Neutrino physics beyond PMNS

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Prospectives du DPhP
16 octobre 2017, Ferme du Manet

DE LA RECHERCHE À L'INDUSTRIE
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Outline

1. Sterile neutrinos

- Reactor antineutrino anomaly and light sterile neutrino searches
- Search for keV sterile neutrinos

2. Neutrino physics at ultra low energies

- Physics cases relevant to the ultra low energy domain
- Envisaged R&D technology

. Light sterile neutrino activities…

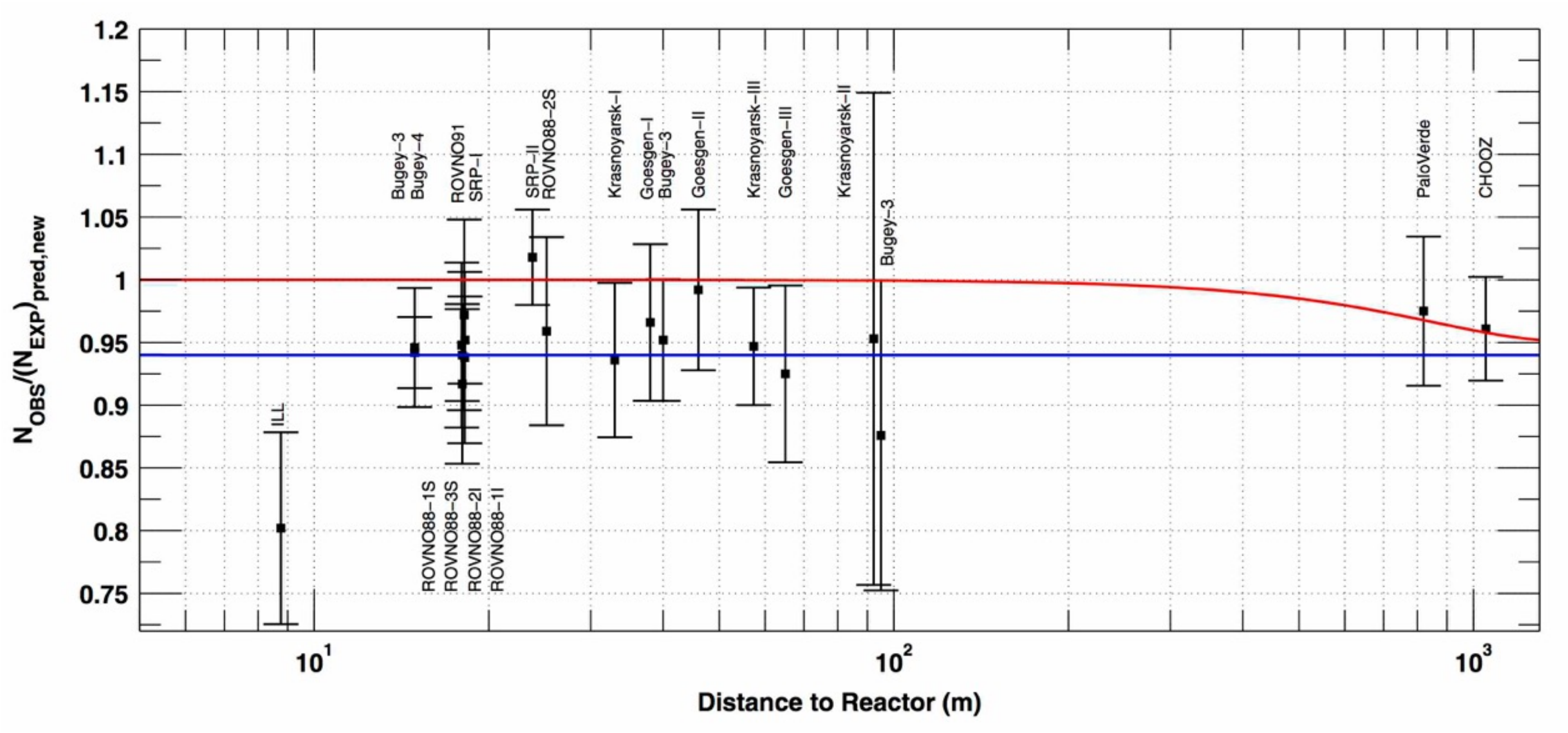
Reactor antineutrino anomaly (RAA)

- Re-evaluation of the ILL β spectra conversion procedure
- Refined corrections to β decay modeling + reactor off-equilibrium effects
- Updated neutron lifetime measurement to normalize IBD cross-section

Th. Mueller et al., Phys. Rev. C 83 (2011)
P. Huber, Phys. Rev. C 84 (2011)

Systematic deficit of measured ν rates with respect to expectations in 19 old reactor experiments with baselines < 100 m

μ = 0.943 ± 0.023
(2.7σ stat. significance)

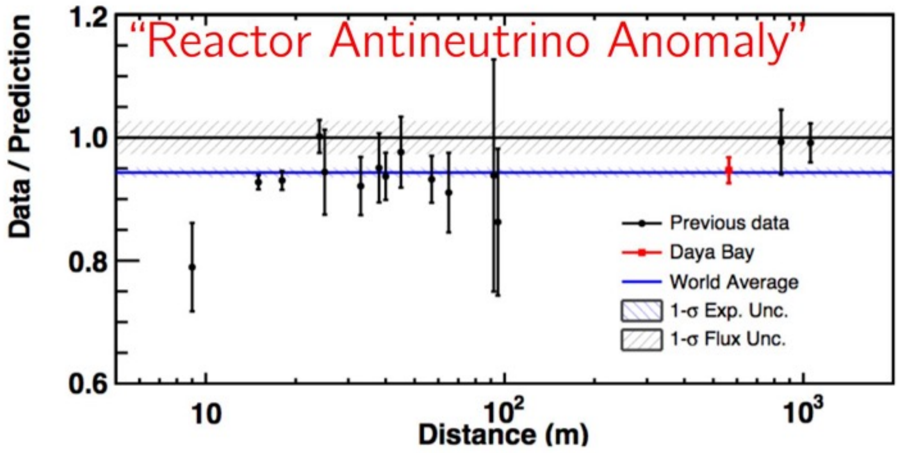


G. Mention et al., PRD 83 (2011)

Reactor ν fluxes: what's new since 2011?

- Daya Bay, Double Chooz, Reno & NEOS reactor ν spectrum measurements

Integral flux measurements confirm the deficit



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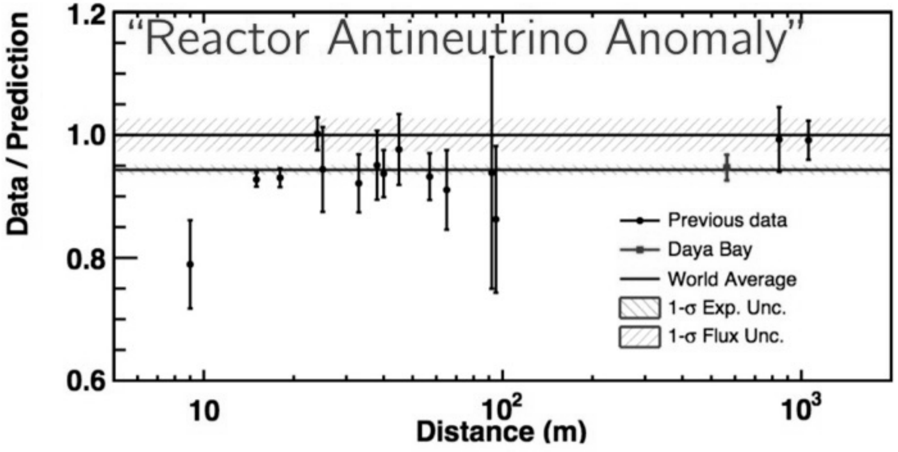
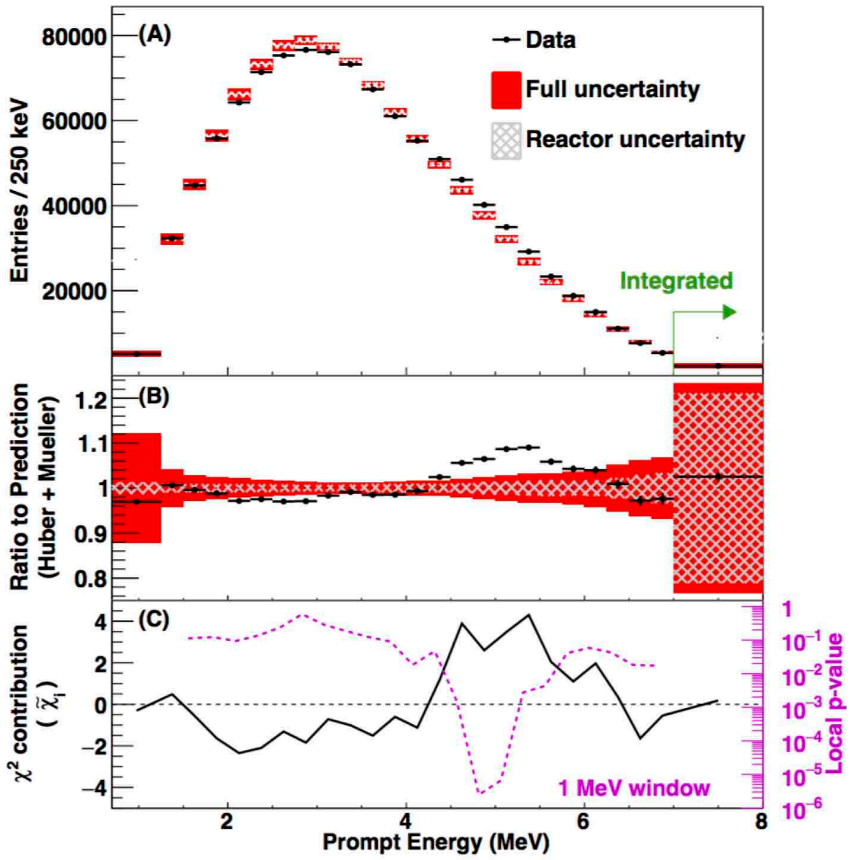


