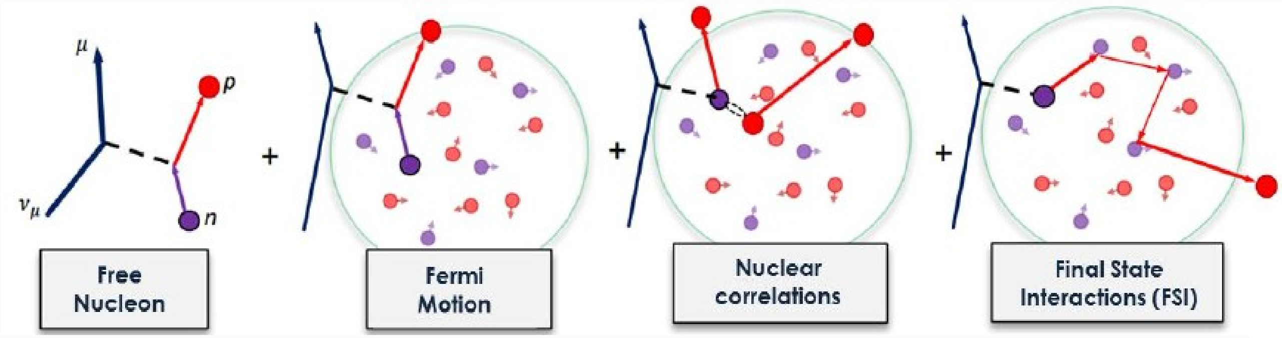
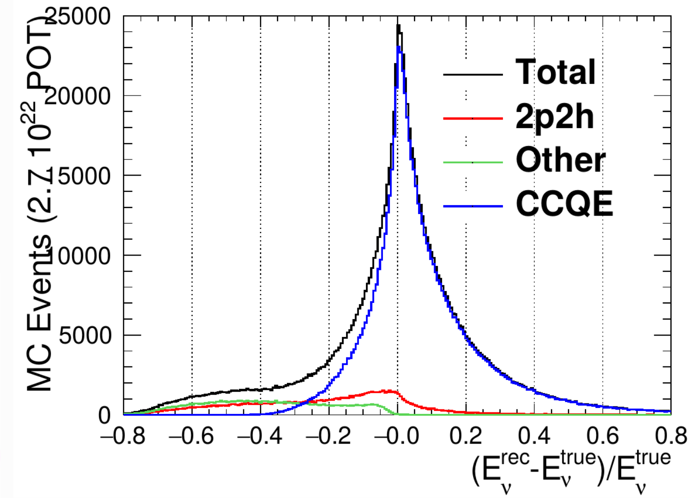
Nuclear physics

