On CEνNS detection by the COHERENT collaboration: perspectives in France & physics applications

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GdR neutrino
November 20th 2017

Outline

1. **Coherent elastic neutrino-nucleus scattering (CEνNS) in a nutshell**

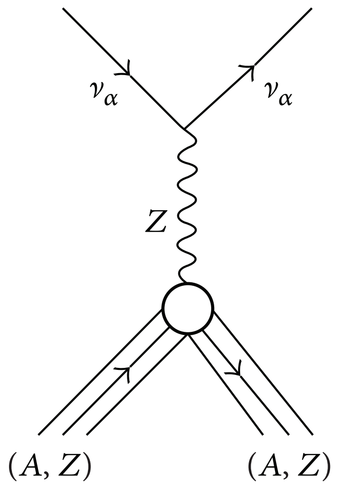
2. **The COHERENT detection: a pragmatic (but still not easy) approach**

3. **Physics applications & perspectives in France**

. CEνNS

Coherent elastic neutrino nucleus scattering

- Neutral current process first predicted by Freedman (1974), which is insensitive to neutrino/antineutrino flavor



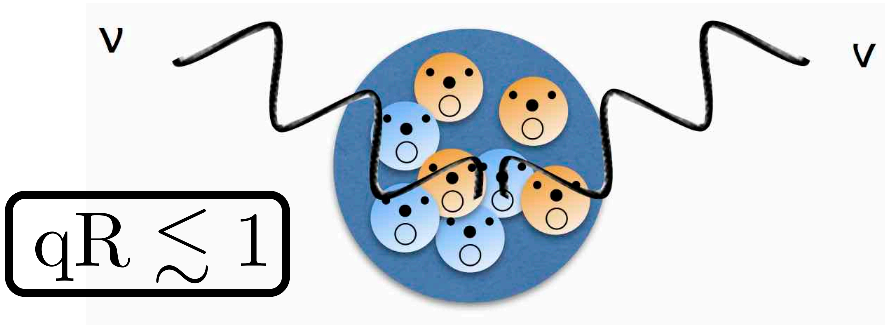
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

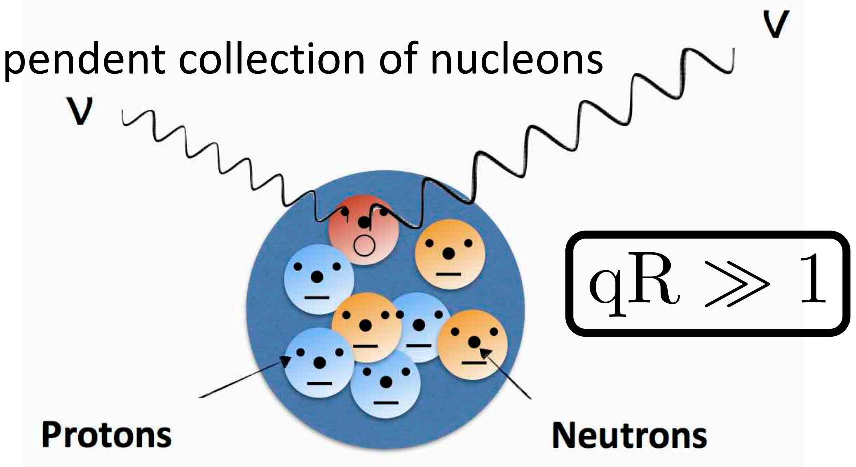
If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

- **Coherence:** the neutrino sees the nucleus as a whole, and not anymore as an independent collection of nucleons



q: momentum transfer
R: nucleus size

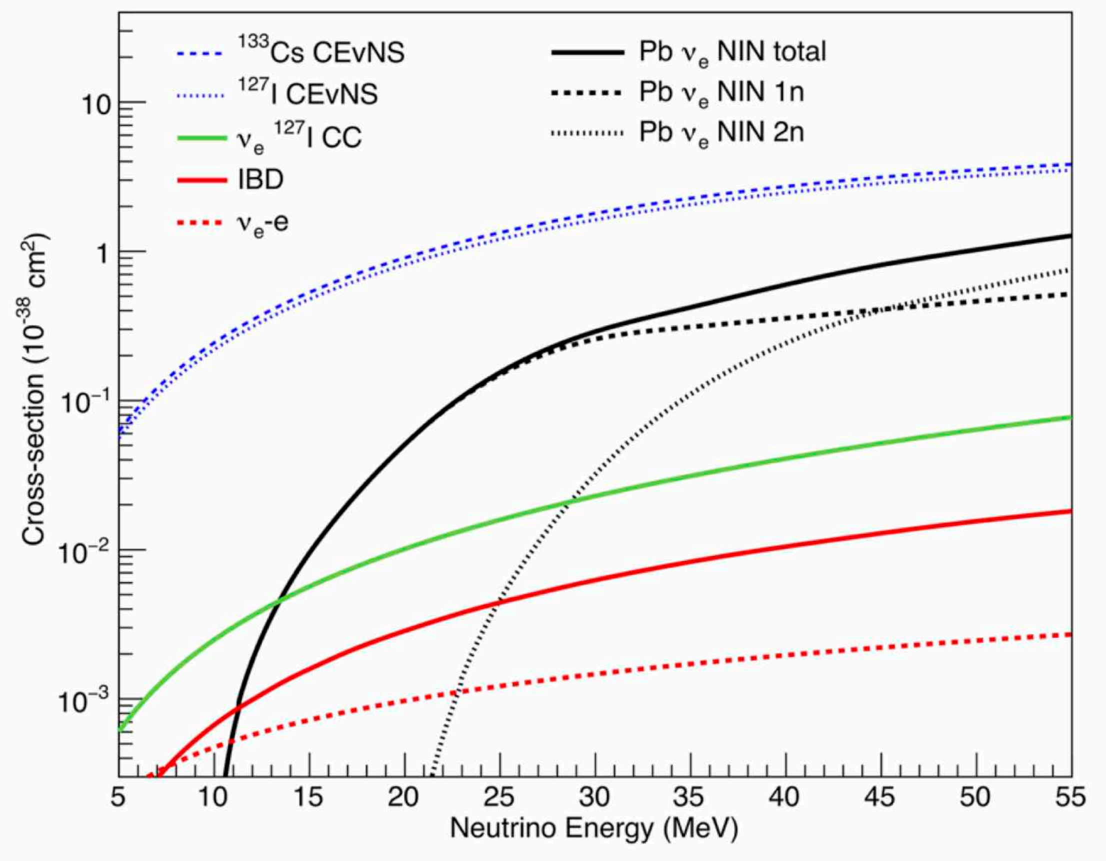
Aluminium: 1/R ≈ 60 MeV
Lead: 1/R ≈ 30 MeV



Coherent elastic neutrino nucleus scattering

- Cross-section mostly scales with the (number of neutrons)^2 in the target nucleus:

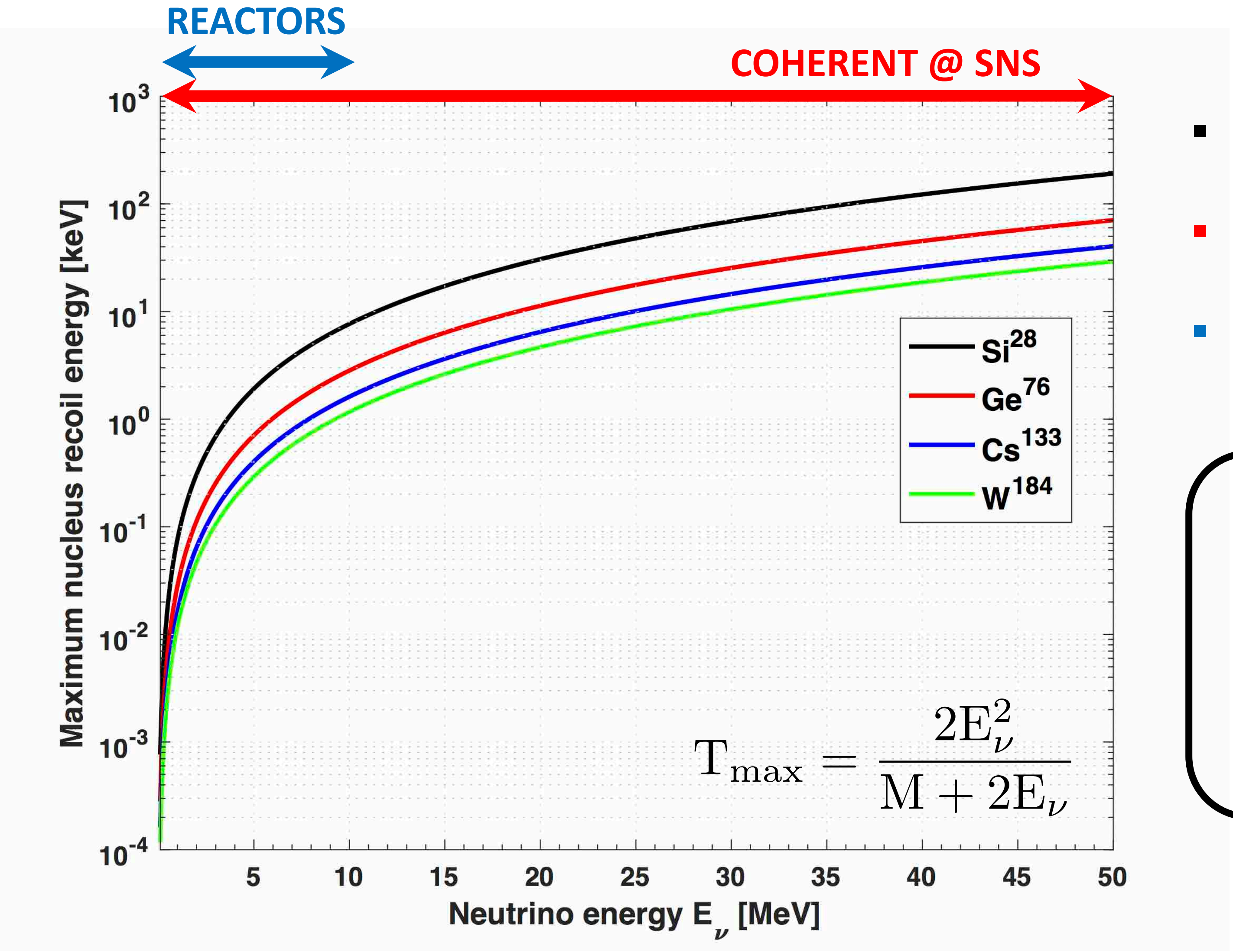
$$\sigma(E_\nu) \approx \frac{G_F^2}{4\pi}\left[Z\left(4\sin^2\theta_W - 1\right) + N\right]^2 E_\nu^2 \approx 0.42 \times 10^{-44} N^2 (E/1\,\mathrm{MeV})^2\,\mathrm{cm}^2$$



- No threshold
- The heavier the target, the larger the boost in the cross-section
- Cross-section x 100-1000 with respect to other ν detection channels for Cs & I targets
- Signature is a "simple" nuclear recoil

Coherent elastic neutrino nucleus scattering

- Typical maximum recoil energies:



$$T_{max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

- The heavier the target, the smaller the recoil energies
- **@ SNS [COHERENT]**: T $\lesssim$ 10 keV for Cs & I
- **@ reactors**: T $\lesssim$ 1 keV depending on target

Push/pull effect between high & low mass nuclei

High cross-section	↔	**Small cross-section**
High energy recoils	↔	**Small energy recoils**

.COHERENT first detection of CEνNS

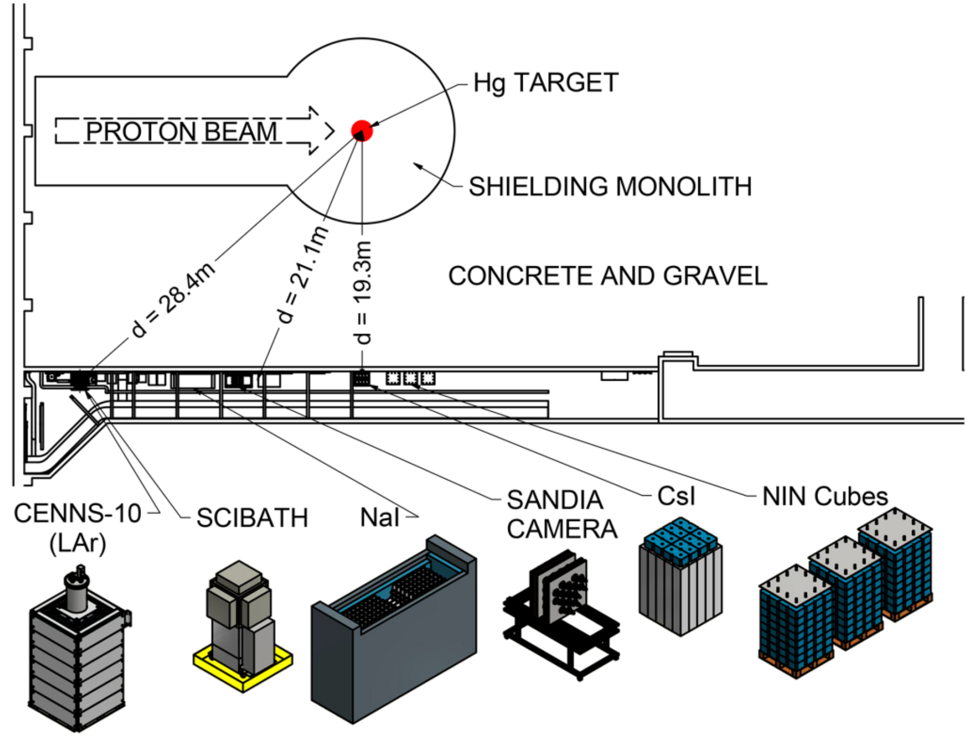
D. Akimov et al. [COHERENT collaboration] Science 357 (2017), 1123-1126