Shape disagreements with respect to predictions: "shape anomaly"



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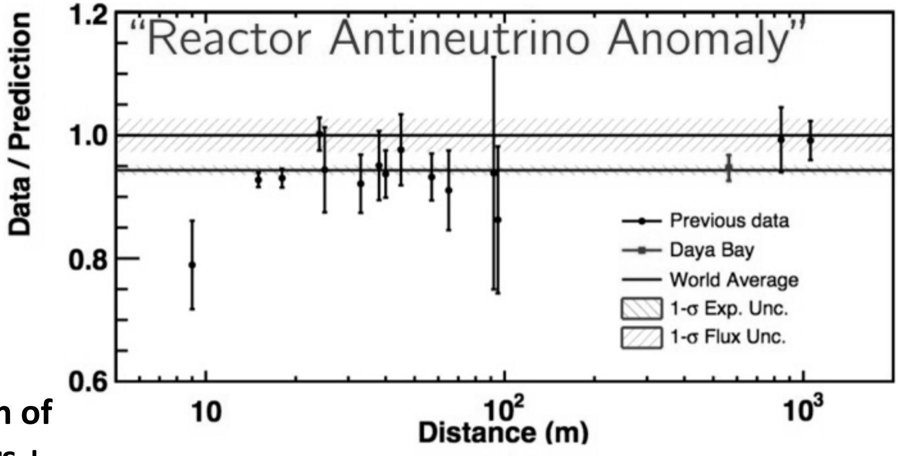
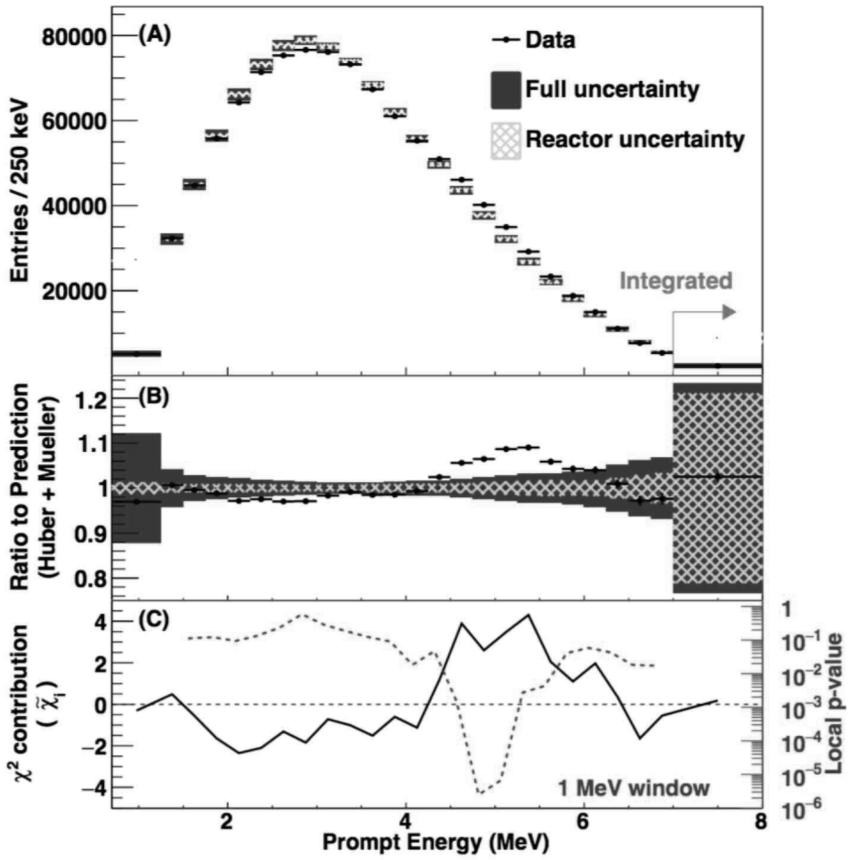
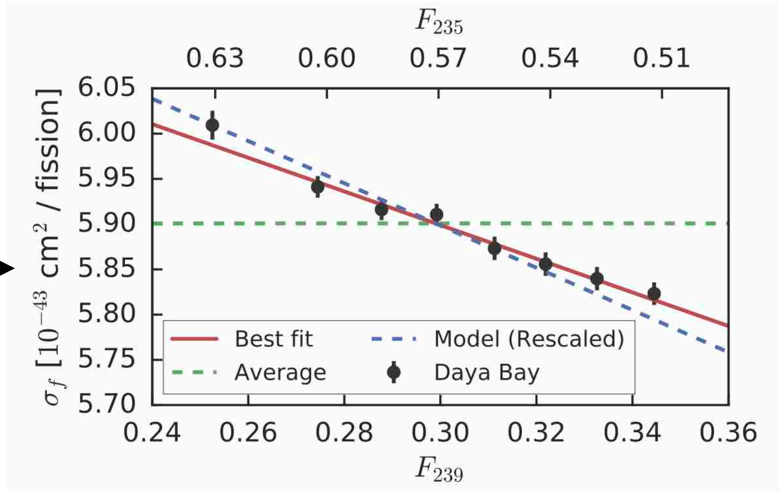
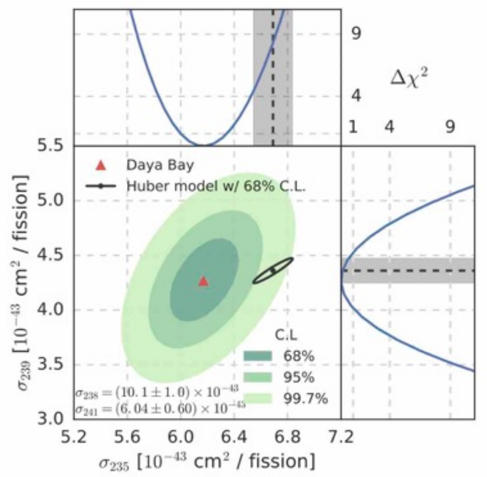




Disagreements with the expected evolution of ν flux with isotopic composition of reactors + ^{235}U individual IBD yield prediction