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



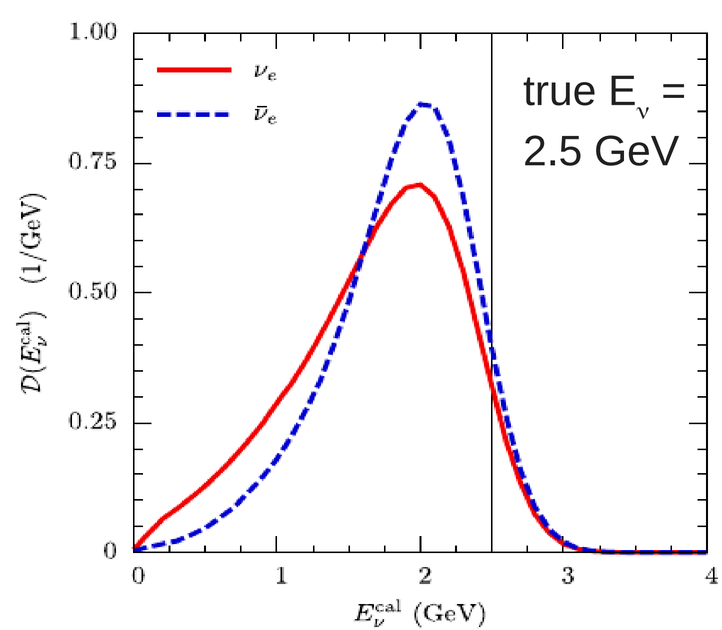


- **Effects on 0nbb searches: gA quenching**

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

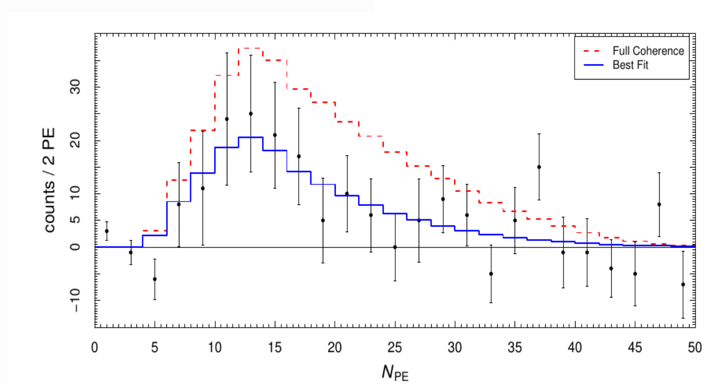
Different terminology for the same problem: g_A quenching → M_A^{QE} puzzle

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:**

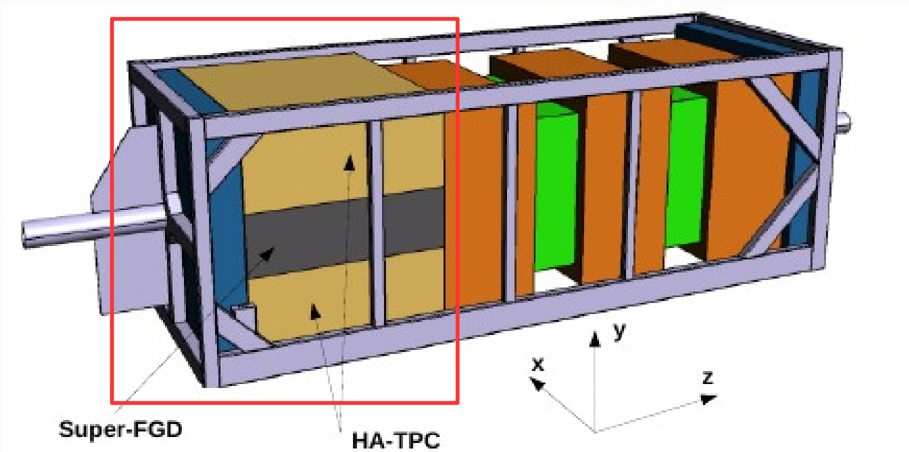
can be sensitive to nucleon form factor when departing from coherence



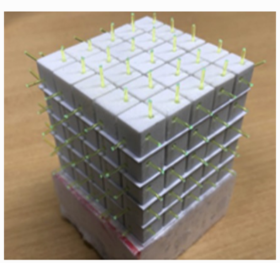
Near detector design

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

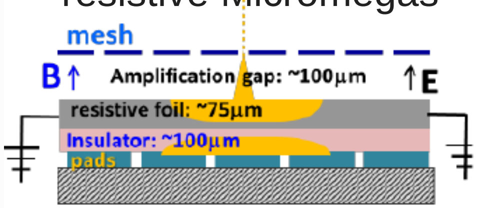
T2(H)K near detector upgrade (ND280)
to be installed in 2021