+

supplementary materials

The COHERENT experiment

- Multiple detectors placed in the "neutrino alley" at the Spallation Neutron Source facility (Oakridge, Tennessee)
- Adopted a pragmatic approach, using well-known detector technologies and taking advantage of the pulsed structure of the ν source to detect the "high" energy CEνNS-induced recoils



Target	Technology	Mass [kg]	Distance [m]	Threshold [keV_{nr}]	Data-taking start date
CsI[Na]	Scintillator	14	20	6.5	Sept. 2015
Ge	HPGe PPC	10	22	5	Early 2017
LAr	Single phase	35	29	20	Dec. 2016
NaI[Tl]	Scintillator	185	28	13	Summer 2016

- SCIBATH, Sandia camera to monitor neutron backgrounds. NIN cubes to monitor neutrino-induced neutron backgrounds

SNS neutrino source

- Proton beam impinging on a mercury target, which produce neutrinos through π^+ decay at rest and "delayed" μ^+ decays:

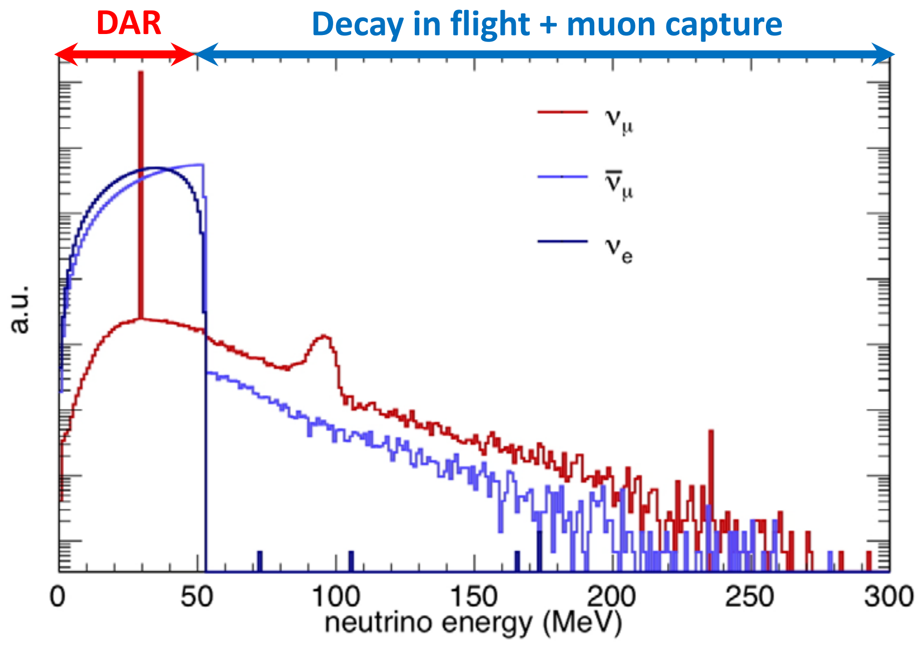
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \xrightarrow{\tau = 2.2\ \mu s} \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Beam related neutrons shielded by iron & steel monolith around mercury target + 12 m of concrete

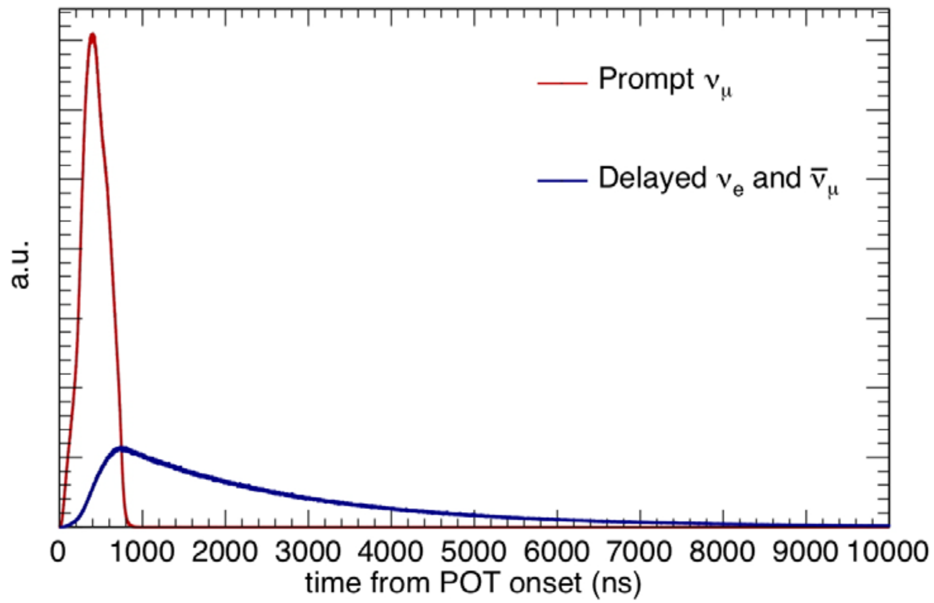
- Beam features: ~ 1 GeV protons, 5×10^{20} POT/day, 60-Hz pulsed with ~ 1 µs spills, neutrino yield ~ 0.08/proton/flavor

Flux ~ 10^7 cm^{-2} s^{-1} @ 20 m

SNS neutrino source energy spectrum



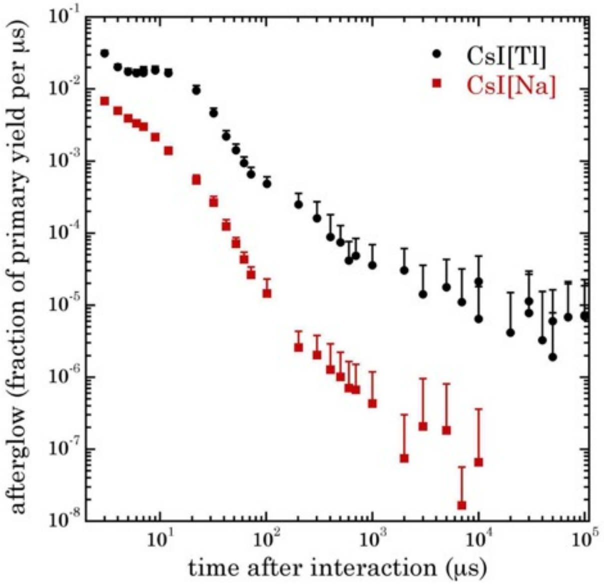
SNS neutrino source time profile



The detection setup (1)

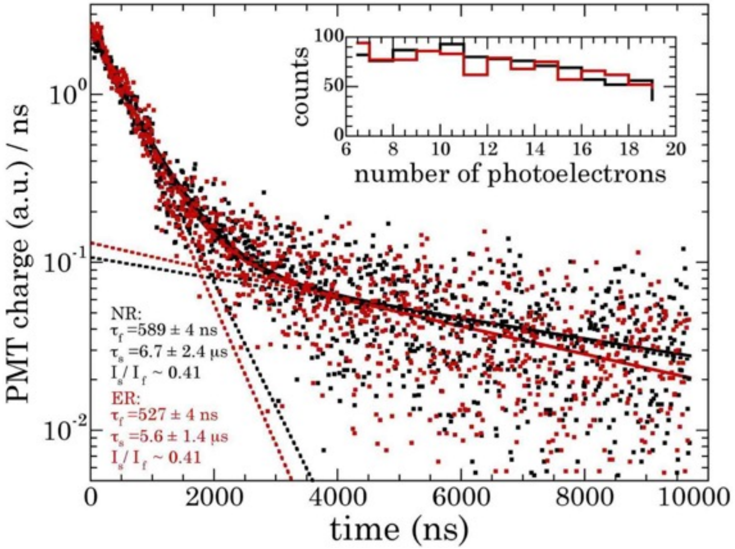
- Commercial CsI[Na] scintillating crystal with many advantages for CEνNS detection:
  - **Large coherent enhancement** to the cross-section thanks to both Cs & I high mass
  - Cs & I nuclei are nearly of the same mass, giving **similar recoils** and simplifying the understanding of the detector response
  - **Very good light yield** (~ 45 ph/keV_{ee}) coupled to high QE PMT enables detection of recoils as low as ~ 4 keV_{nr}
  - **Low internal radioactivity** (U, Th, ^{40}K, ^{134,137}Cs)
  - Possibility to **monitor fast neutron backgrounds** through the inelastic process ^{127}I(n,n',γ)
  - **Short scintillation decay time** (τ ~ 0.6 μs) makes it a fast detector capable to operate in "high" background environments
  - Small probability of afterglow signals (long scintillation decay time component) compared to other commercial crystals such as CsI[Tl]

Afterglow probability for two CsI scintillating crystals



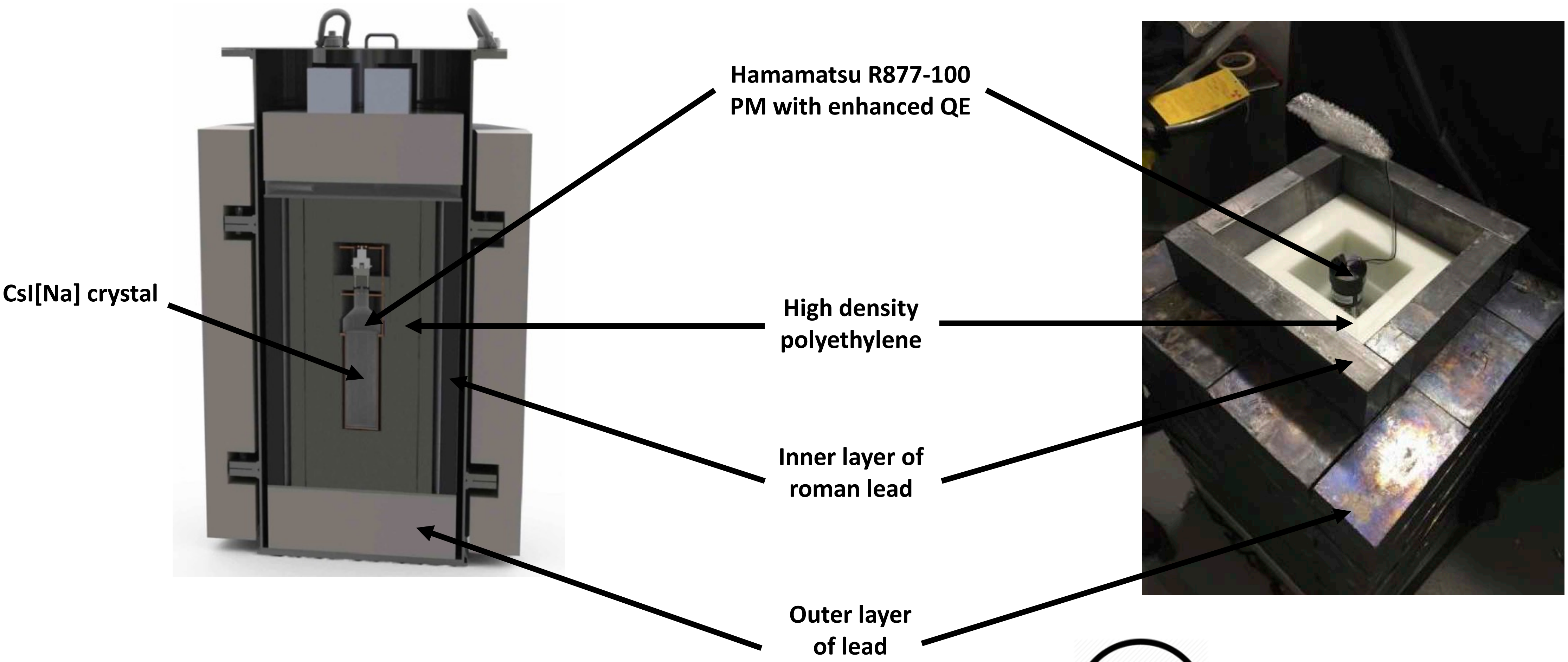
J. Collar et al., Nucl.Instrum.Meth. A773 (2015) 56-65