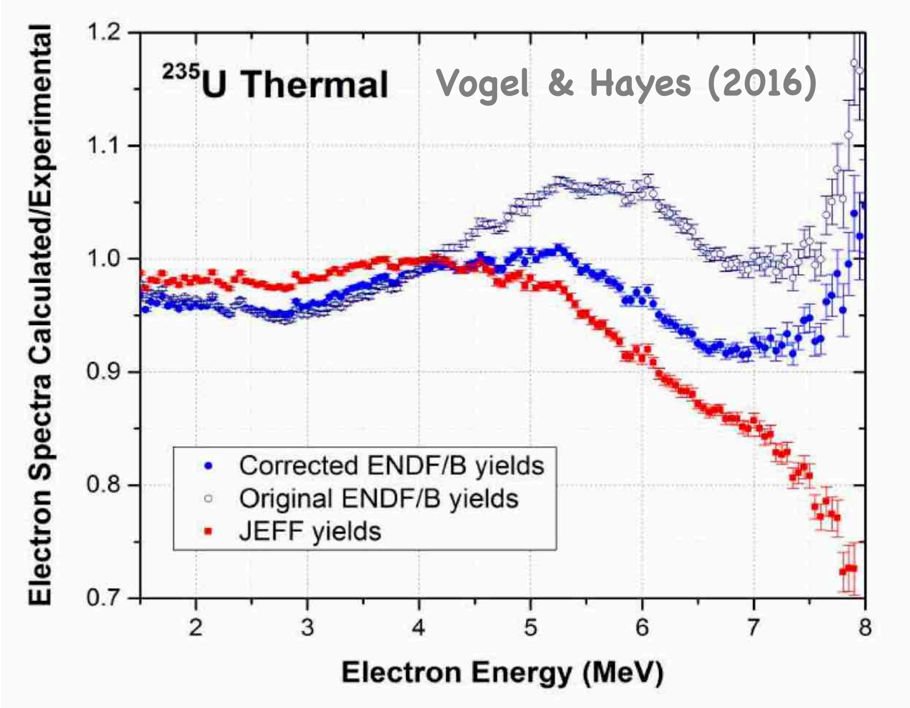




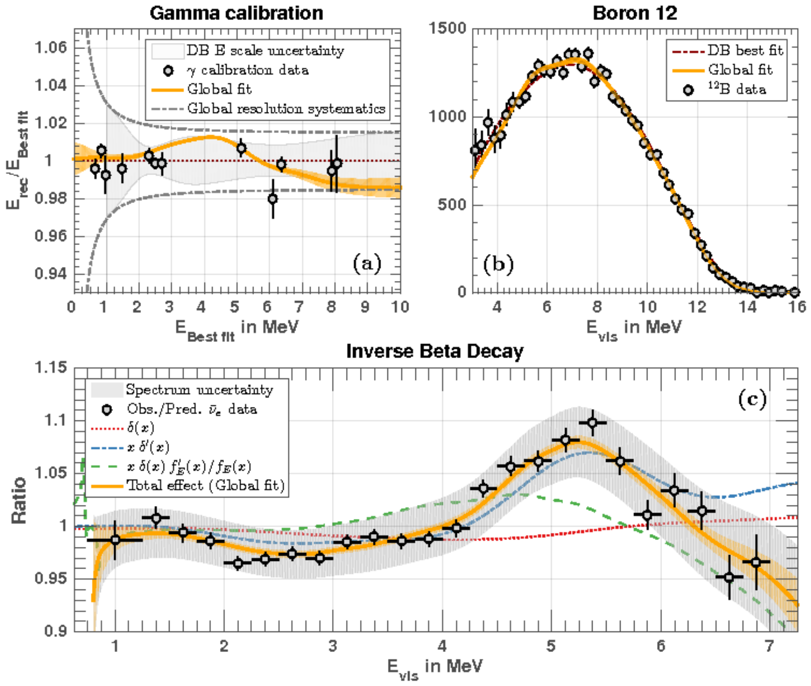
Reactor ν fluxes

- Several theoretical investigations motivated by these results, with different conclusions:
  - Potential weaknesses in reactor ν flux predictions could explain the origin of the rate and shape anomalies: β ILL spectra conversion, treatment of forbidden β decays, problems in nuclear databases, details about reactor physics, etc …
  - Residual non-linearities in the energy scale of detectors could explain the shape anomaly

Effect of nuclear databases on ν flux computation for ^{235}U



Effect of residual non-linearity in Daya Bay's energy scale calibration on ν flux measurement



Mention et al., (2017)

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Problems in the predictions? Detector effects?

Situation unclear…

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Problems in the predictions? Detector effects?

Situation unclear…

NENuFAR project (New Evaluation of Neutrino Fluxes At Reactors) to fully revise calculations and go at a deeper level:

- Lead by DPhP
- Funded by PTC "simulation"
- Try to gather and benefit from all relevant expertise available at CEA: collaboration with DPhN & DEN/DM2S/SERMA (reactor computations), with possible extension to DRT/LIST/LNHB (state-of-the-art β decay modeling) and DAM (nuclear structure calculations)

Search for SBL oscillations

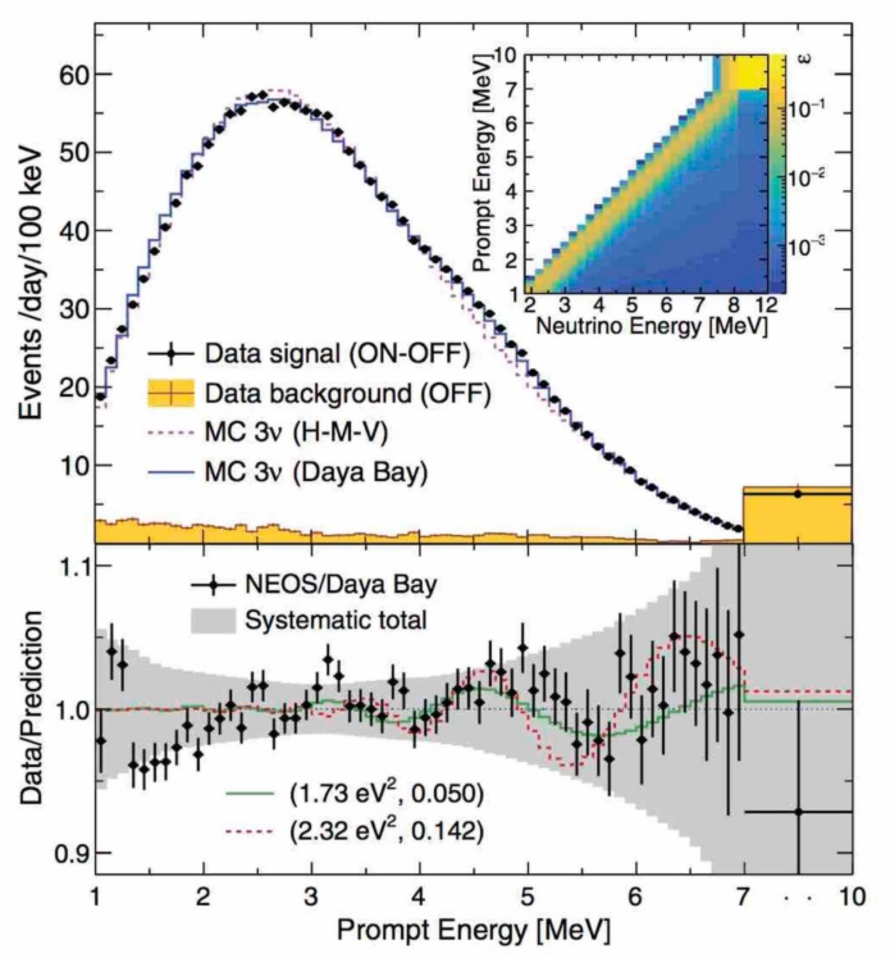
- If RAA is truly here, it could be interpreted by short baseline oscillation generated by a 4th neutrino state with $\Delta m^2_{41} \sim 1$ eV^2
- Many experimental efforts to test the RAA and look for SBL oscillation in the $\nu_e \longrightarrow \nu_e$ channel:

Name	Source	Baseline	Technology	Status
NEOS (Korea)	Commercial reactor	24 m	LS	Over
DANSS (Russia)	Commercial reactor	10-12 m	Segmented PS	Data collection phase
PROSPECT (USA)	Research reactor	7-12 m (movable)	Segmented LS	Construction phase
STEREO (France/Germany)	Research reactor	9-12 m	Segmented LS	Data collection phase
SoLid (France)	Research reactor	5.5-10 m	Segmented PS	Construction phase
Neutrino-4 (Russia)	Research reactor	6-12 m (movable)	LS	Data collection phase
CeSOX (France/Italy)	^{144}Ce source	4-16 m	LS	Data collection in 2018
BEST (Russia)	^{51}Cr source	O(1 m)	Gallium	Conception phase