3D 'pixeled' scintillator

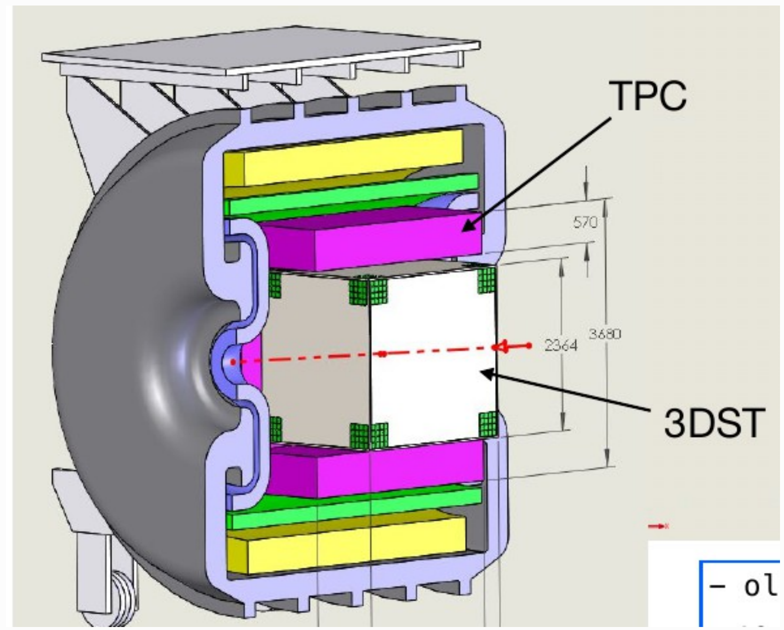


Horizontal TPC with resistive Micromegas



- 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



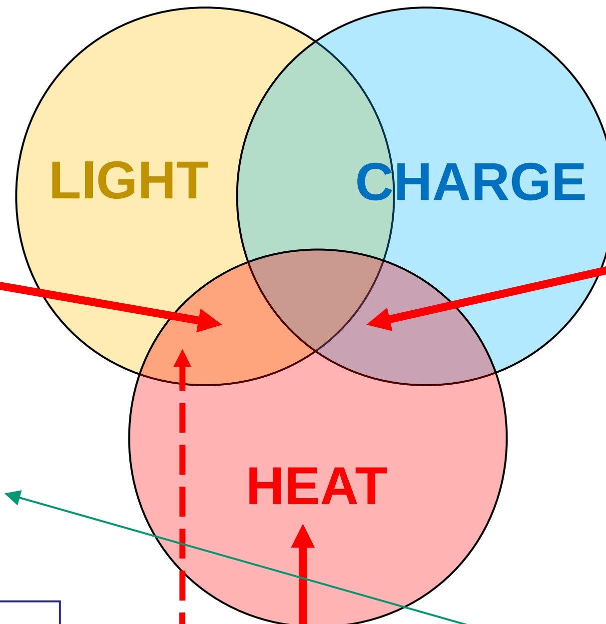
- R&D to adapt to new geometry and magnetic field

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

Bolometric technology in BSMNu

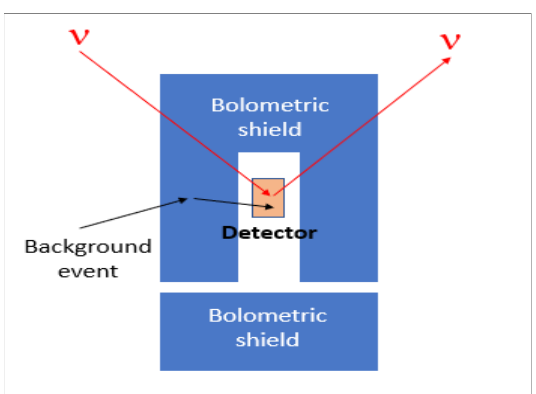
Both **pure** and **hybrid bolometric detectors** are used in BSMNu

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**

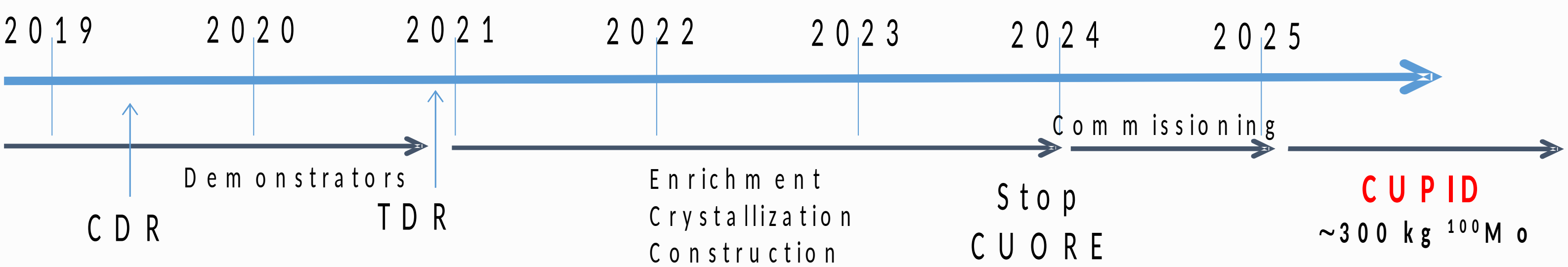
Low threshold in heat channel achieved by **innovative superconductive phonon sensors**