Illustration of CsI crystal fast and slow scintillation time components on both nuclear and electron recoils



The detection setup (2)

- 14 kg radio pure mono-crystal embedded in several layers of passive and active shieldings:

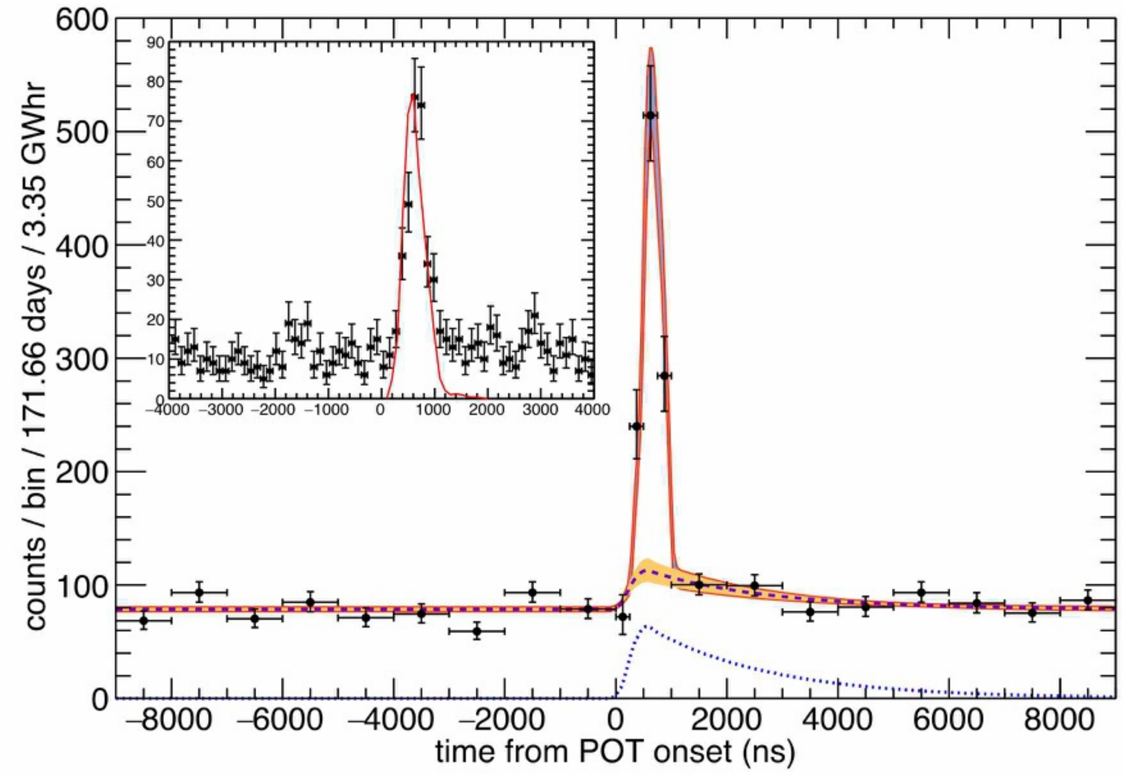


+ muon veto & water shielding…

Beam-related backgrounds

- Thorough study of beam-related backgrounds prior to setup installation at SNS facility:
  - Prompt SNS neutrons able to penetrate the ~ 20 m of moderating materials
  - Neutrino-induced neutrons (NINs) produced by $^{208}Pb(\nu_e,e^- n)$ reactions on lead shieldings

Time profile of beam-related neutron-like backgrounds



- Measured with liquid scintillator cell & ~ same shielding configuration than CsI[Na] detector

- Time profile fitted with three components:
  - Environmental neutrons (atmospheric, cosmogenic, etc..)
  - Prompt neutrons
  - NINs

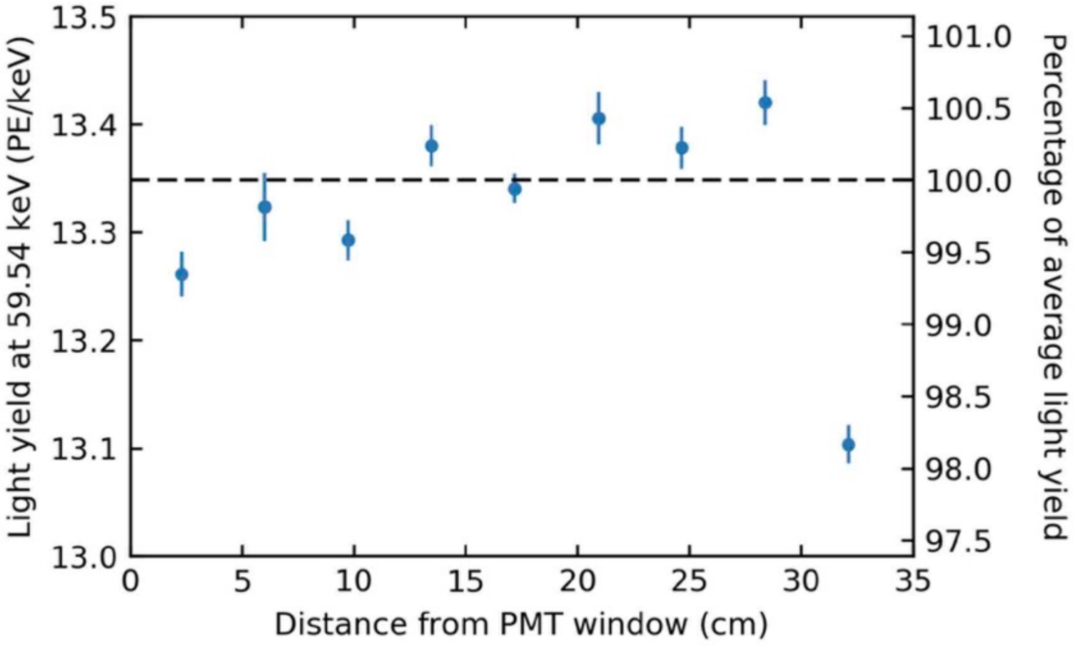
- Propagation of measured count rates to predicted count rates into the CsI[Na] setup done with MC simulations:

Background source	Expected rate in CsI[Na]	CEνNS S/B
Prompt neutrons	0.92 ± 0.23/GWhr	~ 25
NINs	0.54 ± 0.18/GWhr	~ 47

Detector calibrations

- Several radioactive sources to check and characterize detector **light yield** & **light collection uniformity**
  - ^{241}Am (59.54 keV γ) for light yield and light collection uniformity
  - ^{133}Ba source to build a library of low-energy events with light yield $\lesssim$ 10 p.e very similar to expected CEνNS signal
- Neutron generator (DD neutron beam, E ~ 4 MeV) & ^{252}Cf neutron source to measure **quenching of nuclear recoils**

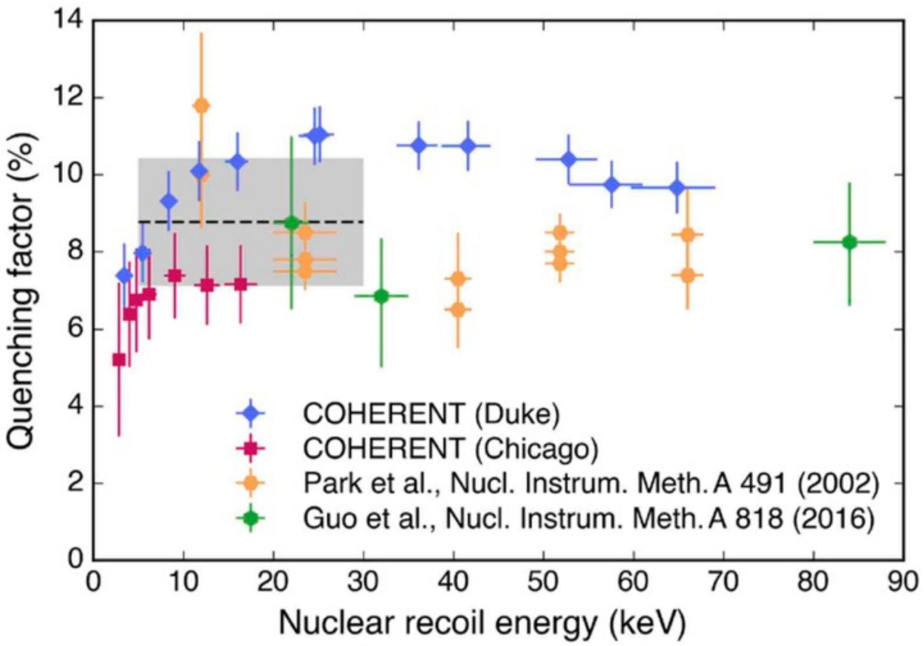
Light collection non-uniformity < 2%



Quenching factor measurements

LY_{nr}/LY_{ee}

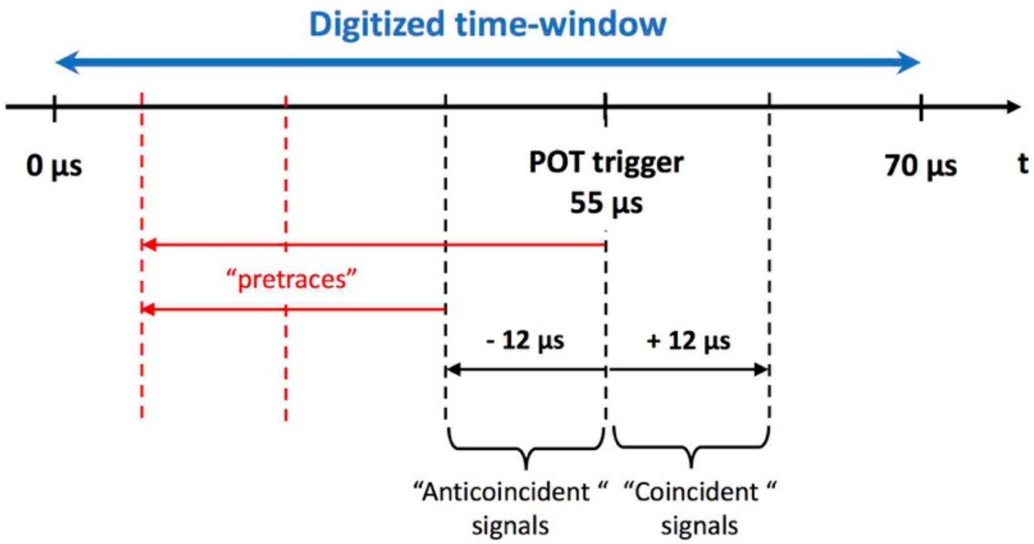
~ 1.17 PE/keV_{nr}

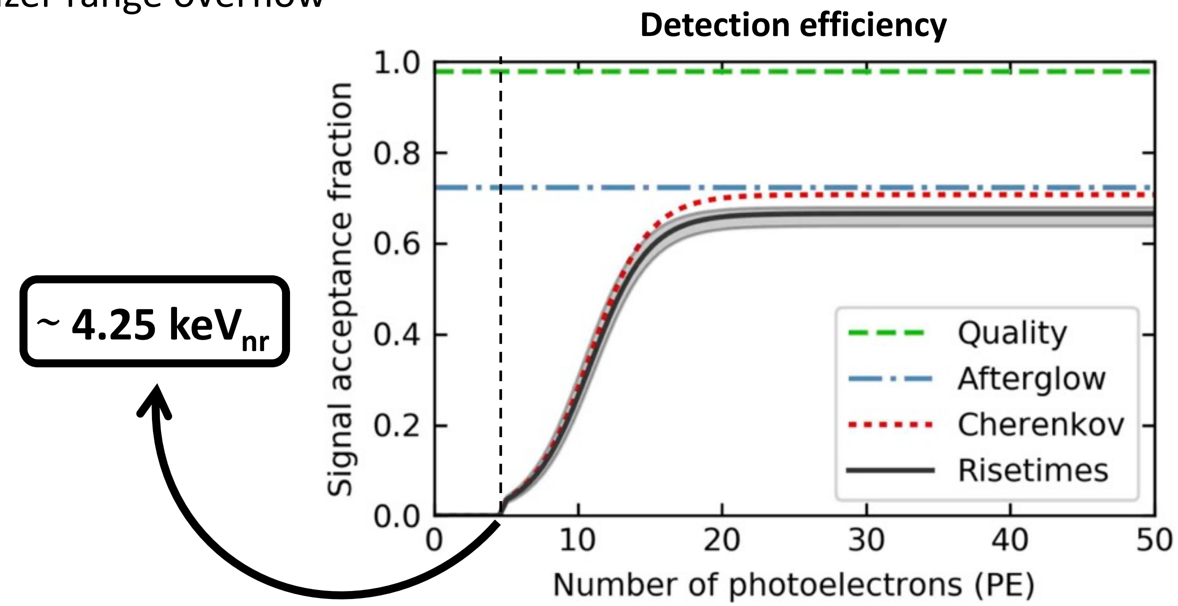


Data analysis strategy

- Scintillator waveforms digitized in a **70 µs time-window** surrounding POT trigger from SNS, split in different regions:
  - 12 µs **coincident (C) region** after POT trigger, where CEνNs signal is expected
  - -12 µs **anti-coincident (AC) region** before POT trigger to estimate steady-state backgrounds
  - 2 x 40 µs **"pretace"** windows to check for scintillator afterglow pulses