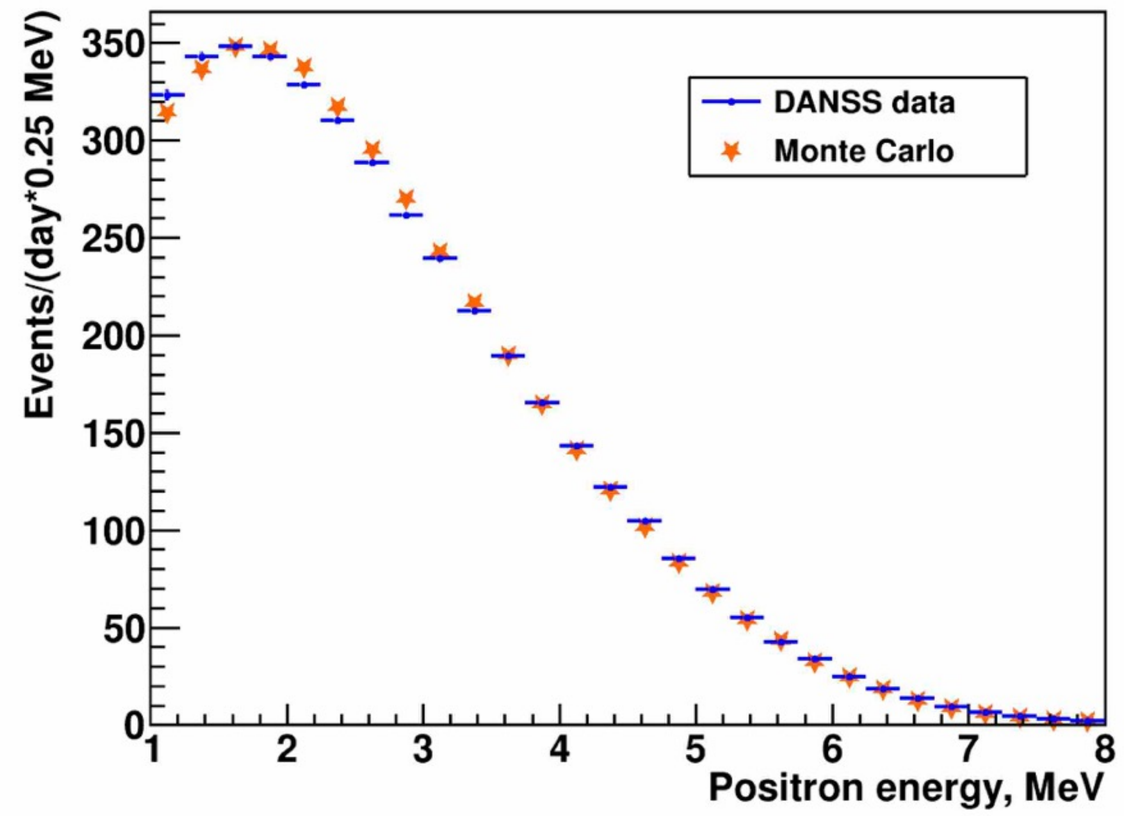
Search for SBL oscillations

- NEOS & DANSS first results: no indication for SBL oscillations in the $\nu_e \longrightarrow \nu_e$ channel

Ko et al., PRL 118 121802 (2017)



M. Danilov, talk at HEP Venice (2017)



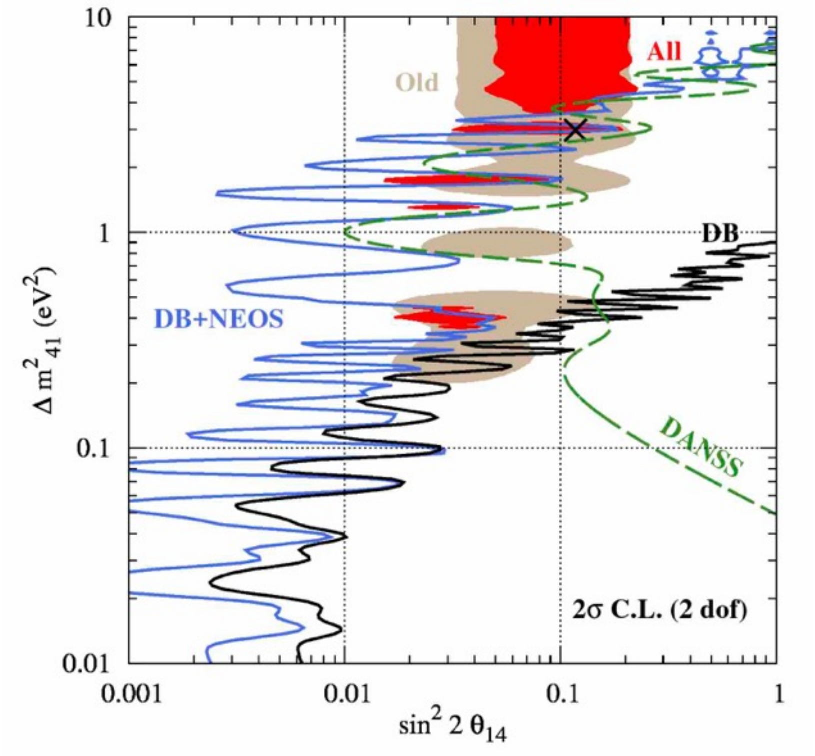
Status of RAA & SBL oscillations searches

- Global fits combining Daya Bay, NEOS & DANSS data with old reactor experiments cannot favor one the following hypotheses to explain the RAA:

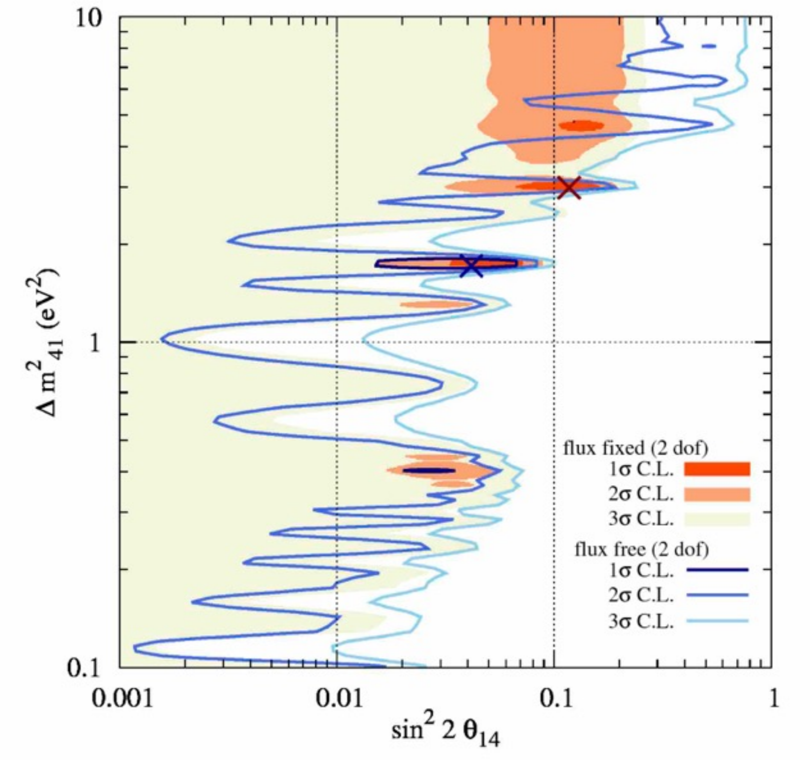
  1. Wrong computation of the reactor ν fluxes
  2. Existence of short baseline oscillations generated by a 4th neutrino mass state

Dentler et al., arXiv:1709.04294 (2017)

Comparison of Daya Bay, NEOS & DANSS exclusion contours with old reactor experiments