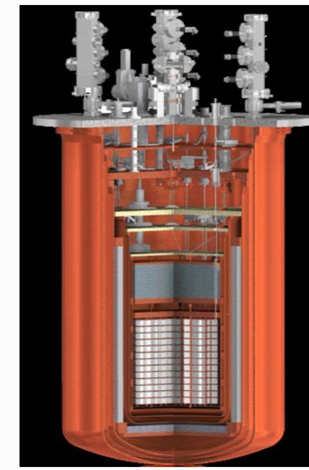
WP5: A.Giuliani, C.Nones, S.Marnieros

Bolometers

CUPID (CUORE Upgrade with Particle ID) is a proposed $0\nu2\beta$ bolometric experiment exploiting the **CUORE infrastructure (LNGS)** and with a **background 100 times lower at the ROI**

Baseline option for CUPID: **$Li_2{}^{100}MoO_4$ scintillating bolometers**

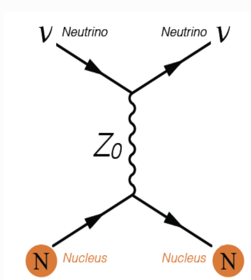




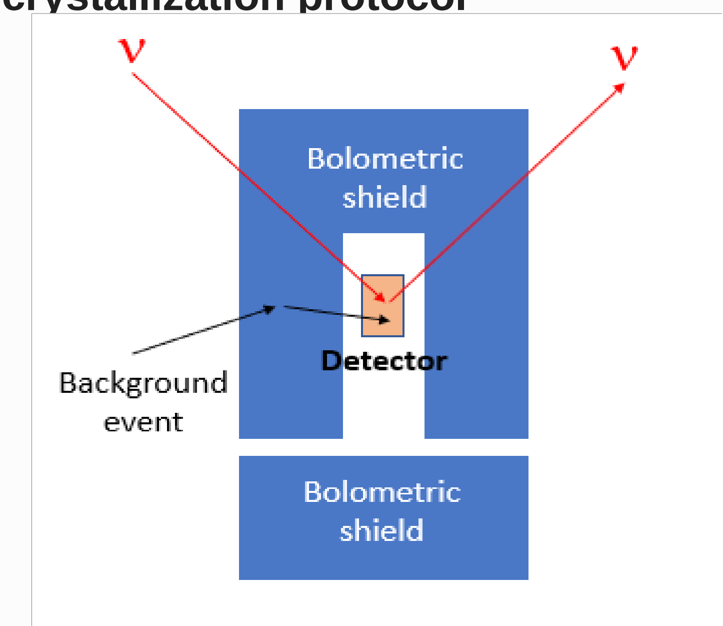
$m_{\beta\beta}$ < 10 – 20 meV

- Conclude **CUPID-Mo data taking** and analysis
- Develop **new demonstrators** for setting **enrichment/purification/crystallization protocol**

RICOCHET and NUCLEUS aiming at studying Coherent Elastic ν-Nucleus Scattering (CENNS) at a nuclear reactor



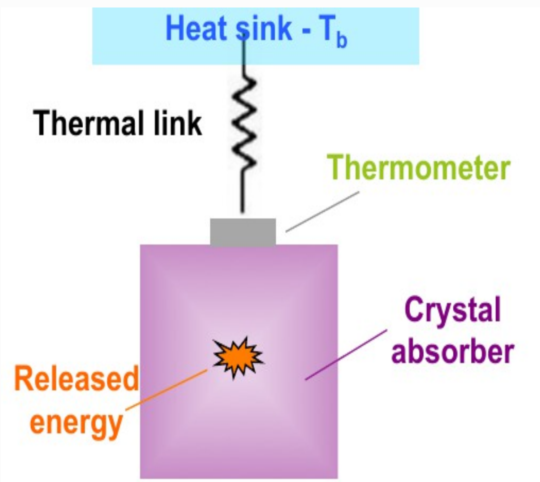
- Neutrino magnetic moment
- New massive weak-interaction mediator
- Non-standard interactions
- Active-to-sterile neutrino oscillations
- In applications, nuclear reactor monitoring