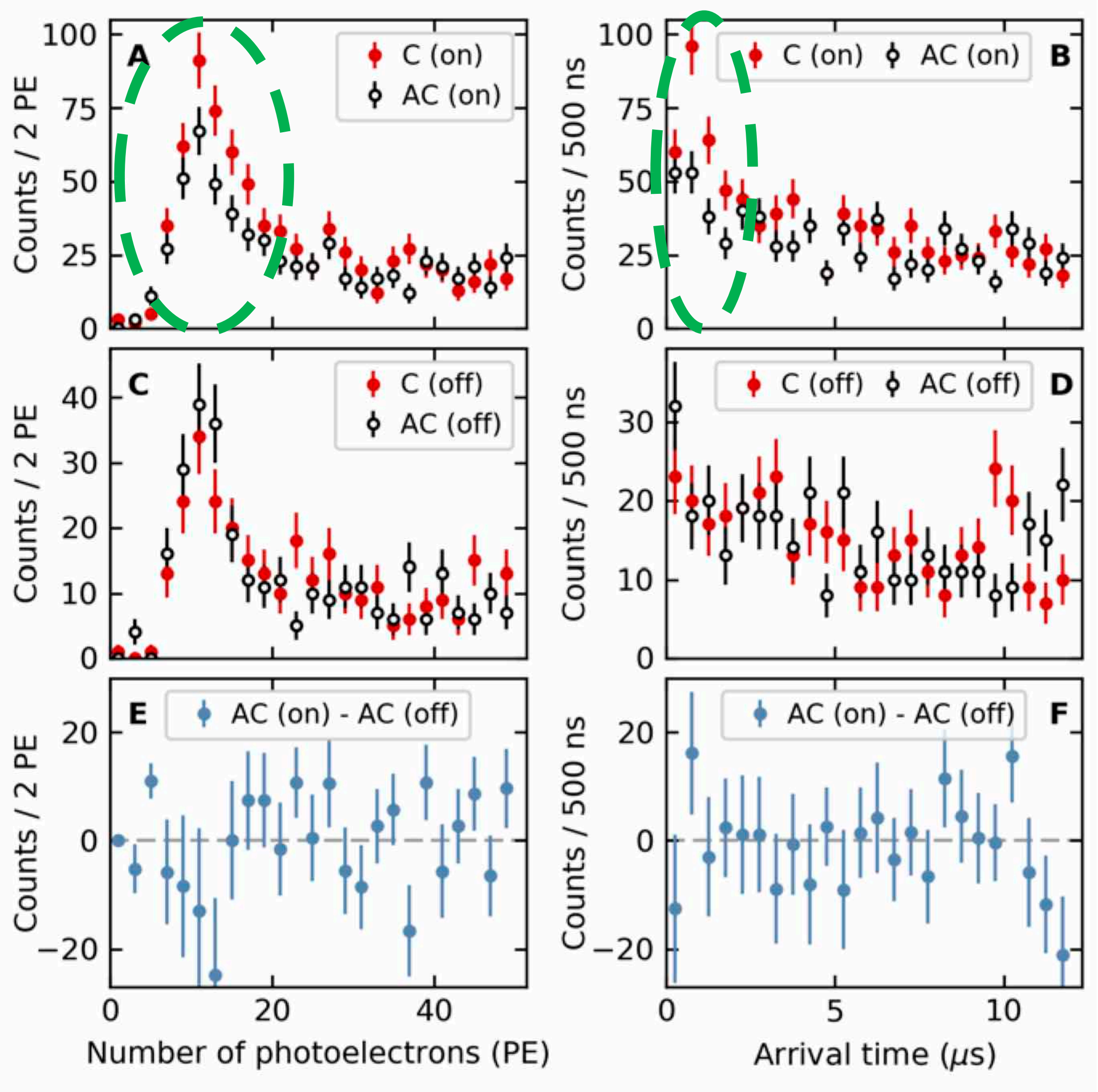
- Use of reconstruction software & algorithms to find: onsets of signals, integrated charge, number of peaks, rise times, etc…
- Many selection criteria apply to events found in the **C** & **AC** regions
  - "Risetime" & "Cherenkov" cuts to remove Cherenkov light emission in PMT window, random grouping of dark current PEs, etc…
  - Afterglow cuts: no spurious signal in **pretace** regions
  - Quality cuts: muon veto coincidences, PMT saturation & digitizer range overflow





Data analysis results

- **Beam ON/OFF data:** 308.1/153.5 live-days



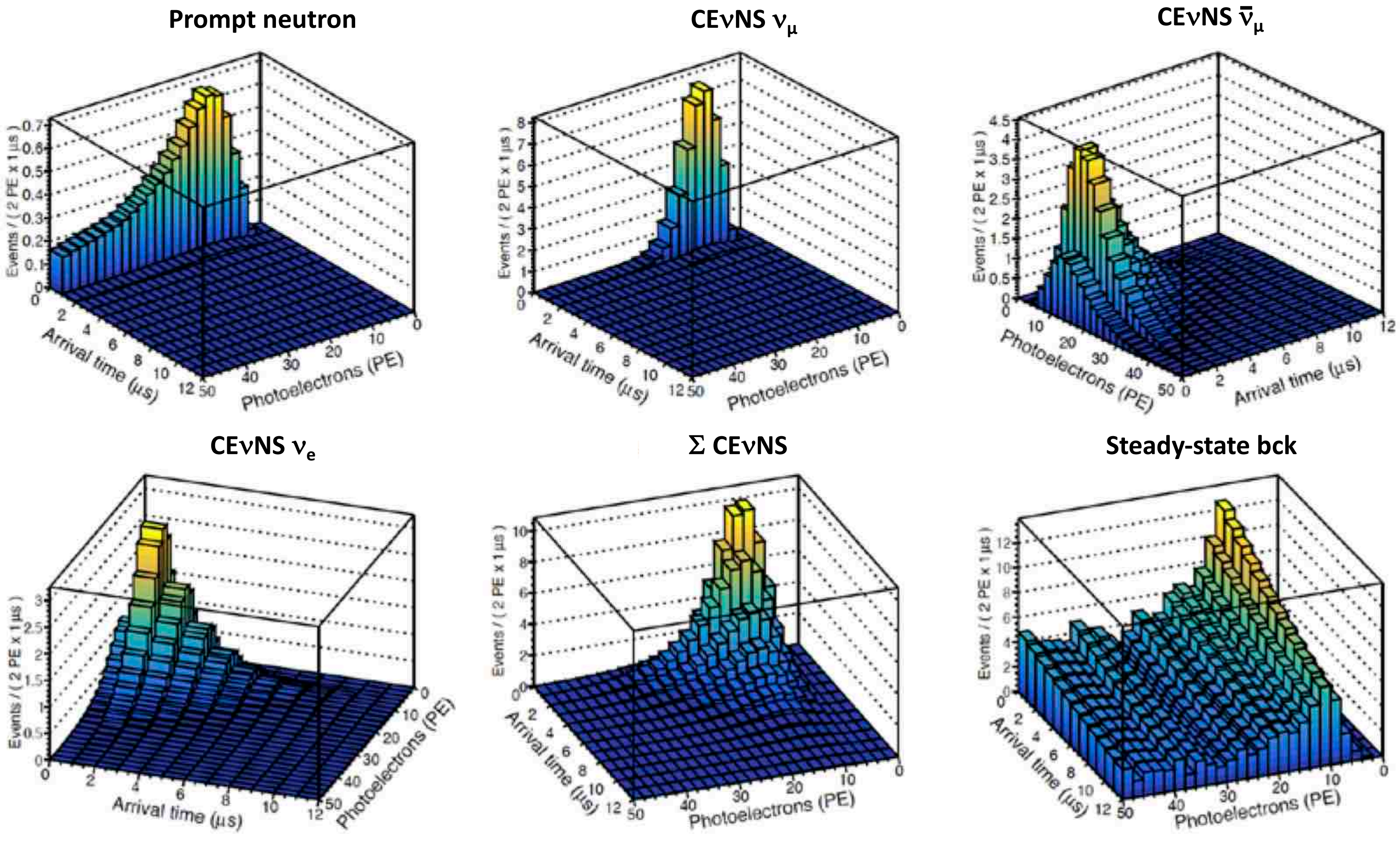
Comparison of C(ON)/AC(ON) data shows **excess**

Comparison of C(OFF) and AC(OFF) data shows same background conditions in C & AC regions ✓

Comparison of AC(ON) and AC(OFF) data shows good stability of environmental backgrounds ✓

Statistical analysis (1)

- 2-D (E, t) PDFs for CEνNS signal and backgrounds are constructed to fit the C(ON) data:



- Steady-state background model built from AC(ON) data
- Prompt neutron background model from previous on-site measurements
- NIN backgrounds negligible
- CEνNS signal modeling from standard model prediction, taking into account axial and vector couplings & nuclear form factors

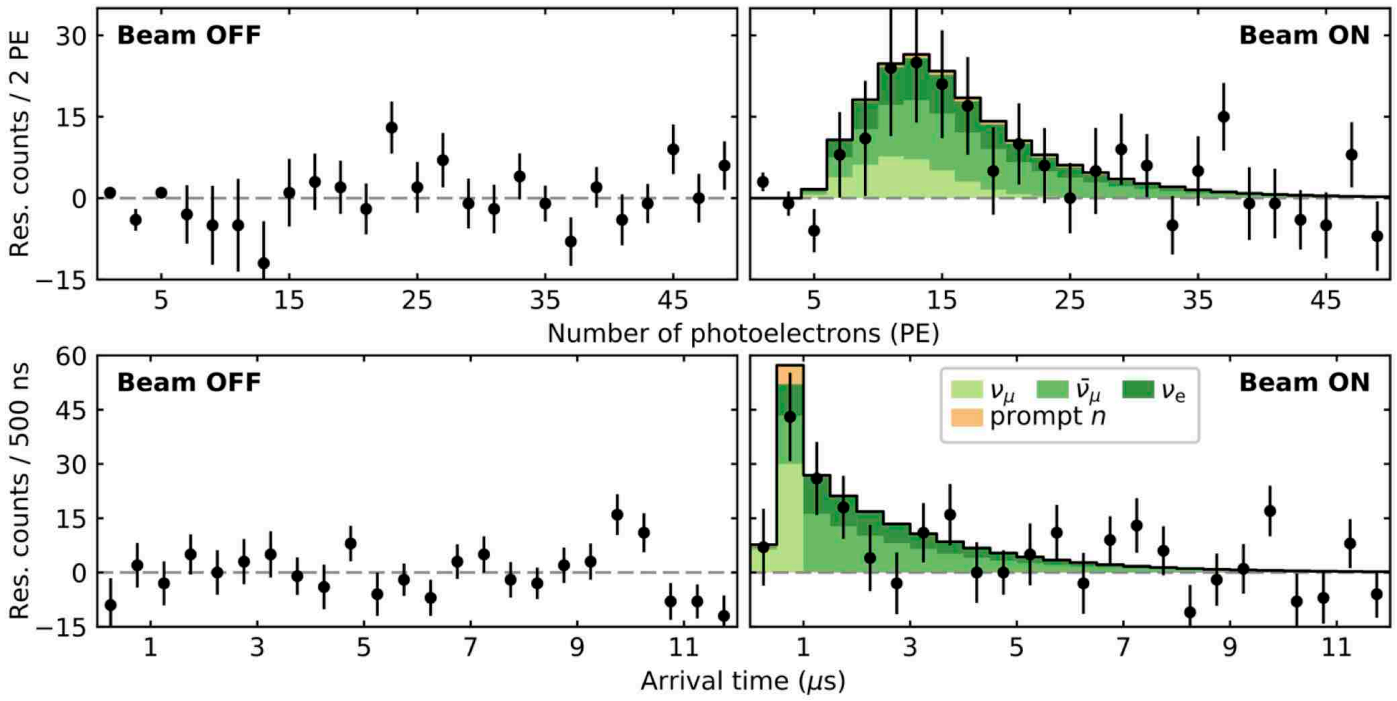
Statistical analysis (2)

- Number of CEνNS counts fitted with a binned likelihood:

Breakdown of main systematics

Source of systematic	Contribution
Form factor (in CEνNS cross-section)	5%
ν flux from SNS	10%
Light yield non-uniformity	Negligible
CsI[Na] quenching factor	25%
Det. efficiency	5%
Source-detector baseline	Negligible
Prompt neutron background	25%
Steady-state background	Missing

Residual differences in the A & AC regions with beam ON & OFF data along with BF model



$N_{CE\nu NS}$ = 134 ± 22

$N_{CE\nu NS}/N_{SM}$ = (77 ± 16) %

$N_{CE\nu NS}$ = 0 disfavoured at the 6.7σ level

. CEνNS: physics potential

ν non-standard interactions

- Models with non-standard neutrino interactions (NSI) were proposed as an alternative solution to neutrino mixing for explaining neutrino flavor transitions.