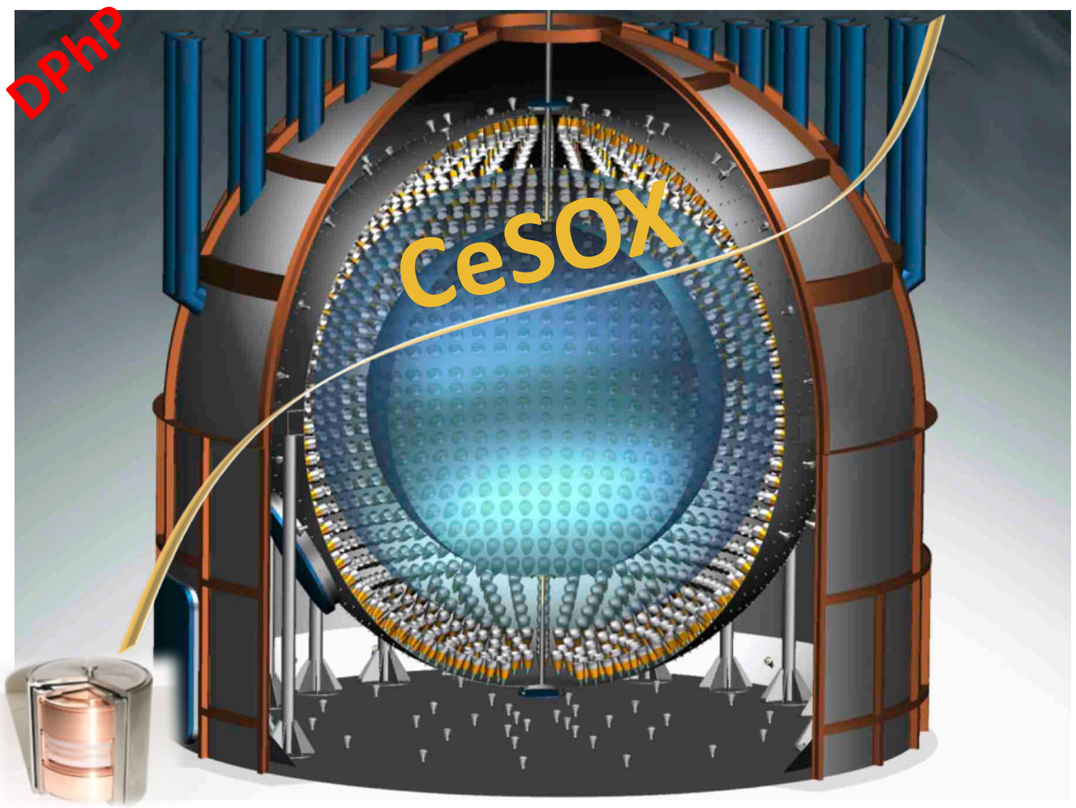


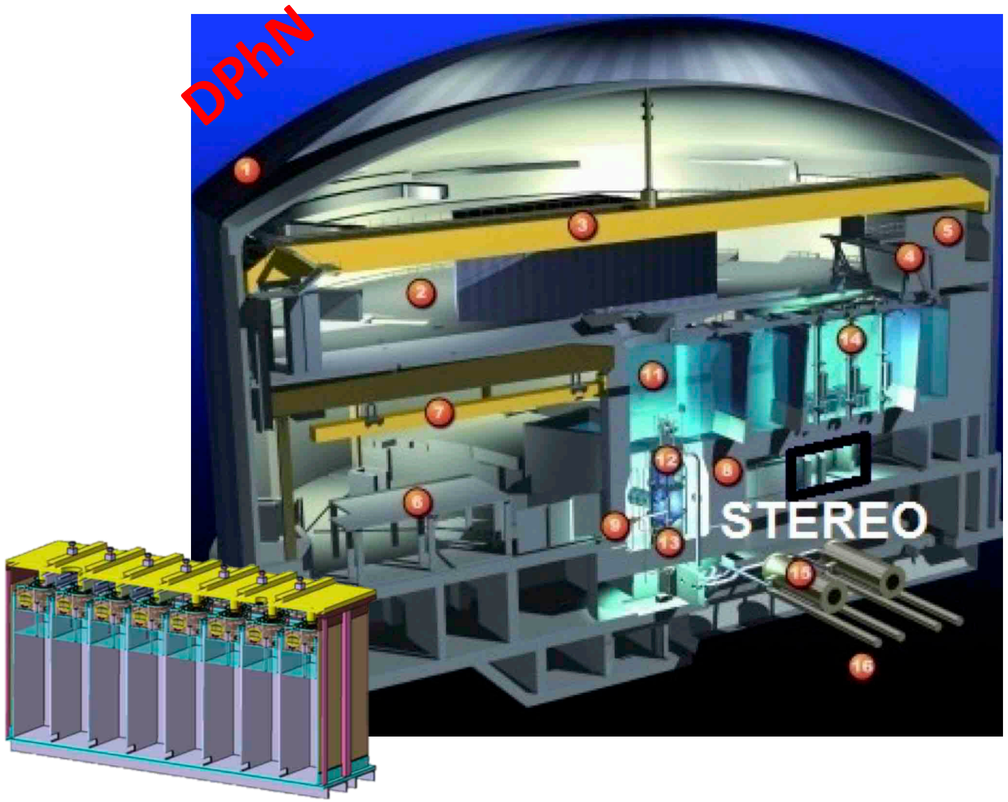
"Free" fluxes vs "Fixed" fluxes analyses with all available reactor data



RAA & SBL oscillations searches at Irfu

- Experimental efforts to test RAA search for SBL oscillations are more than necessary, story not yet over.
- **CeSOX & STEREO** have unique advantages to definitively address the RAA and the existence of light sterile neutrinos





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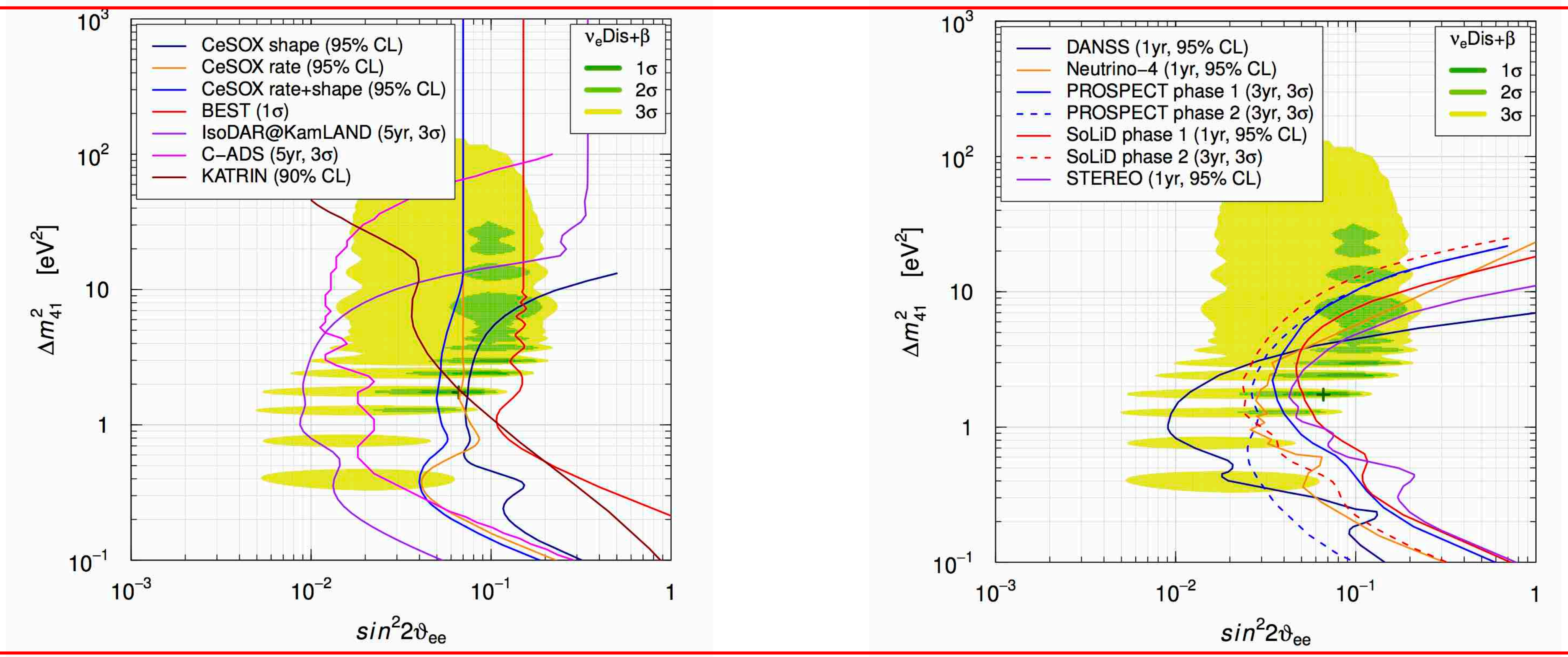
S. Gariazzo, et al. JHEP 1706 (2017) 135