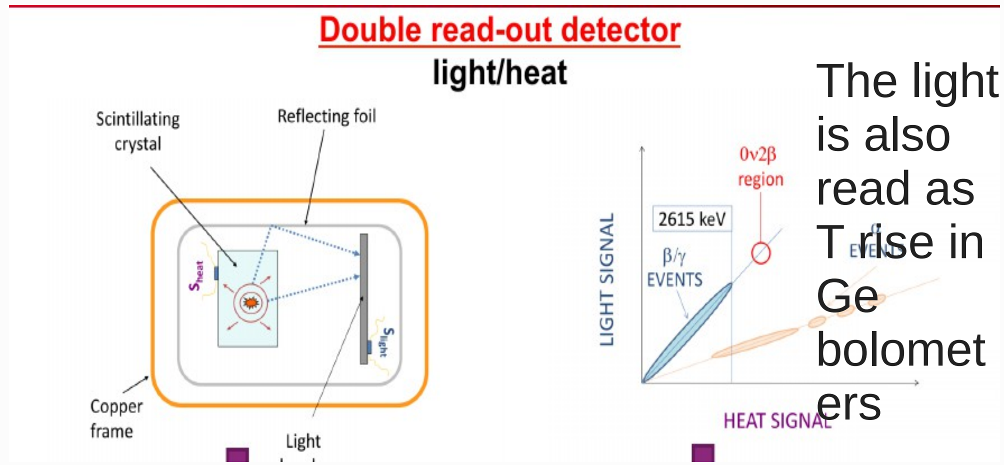


- Low threshold bolometers based on **advanced phonon sensors**
- Internal **active bolometric shields** for background control

→ Applications both in $0\nu2\beta$ and CENNS

Hybrid bolometers in CUPID



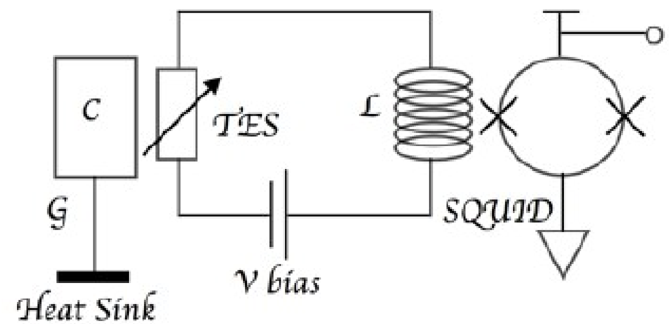


The light is also read as T rise in Ge bolometers

DT = DE/C
At cryogenic temperature C is small enough (eg 100g Ge crystal kept at ~ 15 mK will experience a ~ 0.3 mK temperature rise following a 1 MeV energy deposition)

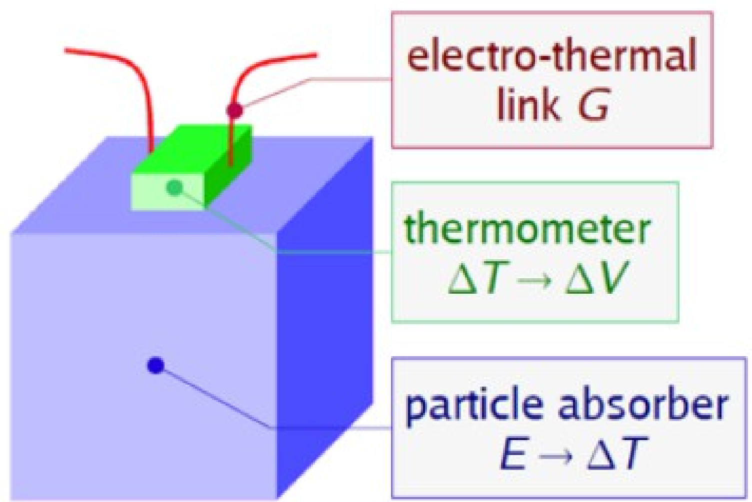
The most mature sensor technology is represented by Neutron Transmutation Doped (NTD) germanium thermistors, consisting of a small Ge crystal whose resistance rises sharply as the temperature decreases.
Possible alternatives are Transition Edge Sensors (TES), in which a superconductive film is kept within the normal-to-superconducting transition, or microwave Kinetic Inductance Detectors (KID), which measure the change of the kinetic inductance of a superconductive element following the absorptions of athermal phonons.
The sensor baseline for CUPID, both for the Li 2 MoO 4 crystals and the light detectors, consists of Ge thermistors, although TESs and KIDs are under study as possible light detectors for their superior signal-to-noise ratio and speed.

Readout Scheme



Readout of TES done using **SQUID** amplifiers, quantum-limited magnetometers, ideal for small currents.

Small changes in temperature can be captured by **Transition Edge Sensors** (TES), which allow great sensitivity to small temperature depositions.