- Now ruled out by oscillation data at the leading order. Might still be present at a sub-leading order though: it is for example still argued that presence of NSIs could affect the measurements of the ν oscillation parameters (see next slide).

- Appears in many extensions of the standard model: seesaw models, R-parity violating supersymmetric models, GUTs, extra dimensions, etc…

- At low energies (E << M_W), phenomenology of neutral current NSIs is described by point-like 4-fermion interactions such as:

$$\mathcal{L}_{\nu\mathrm{Hadron}}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\right] \left(\varepsilon_{\alpha\beta}^{qL}\left[\bar{q}\gamma_\mu(1-\gamma^5)q\right] + \varepsilon_{\alpha\beta}^{qR}\left[\bar{q}\gamma_\mu(1+\gamma^5)q\right]\right)$$

- CEνNS can be sensitive to **non-universal $\boldsymbol{\varepsilon_{\alpha\alpha}}$** and **flavor changing** couplings $\boldsymbol{\varepsilon_{\alpha\beta}}$ to u & d quarks

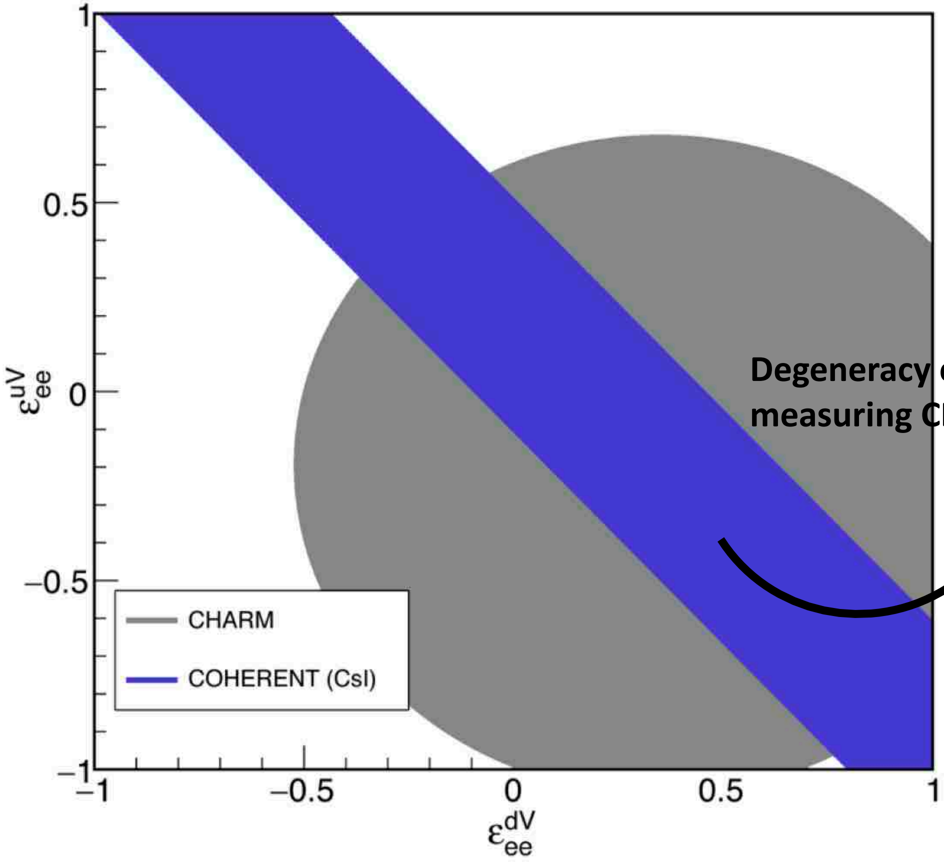
Existing bounds & COHERENT constraint

- CEνNS complementary to constraints brought by accelerator, beam and solar neutrino oscillation experiments + collider experiments (LEP, ATLAS, CMS, etc…) + high-energy neutrino scattering experiments (CHARM, NuTeV, etc…):

	NSI parameter limit	Source
ν_e NSI	$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
	$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
	$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
	$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
	$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
	$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
	$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
	$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
	$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
	$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
ν_e NSI	$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
	$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
	$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
	$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Davidson et al. (2003)

Constraint on ε_{ee} by COHERENT data



Degeneracy can be solved by measuring CEνNS on several nuclei

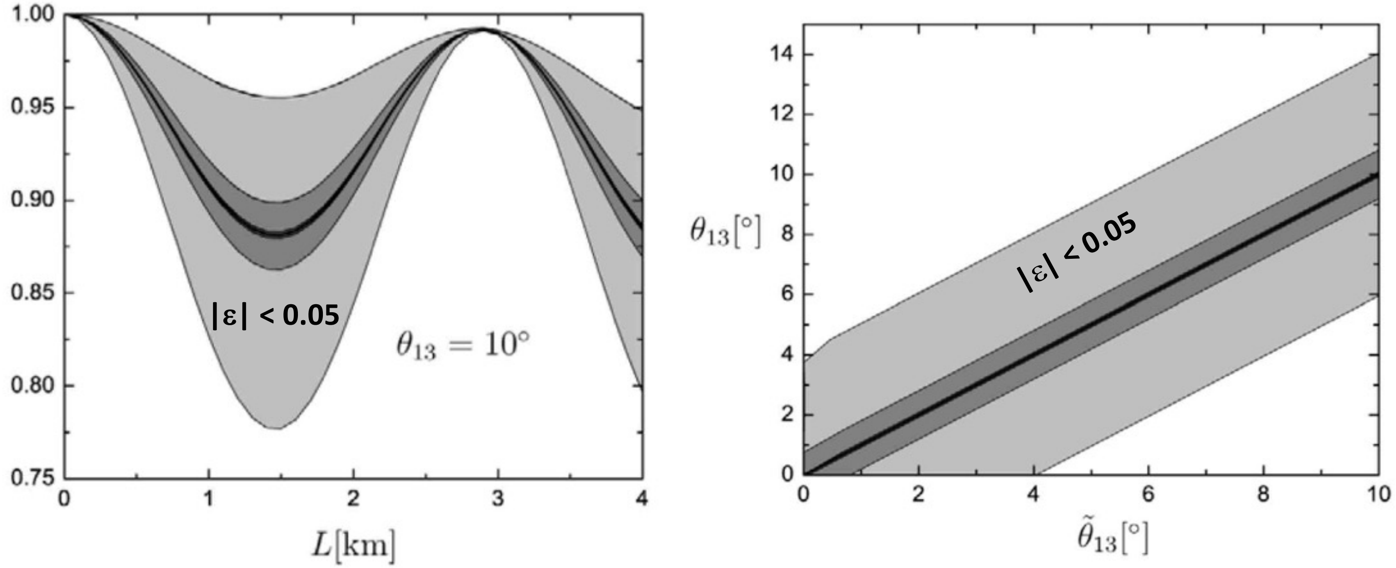
Akimov et al. (2017)

Measurements of oscillation parameters

- Small ν NSI can affect measurements of oscillation parameters and lead to "degeneracy" problems: see for example LMA-D solution of solar neutrino oscillations.

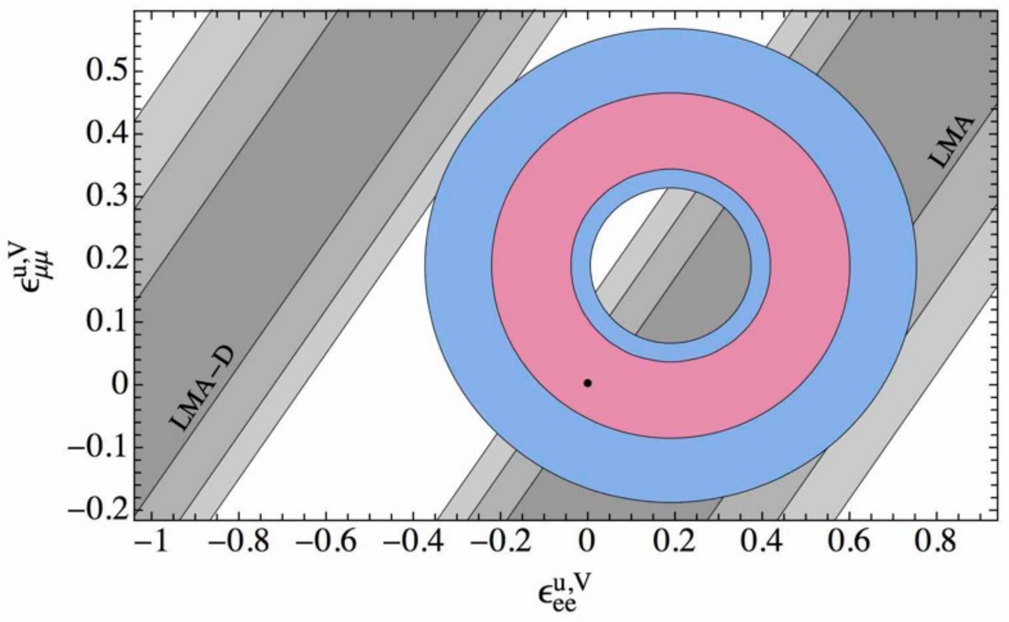
- Scattering data, such as those provided by CEνNs, are helpful.

Impact of small NSIs to measurement of θ_{13} at reactors…



Ohlsson & Zhang (2009)

LMA-D/LMA degeneracy problems in the presence of NSIs



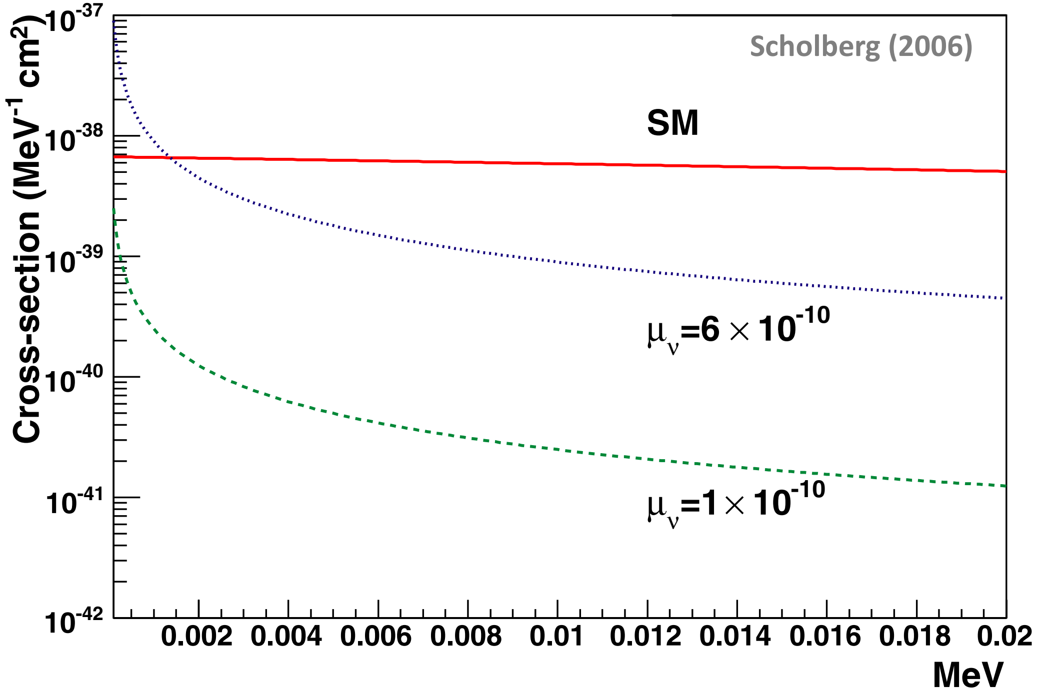
LMA-D excluded by COHERENT data at the 3σ level

Coloma et al. (2017)

ν magnetic moment

- Standard model prediction: $\mu_\nu \lesssim 10^{-19}\ (m_\nu/1\ \mathrm{eV})\ \mu_B$
- Current laboratory limits: $\mu_\nu \lesssim 10^{-(10\text{-}11)}\ \mu_B$
- « Large » μ_ν would sign BSM physics (Majorana neutrinos, neutrino « milli-charge », extra-dimensions, etc…)