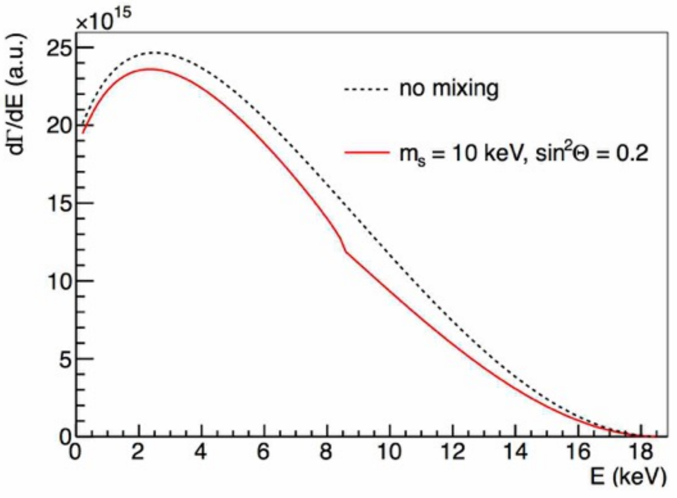


- Very interesting possibility to combine with **KATRIN** search for light steriles: sensitivity gain at high Δm^2

. keV sterile neutrino related activities…

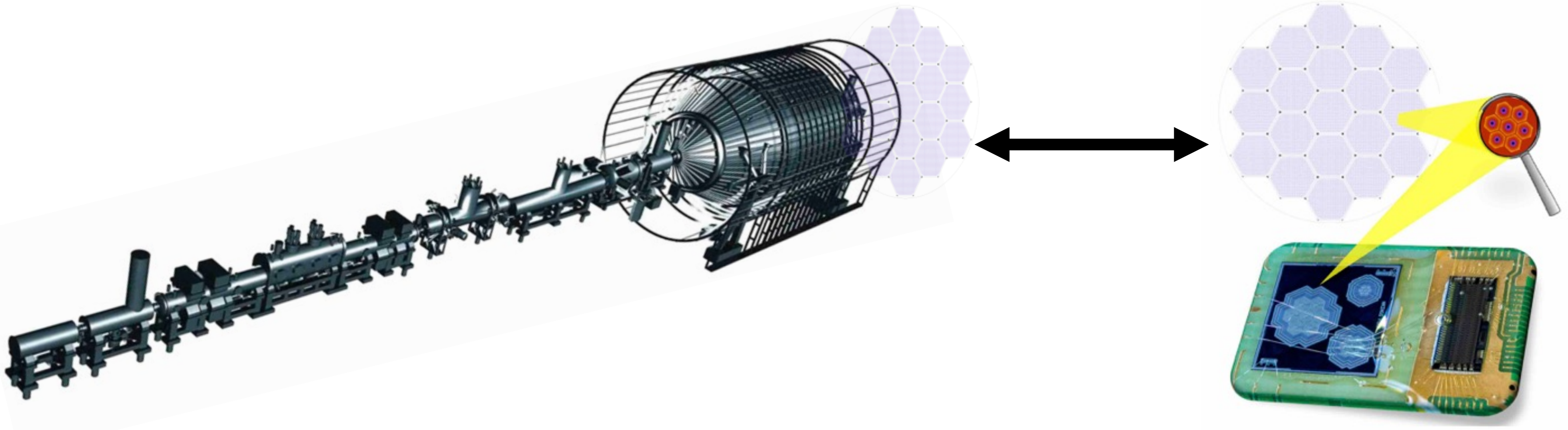
TRISTAN: TRitium Investigation on STerile to Active Neutrino mixing

- Look for a "kink" in the β spectrum of tritium, which would sign mixing of active ν_e neutrinos with a new mass state in the keV range (good candidate for DM)



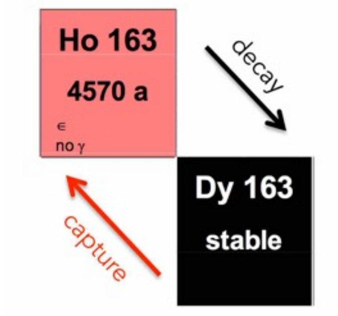
- Need to measure full ^3H β spectrum: **TRISTAN** second phase of KATRIN experiment will use new pixelated Si sensors developed at MPI (Munich) and KIT (Karlsruhe)

- New R&D activity at DPhP:
  - detectors characterized with low noise readout electronics developed at DaP & DEDIP
  - tested in a cooking pot sent in the upper atmosphere in a balloon flight experiment & at Troitsk exp.



DyNO: search for relic keV ν trapped in the galactic halo

- Search for capture of ν_e trapped in our Galaxy on ^{163}Dy ($E_\nu \geq 2.8$ keV) $\quad ^{163}\mathrm{Dy} + \nu_e \rightarrow ^{163}\mathrm{Ho} + e^-$

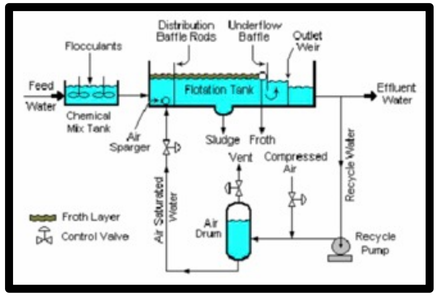


- Hence, would be sensitive to mixing with a 4th mass state at the keV scale
- Strategy: look for excess of ^{163}Ho in dysprosium rich ores with respect to expected background
- Challenging multi-step procedure:

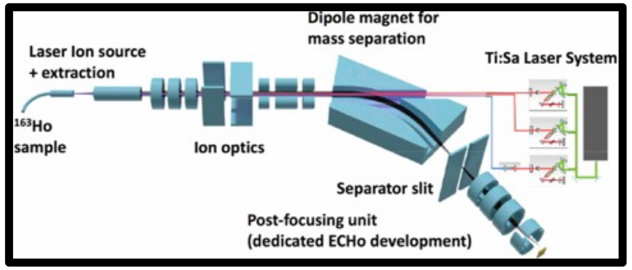
T. Lasserre et al., arXiv:1609.04671 [hep-ex]