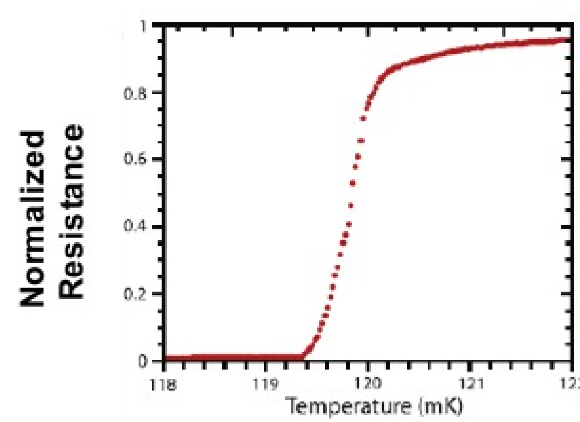


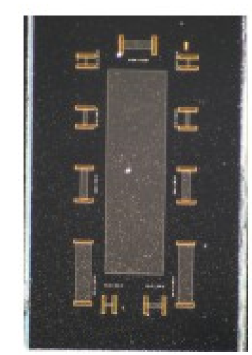
The **absorber** allows conversion from energy to heat (phonons)

For semi-conductors and superconductors, only lattice vibrations contribute to thermal capacitance ($C \sim T^3$)

Small detectors & low temperatures
=
lower thresholds

TES Resistance @ Tc





NUCLEUS

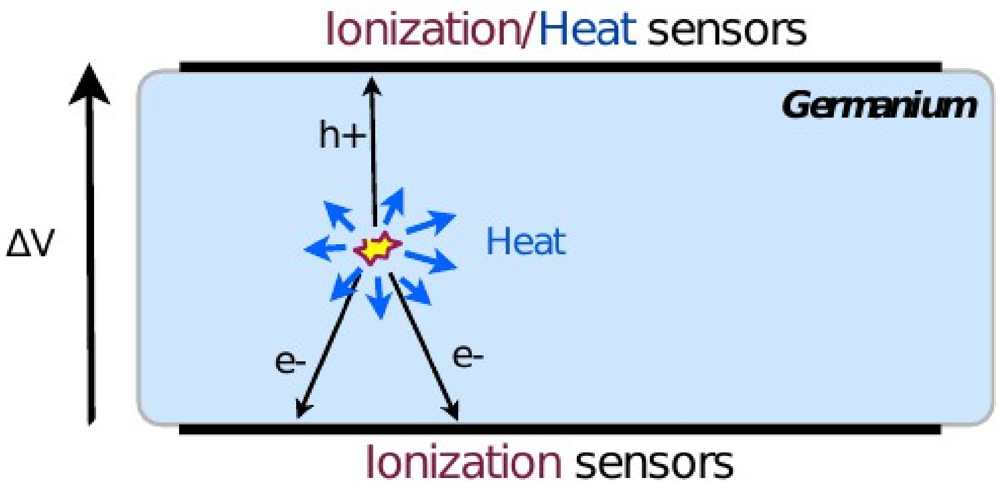
Slow detectors → shielding + small detectors to allow small dead time above-ground
Small detectors also enble low threshold

Each target crystal will be equipped with an evaporated tungsten TES (superconducting transition temperature $T_c \sim 15$ mK) readout by SQUID (Superconducting QUantum Interference Device) electronics. This thermometer technology was developped for the CRESST experiment

The NUCLEUS collaboration also envisions to use target crystals made of Mo-doped Li_2WO_4 material, such as those developed in the BASKET project. This target material basically exhibits the same advantage than $CaWO_4$ for the detection and study of CEvNS, except that **the presence of ^6Li allows to tag neutrons through the $^6Li + n \rightarrow \alpha + t$ reaction, which has a large cross section. If the energy release of the $\alpha + t$ event $E = 4.78$ MeV $+ E_n$ (E_n being the initial energy of the neutron) is properly measured, Mo-doped Li_2WO_4 target crystals would allow the monitoring and the characterization of the neutron backgrounds in the direct vicinity of the target volume.**
This feature would be a key advantage in a reactor CEvNS experiment because neutrons are the ultimate type of background to fight against, as they are indistinguishable from a CEvNS nuclear recoil.

RICOCHET

Double Energy Measurement for Semiconductor Germanium Detectors



- Ionization / heat ratio depends on the particle type
- Achieve a 10 eV ionization resolution
- Great synergy with the EDELWEISS collaboration