ν-nucleus scattering at 30 MeV, Ne

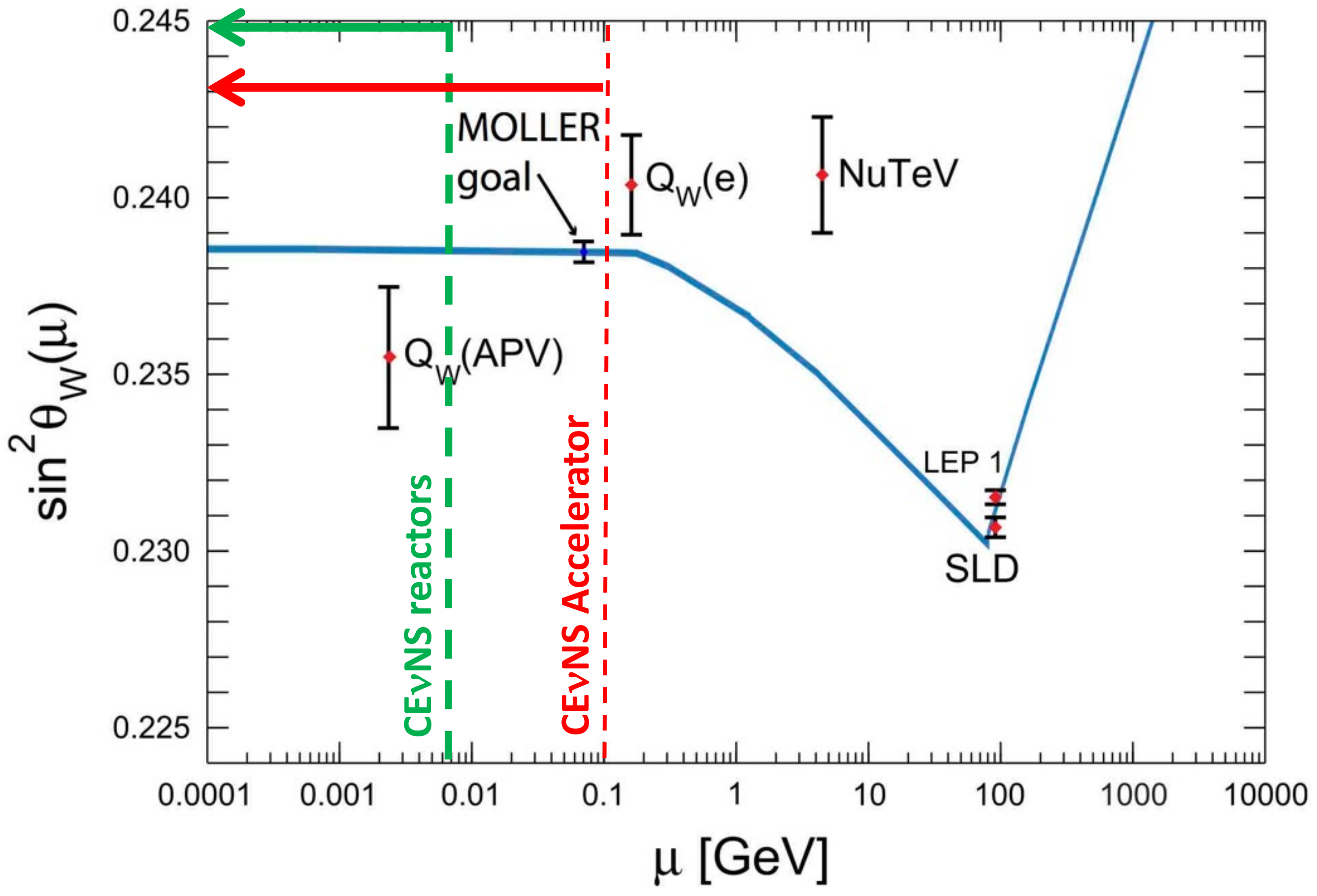


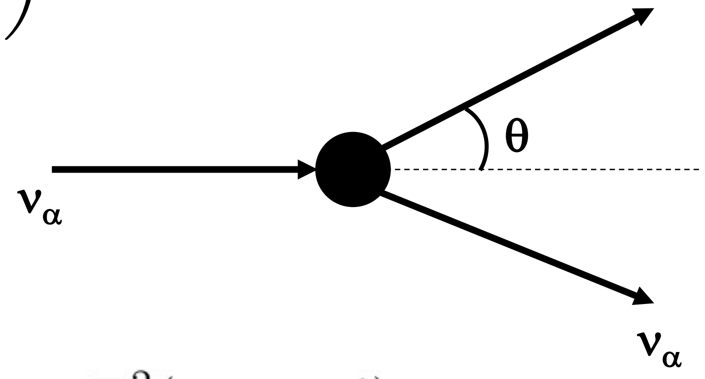
$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu Z^2}{m_e^2}\left(\frac{1 - T/E_\nu}{E_\nu} + \frac{T}{4E_\nu^2}\right)$$

Very low energy threshold detectors might significantly improve the limits

Running of the weak mixing angle

$$\sigma(E_\nu) \simeq \frac{G_F^2 E_\nu^2}{4\pi}\left(N - (1 - 4\sin^2\theta_W)\right)^2$$





$$Q^2 = 2E^2(1+\cos\theta)$$

- Can in principle probe running of $\sin^2\theta_w$ in very low momentum transfer regions
- Competitive with other dedicated experiments (Møller scattering & atomic parity violation experiments)?

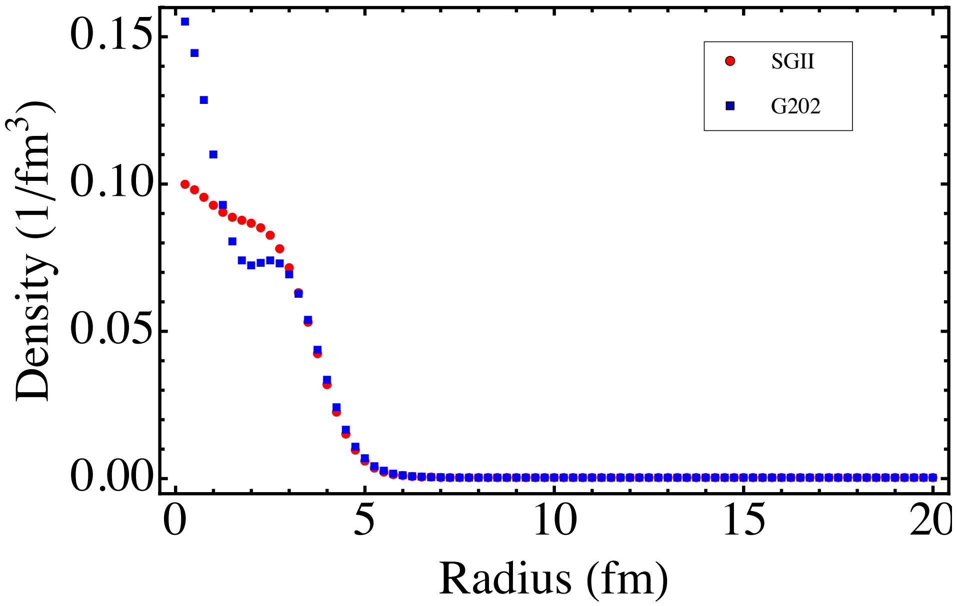
Insights into nuclear structure (1)

- Measuring nuclear weak (neutron) density:

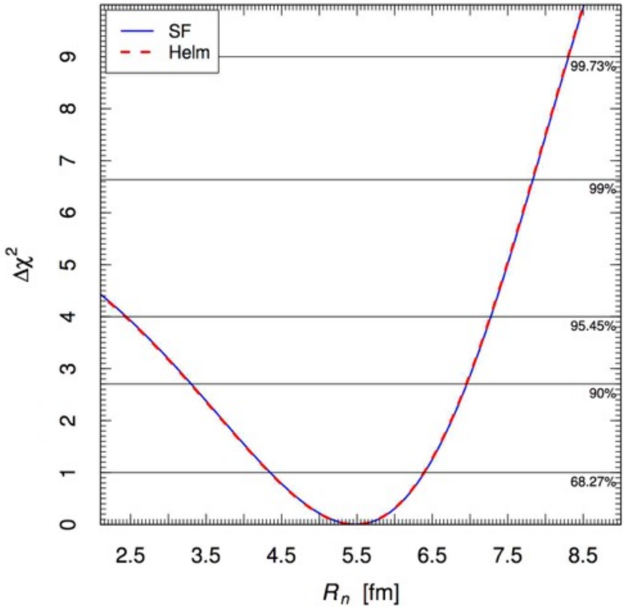
$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E^2}\right)\left[N F_N(q^2) - Q_W Z F_Z(q^2)\right]^2$$

- Nuclear form factors $F_{N,Z}(q)$ are Fourier transforms of the neutron & proton densities

Ar^{40} nucleus neutron density as calculated by some "Skyrme" models



Estimate of neutron rms radius in Cs and I using COHERENT data



$R_n = 5.5^{+0.09}_{-1.1}$ fm

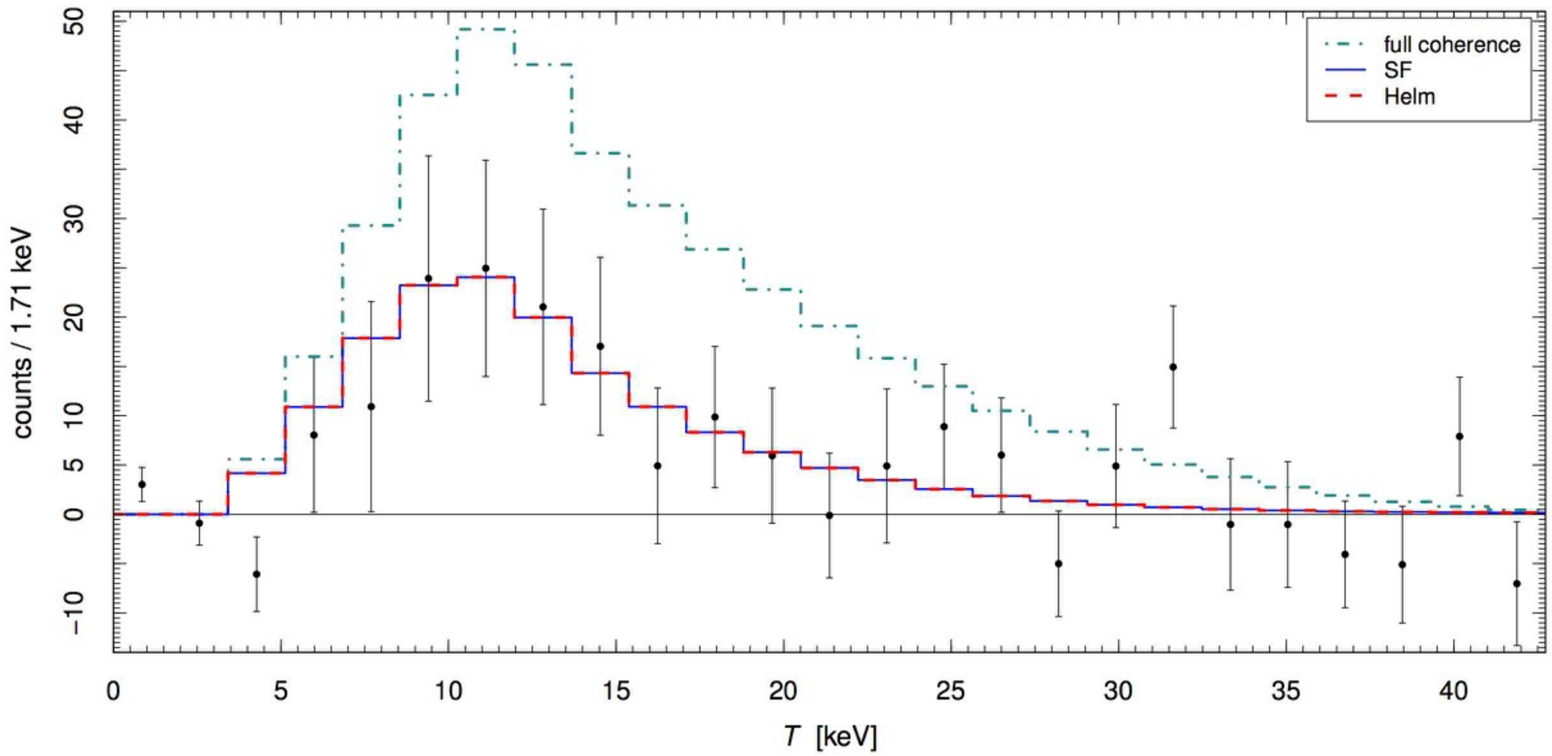
Cadeddu et al. (2017)

Insights into nuclear structure (2)

- Measuring nuclear weak (neutron) density:

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E^2}\right)\left[N F_N(q^2) - Q_W Z F_Z(q^2)\right]^2$$