Ore extraction

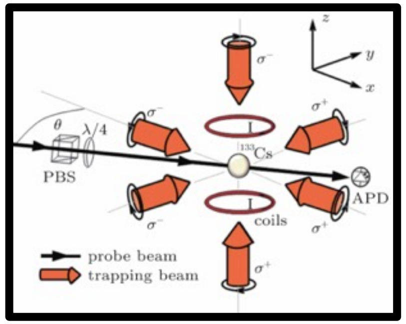
Chemical extraction

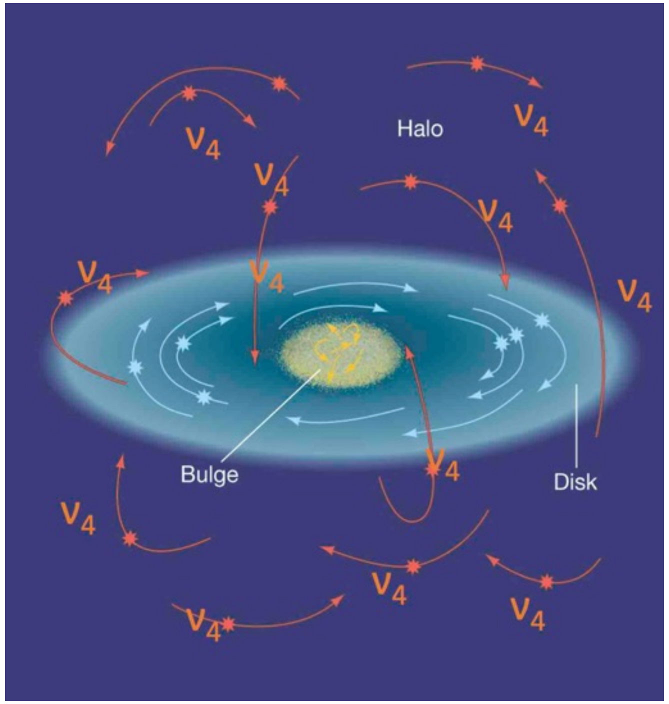


Mass spectrometry

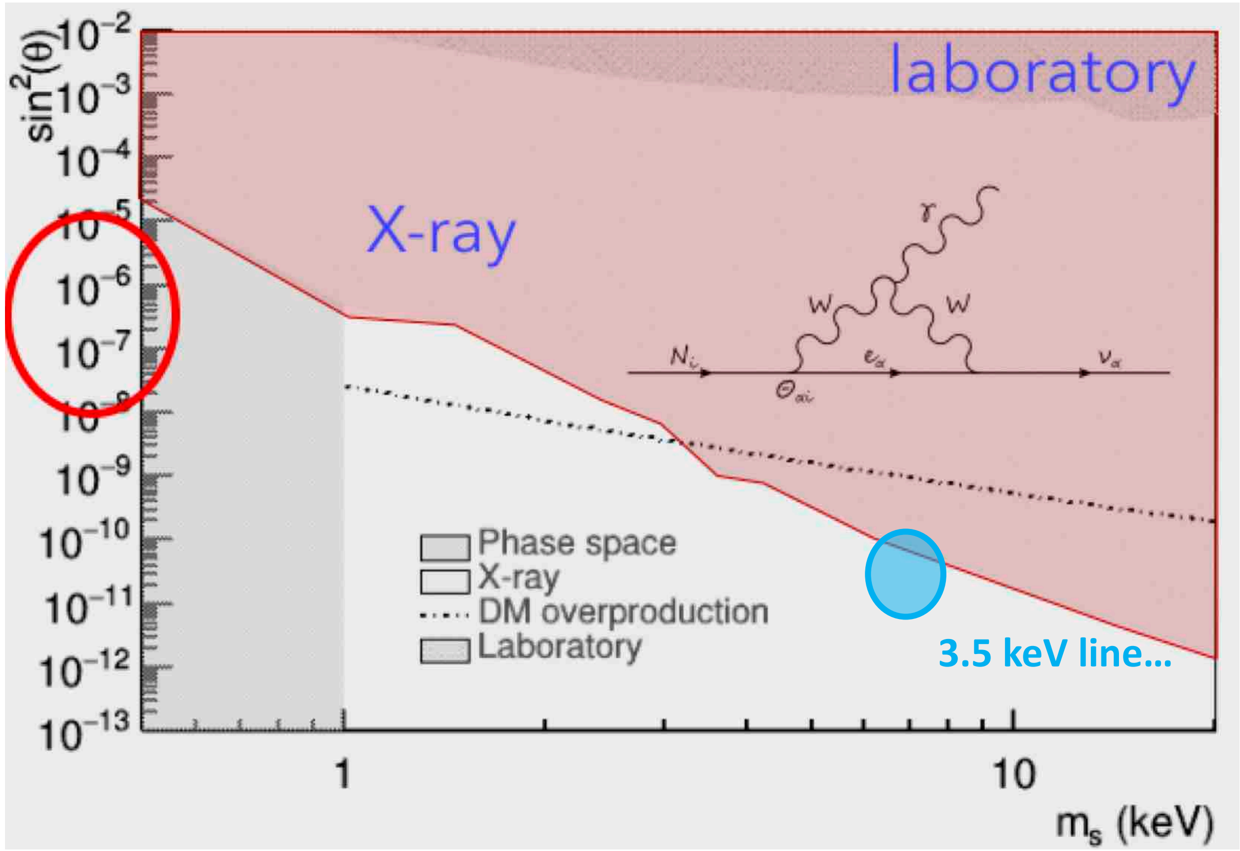


Magneto optical trap

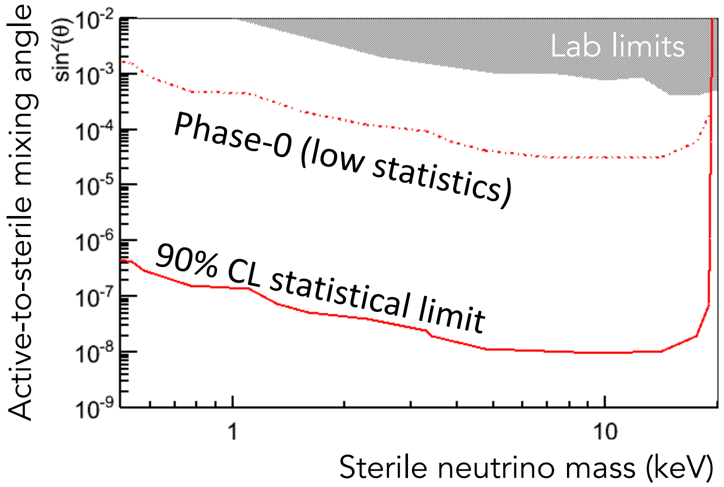




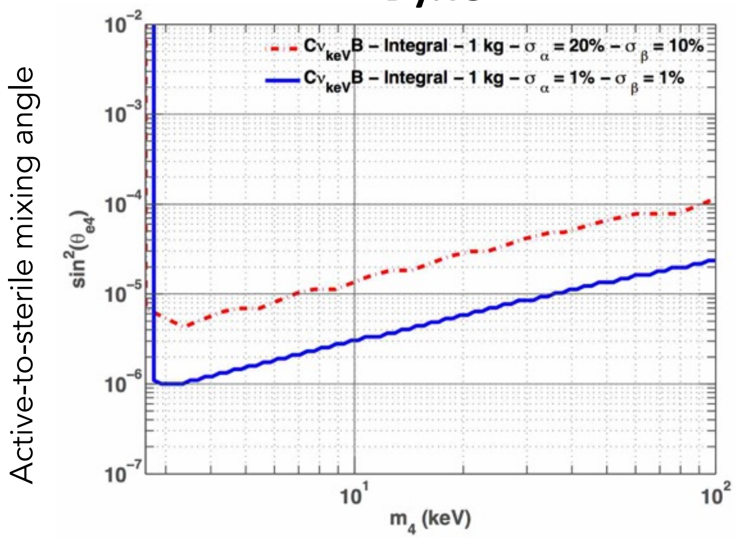
TRISTAN & DyNO sensitivities to mixing



TRISTAN



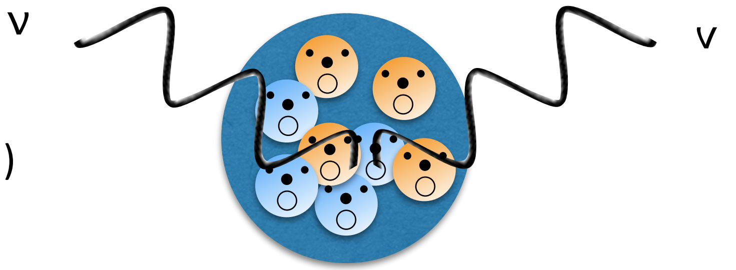
DyNO



. Going to ultra low energies…

Ultra low energy neutrino physics

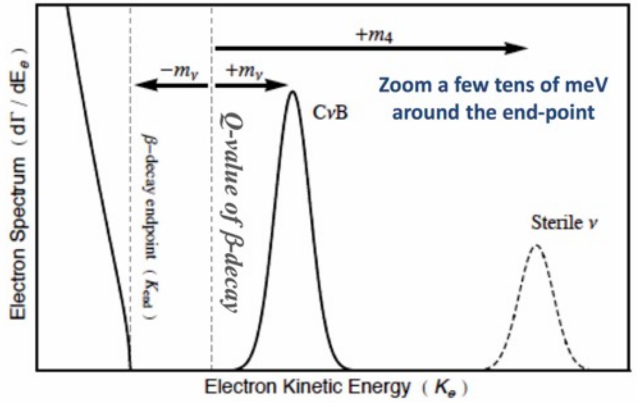
- **Coherent neutrino-nucleus scattering (CEνNS):** extremely low recoils energies ($\lesssim$ 100 eV)
  - High cross-section (up to 1000 higher than IBD)
  - Fine tests of the standard model at low energies (Weinberg angle, magnetic moment, search for non-standard interactions)
  - Nuclear physics application: studying nuclear structure (weak charge density distribution, etc…)
  - Supernovae dynamics, irreducible background to direct DM searches
  - Promising for non-proliferation applications (compact neutrino detectors)



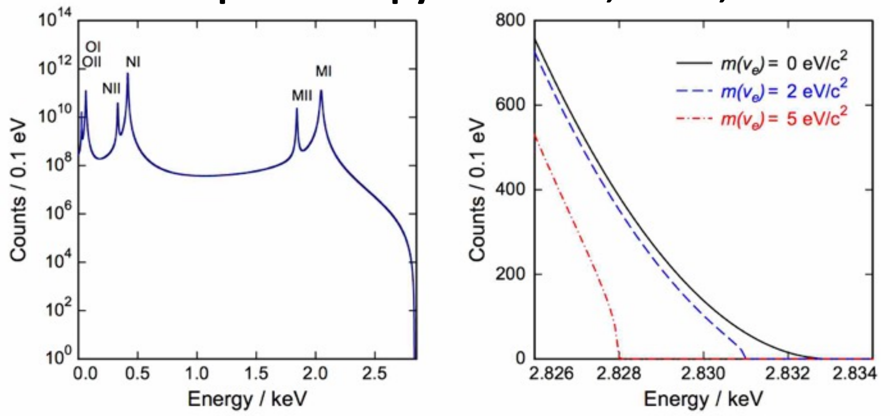
- **Direct measurement of neutrino absolute mass scale:** precisely measuring electron capture or β decay spectrum from low Q_β radionuclides (^{163}Ho, ^{187}Re) with micro-calorimetry techniques
- **Detection of big bang relic neutrinos:** detecting e^- from neutrino capture on ^{3}H at $E = Q_\beta + m_\nu$

Need ultra low energy resolution (< 10^{-3} !)