- Nuclear form factors $F_{N,Z}(q)$ are Fourier transforms of the neutron & proton densities



Evidence from departure from full coherence in COHERENT data ($F(q^2) \leq 1$)

Cadeddu et al. (2017)

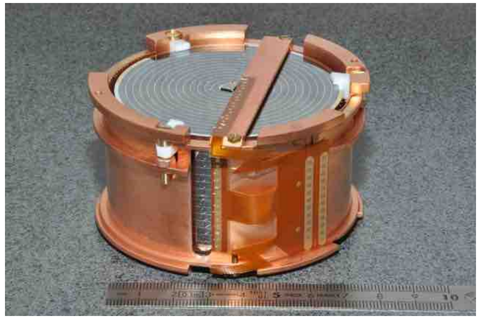
. CEνNS: perspectives in France

Situation & opportunities in France

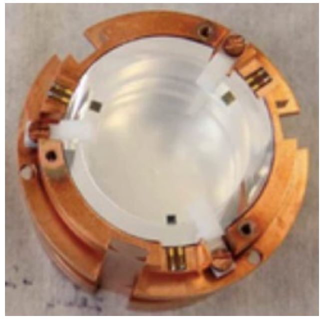
- Growing interest to detect & measure the process at reactors:
    - benefit from high ν fluxes to do precision physics at low energies
    - very interesting to probe the potential of CEνNS for non-proliferation purposes

- The Chooz nuclear power plant is a “natural” and interesting location:
    - two powerful reactor cores
    - good experience and contact established with EDF people (Double Chooz experiment)
- Reactor ν detection through CEνNS requires very low threshold detectors: idea is to **repurpose DM & 0νββ bolometers.**
- Great bolometer expertise in France, with several research groups that already expressed a strong interest in the measurement of CEνNS at reactors
- German (CRESST/ν-CLEUS) & American (RICOCHET) research groups also interested

EDELWEISS Ge macro-bolometer

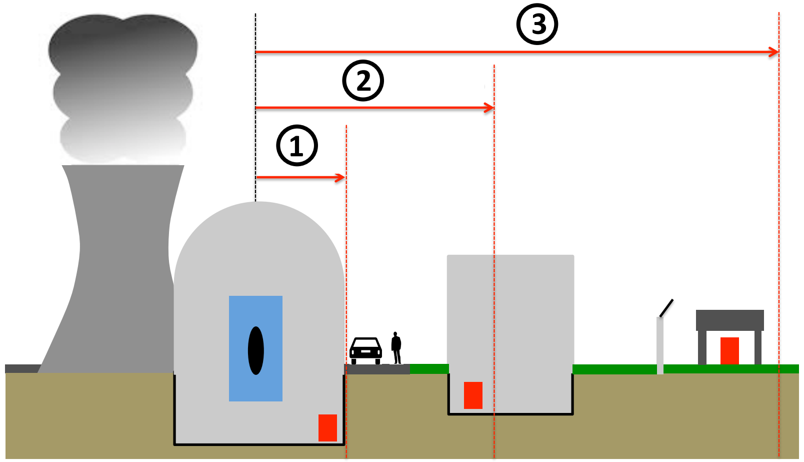


LUMINEU Li_2MoO_4 macro-bolometer



Detection strategy at reactors

- Detection at reactors more complicated since recoils are of smaller energies
- Many possible strategies, which define the detector specifications & key parameters for a successful experiment:
  - Detector energy threshold & time response
  - Overburden & shielding



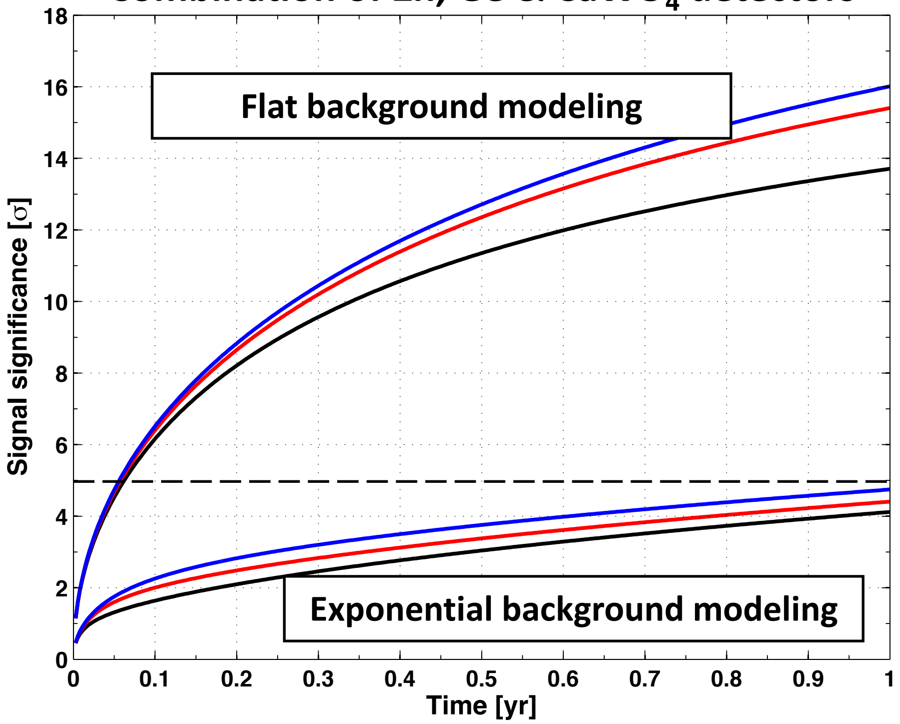
	Strategy	Detector mass and E_{th} *	Overburden	Backgrounds	Time response	
①	Short range (< 10 m)	O(10-100 g) E_{th} < 300 eV	Very low (< 10 mwe)	- Cosmogenic - Radiogenic - Reactor-induced - Atmospheric	< 1 ms	
②	Mid range (< 100 m)	O(0.1-1 kg) E_{th} < 100 eV	Very Low (< 10-20 mwe)	- Cosmogenic - Radiogenic - Atmospheric	< 1 ms	→ **VNS at Chooz**
③	Long range (< 0.5-1 km)	O(1-10 kg) E_{th} < 50 eV	Moderate (< 100 mwe)	- Cosmogenic - Radiogenic	O(1-10 ms)	→ **DC near lab**

* to get O(1 d^{-1})

Detection prospects at Chooz

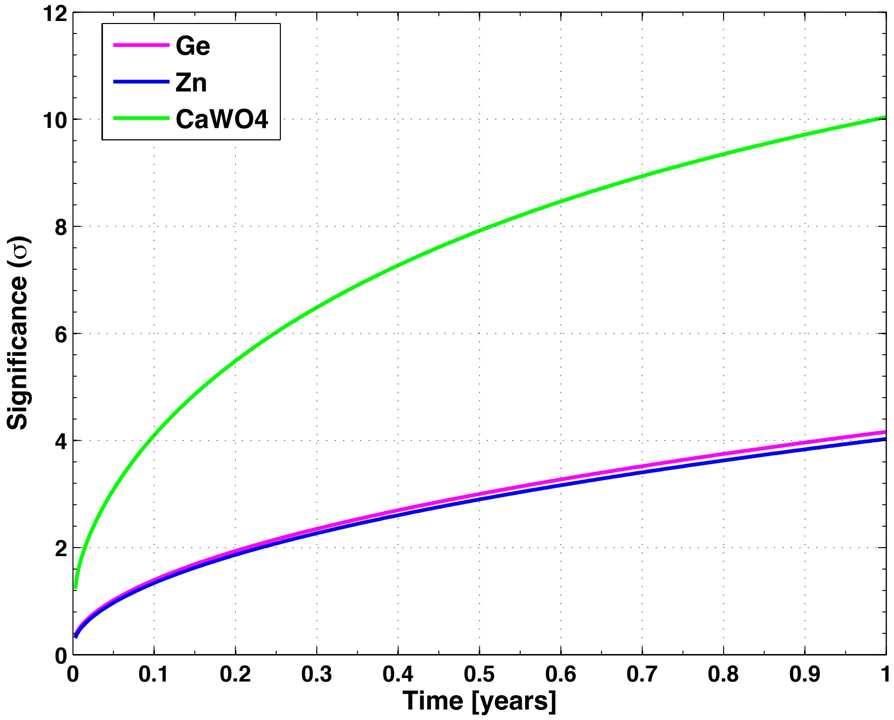
Double Chooz near laboratory (~ 400 m)

Combination of Zn, Ge & $CaWO_4$ detectors



- Detection within reach in a year
- Low signal rate but low background rate:
  - Need few kg of detector with **very low thresholds (< 100 eV)**
  - Benefit from DC pit which could provide efficient shieldings

Very near site (< 100 m)

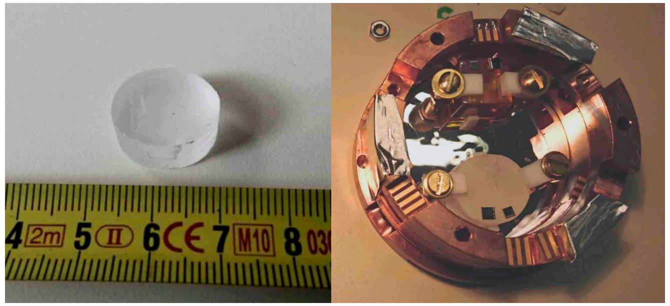


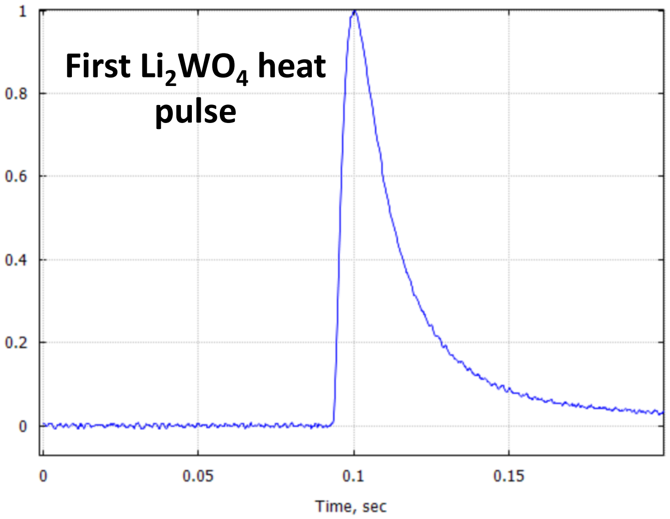
- Detection within reach in a few weeks
- High signal rate but "high" background rate:
  - Need 0.01-0.1 kg of detector **with very low thresholds (< 100 eV) & fast timing response (< 1 ms)**
  - Need a **clever & efficient shielding configuration** in a small footprint…

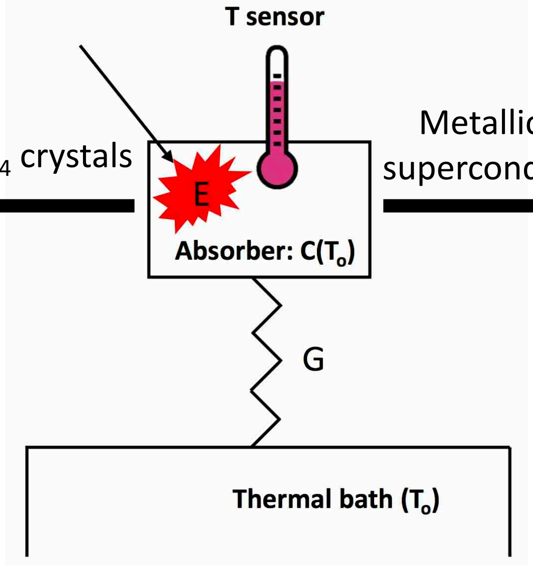
On-going efforts: detector developments

- Some detector R&D programs have been funded and are already started: **development of innovative absorber materials & thermal sensors** to lower energy thresholds and increase detector time response.

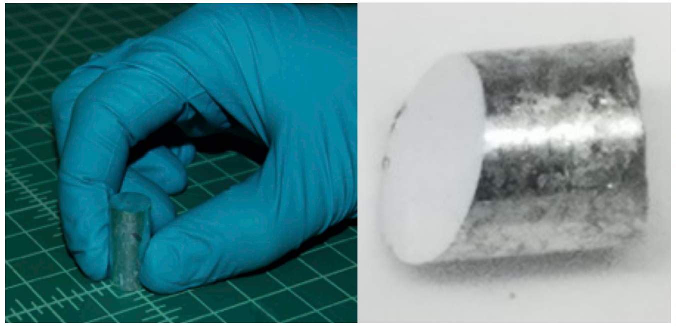
BASKET program

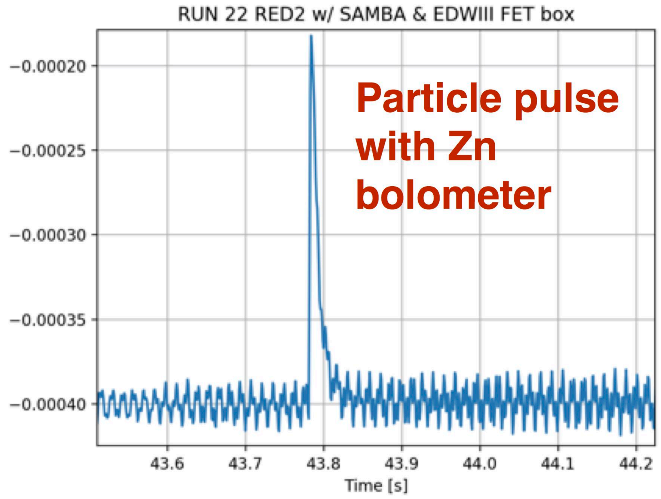






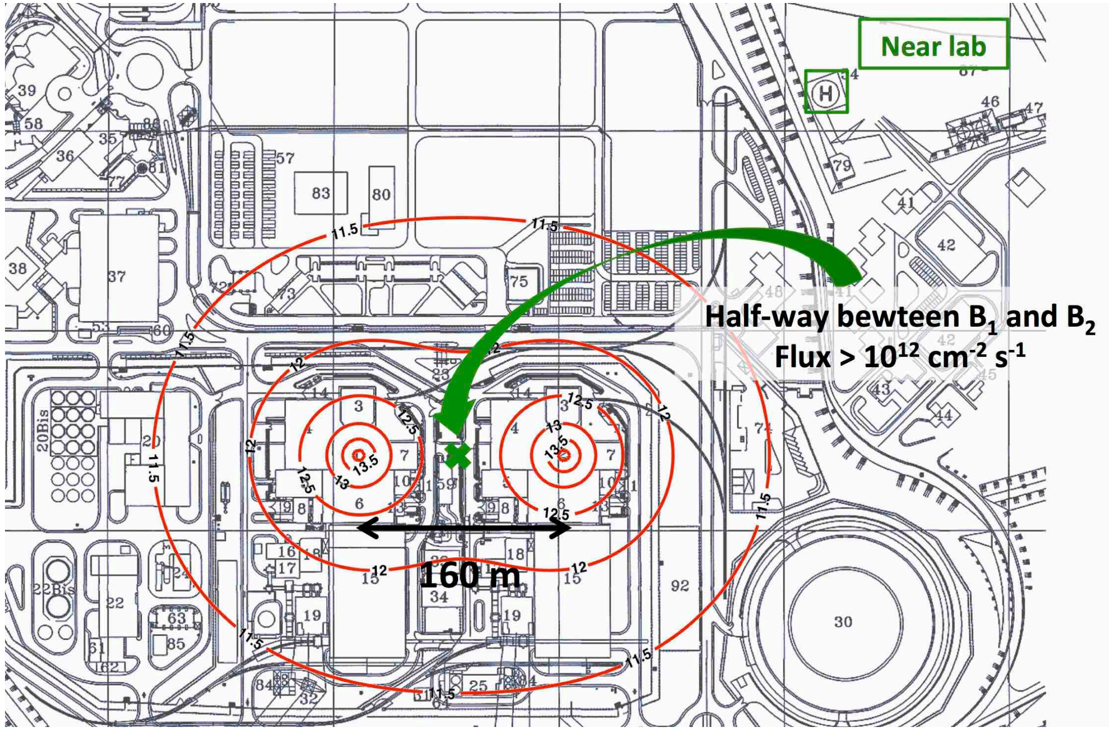
RICOCHET program





On-going efforts: very near site at Chooz

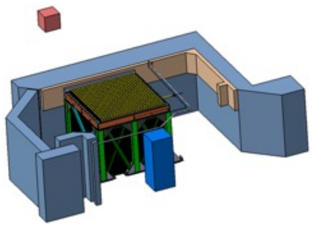
- Good & regular contact with EDF people, who are very willing to host a new reactor ν experiment.
- A suitable room in the basement of an administrative building has been identified: can host a dedicated experiment with a 1-2 m footprint.
- First muon & neutron background measurements have started & are of paramount importance to design the experiment: an overburden less than 10 m.w.e is expected



First µ background measurements at VNS (Chooz)

Call for new collaborators

- Conceptual design studies for the experiment have started. Following work packages have been identified:



Passive/active shieldings
- Lead, polyethylene
- Muon veto

cea

Cryogenic detectors

cea
Massachusetts Institute of Technology
iPNL
CSNSM
TUM Technische Universität München
Max-Planck-Gesellschaft

Safety & on-site integration
- Safety files
- Technical coordination

cea

Data acquisition & handling

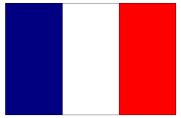
Calibration

Electronics

Data analysis & simulation

cea
Massachusetts Institute of Technology

Current actors



Massachusetts Institute of technology
Rachel Carr Joseph Formaggio Joseph Johnson
Alexander Leder Valerian Sibille
Sarah Townbridge Lindley Winslow

University of Wisconsin, Madison
Kimberly Palladino

Northwestern University
Enectali Figueroa-Feliciano Hong Ziqing

IPNL Lyon
Corinne Augier Julien Billard Jules Gascon
Maryvonne de Jesus Alexandre Julliard
Romain Maisonobe

CEA-Saclay, DRF/Irfu
Thierry Lasserre Claudia Nones
Guillaume Mention Matthieu Vivier

CSNSM, Orsay
Louis Dumoulin Stefanos Marnieros
Emiliano Olivieri

Technical University of Munich
Xavier Defay Alex Langenkaemper
Elizabeth Mondragon Lothar Oberauer
Stefan Schoenert Michael Willers

MPI, Munich
Michele Mancuso Frederica Petricca
Raimund Strauss

Next face-to-face meeting by beginning of next year at IPNL: new french collaborators are welcome !!

Conclusions/Summary

- First detection of CEνNS by COHERENT collaboration 40 years after 1st prediction

- Very interesting process:
  - opens the possibility to significantly **scale down neutrino detector sizes**
  - probes **new physics beyond standard model** at low energy
  - important for doing precision **neutrino oscillation physics** & rule out sub-leading effects (NSIs, etc…)
  - applications in **astrophysics** (supernovae dynamics), **dark matter direct detection** (neutrino floor)
  - attractive for **reactor monitoring**

- Detection has yet to be done at reactors. Much more challenging: require significant progresses in low threshold detector technologies (bolometers)

- Efforts & discussion have started in France: a promising site has been identified at the Chooz nuclear power plant

- Timescale of such a project is of the order of 5 years from now

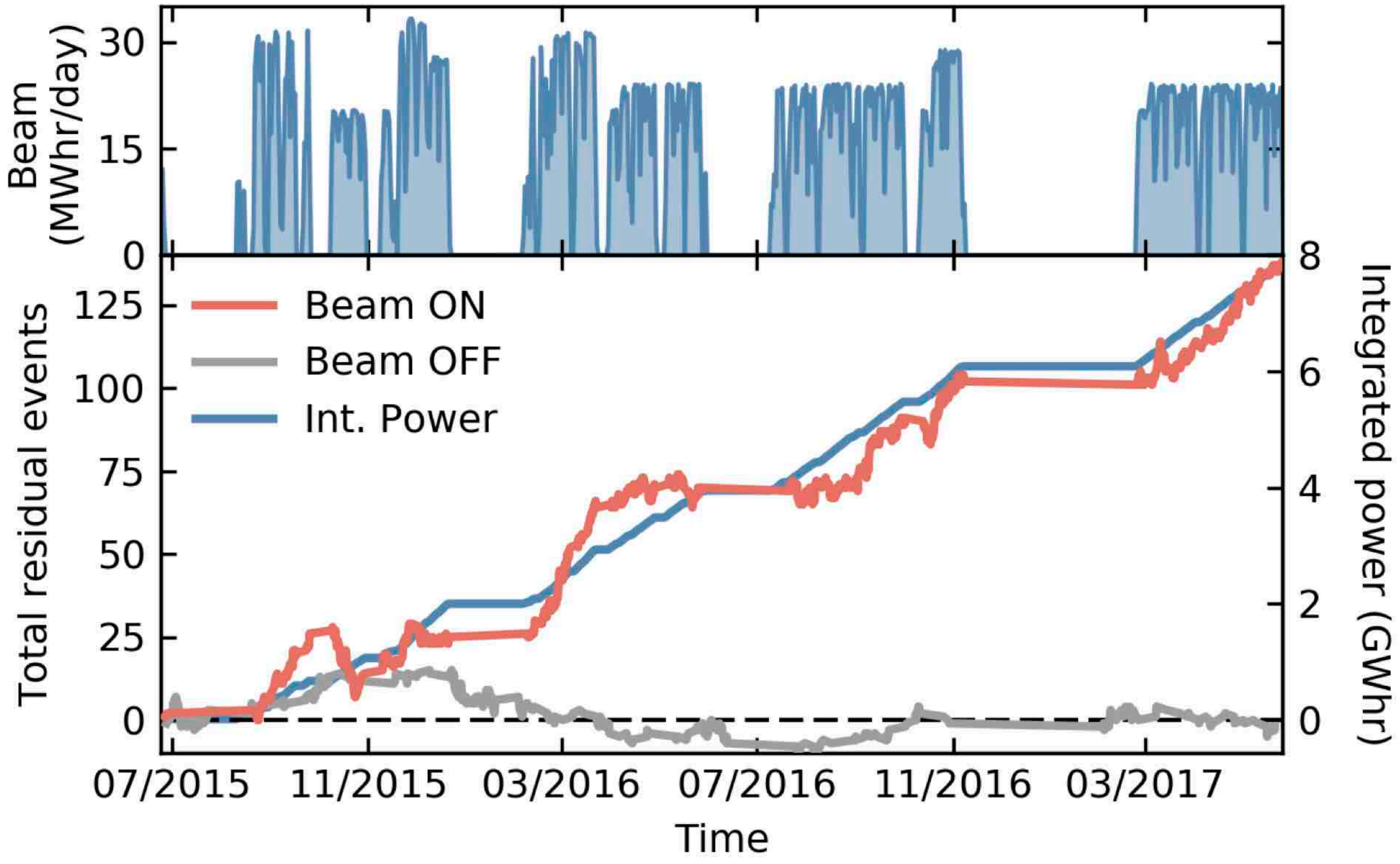
- We are looking for new collaborators!

THANK YOU !

. Backup

COHERENT signal: correlation with beam power

- Strong correlation of excess in C(ON) data with cumulative beam power:



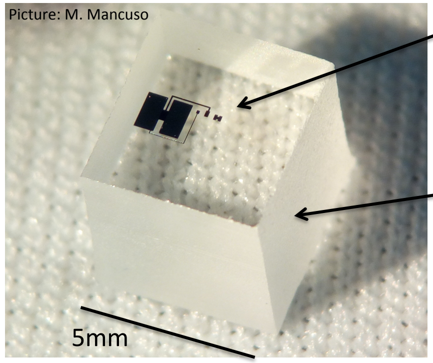
Events with:

0 < PE < 30 photoelectrons
0 < t < 6 µs

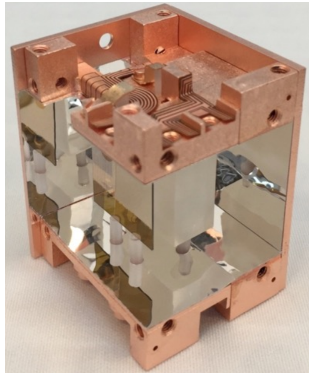
On-going efforts at reactors

Name	Reactor & power	Baseline	Technology
TEXONO	Kuo-Sheng Power Plant (Taiwan), 2.7 GW_{th}	28 m	Ge ionization + CsI[Tl] detectors
CONNIE	Angra dos Reis Power Plant (Brazil) 3.8 GW_{th}	30 m	Si charged couple devices
MINER	TAMU research reactor (Texas), 1 MW_{th}	2 m	Ge bolometers
ν-CLEUS	Chooz Power Plant (France) 2 x 4.25 GW_{th} ?	400/80 m	$CaWO_4$ + Al_2O_3 bolometers
RICOCHET	Chooz Power Plant (France) 2 x 4.25 GW_{th}? MIT research reactor 6 MW_{th} ?	400/80 m < 10 m	Ge/Ze bolometers

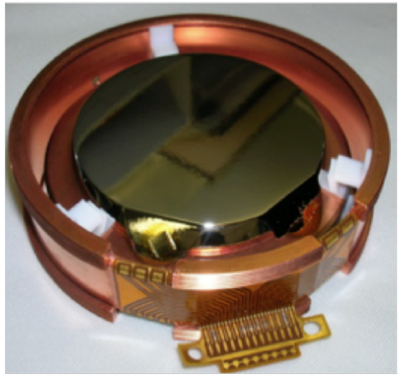
Sapphire



$CaWO_4$



Ge



Zn