CνB: PTOLEMY



^{163}Ho spectroscopy: HOLMES, ECHo, MARE



Detecting and measuring CEνNS at Chooz?

- Process detected by the **COHERENT** collaboration this summer (“classical” detection techniques): pragmatic approach

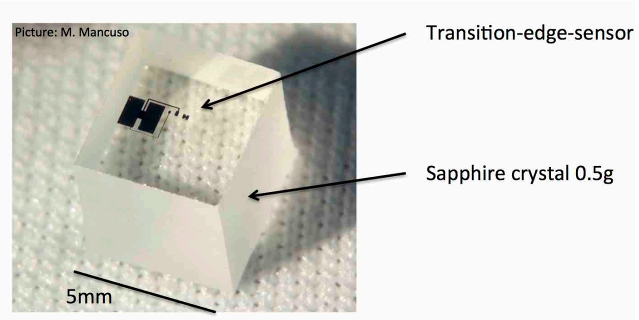
- Prospective for measuring CENNS at Chooz with low temperature macro-bolometers are under study. Two options:

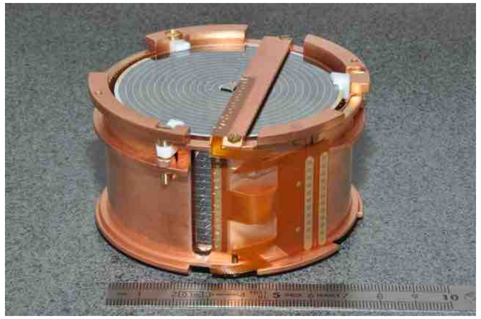
  - Using the Double Chooz near lab (~ 400 m): low signal rate, but low background rate
  - Using a “very near site” (~ 100 m): high signal rate but high background rate

- Many challenges:

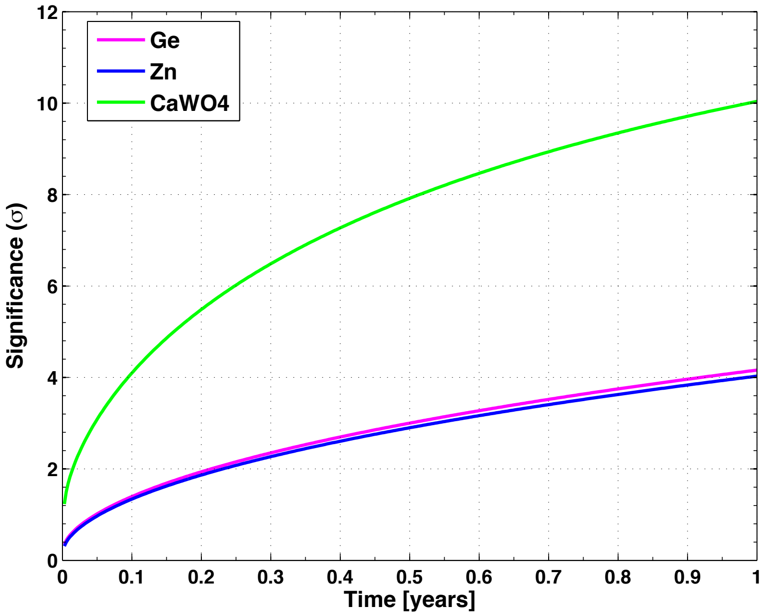
  - Reduce macro-bolometers energy threshold down to 10-100 eV
  - Speed up macro-bolometers time response: from ms to µs scales (especially relevant for very near site)

- On-going discussions with potential partners at MIT/IPNL (“Ricochet” project) & MPI Munich (ν-CLEUS project) for repurposing 0.1-1 kg of DM detectors at Chooz



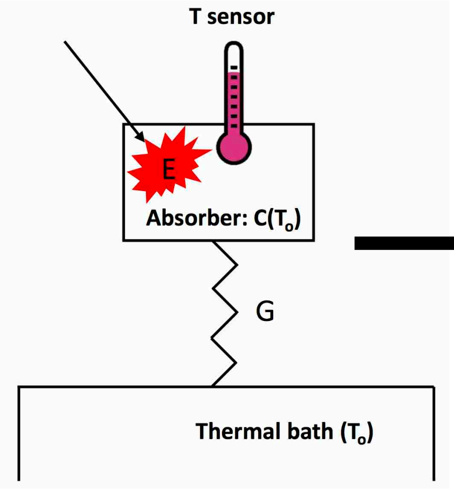


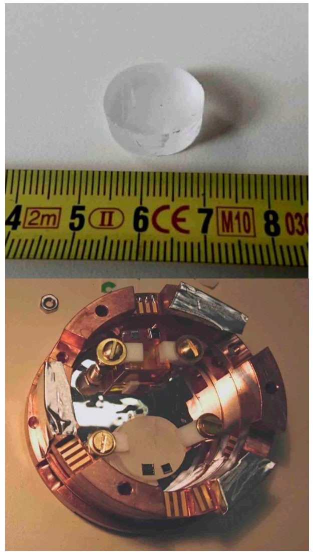
Expected sensitivity (80 m from the cores)



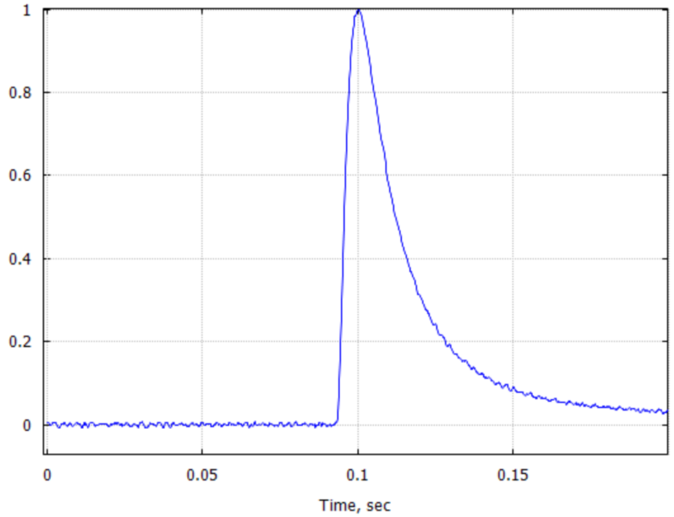
BASKET R&D program

- **BASKET** (Bolometers At Sub-KeV Thresholds) aims at conducting a R&D program on innovative crystals and temperature sensors to:
  - Lower energy threshold
  - Improve time response
  - Improve energy resolution
  - Improve background rejection





First BASKET Li_2WO_4 detector light !



- Lead by DPhP. Partnership with DRT/LIST, DRT/LETI & CNRS/CSNSM: gather and benefit from different high-level expertises in the field of cryogenic detectors and electronics

- Funded by PTC “Intrumentation” and Labex P2IO

- Many synergies and applications: neutrino physics (00νβ, CEνNS, neutrino mass, CνB), high-resolution spectroscopy for radionuclide metrology, etc…

Summary

1. Sterile neutrinos

- **NENuFAR** + **CeSOX + KATRIN**: address the RAA & search for light sterile neutrinos
- **TRISTAN** + **DyNO**: search for keV mass states

2. Neutrino physics at ultra low energies

- Prospective for a CEνNS experiment at Chooz
- **BASKET** R&D program: innovative cryogenic detectors for neutrino physics at ultra low energies & beyond…

Backup slides

CeSOX + STEREO + KATRIN combination

The RAA+GAA parameter space is probed at 98% C.L.