FROM RESEARCH TO INDUSTRY

Toward CEνNS detection at Chooz

GDR Neutrino meeting
May 30th 2017, APC Paris

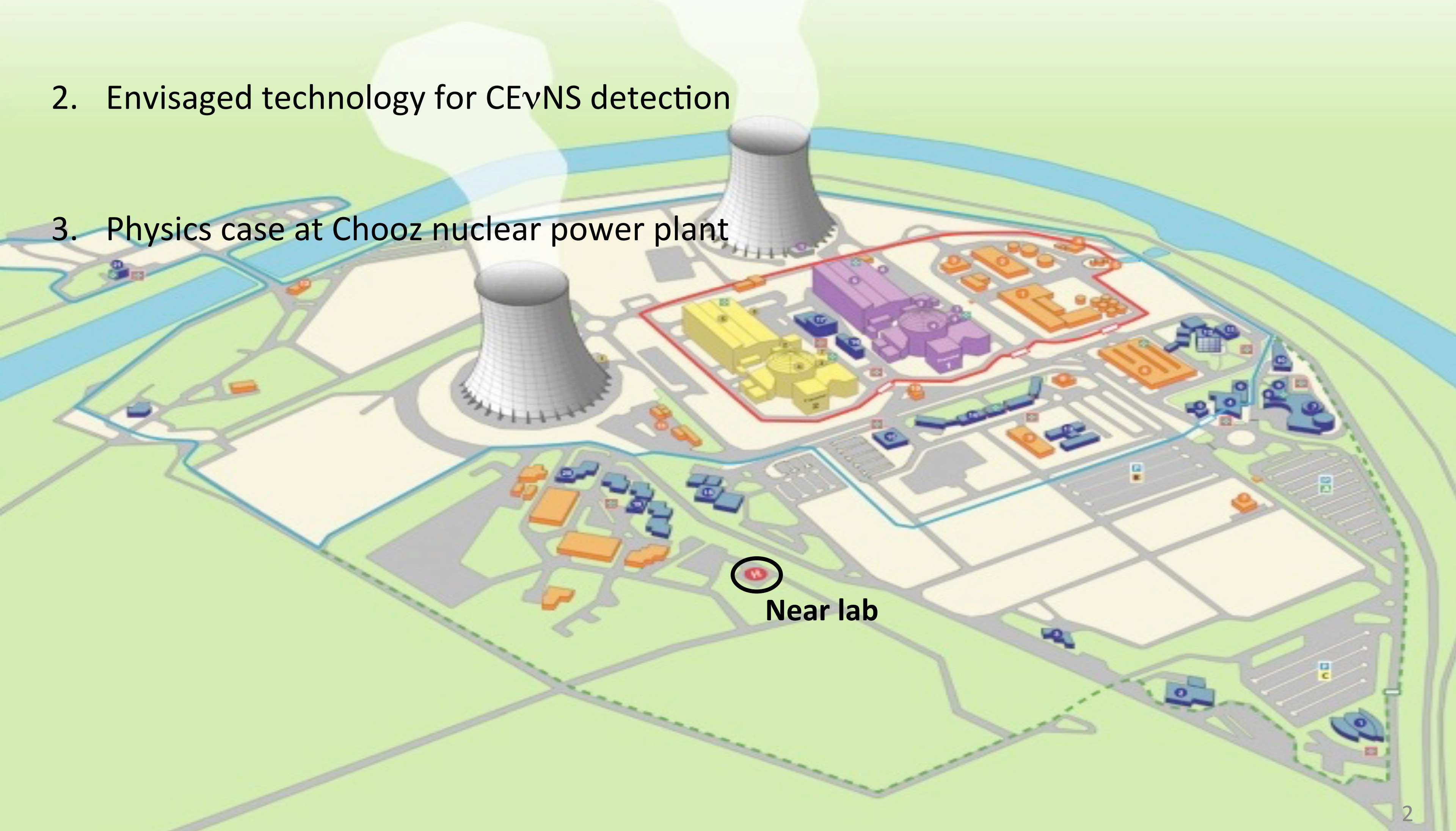
Matthieu Vivier
T. Lasserre
G. Mention
C. Nones

CEA-Saclay, DRF/Irfu/DPhP

www.cea.fr

Outline

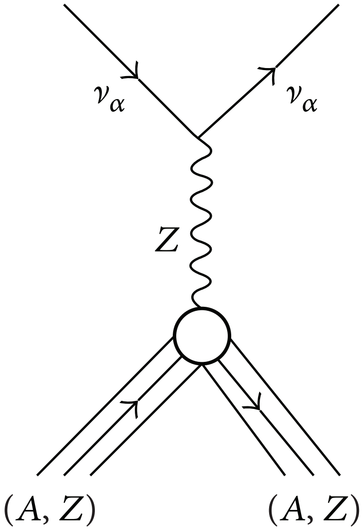
1. **Coherent Elastic Neutrino Nucleus Scattering**
2. Envisaged technology for CEνNS detection
3. Physics case at Chooz nuclear power plant

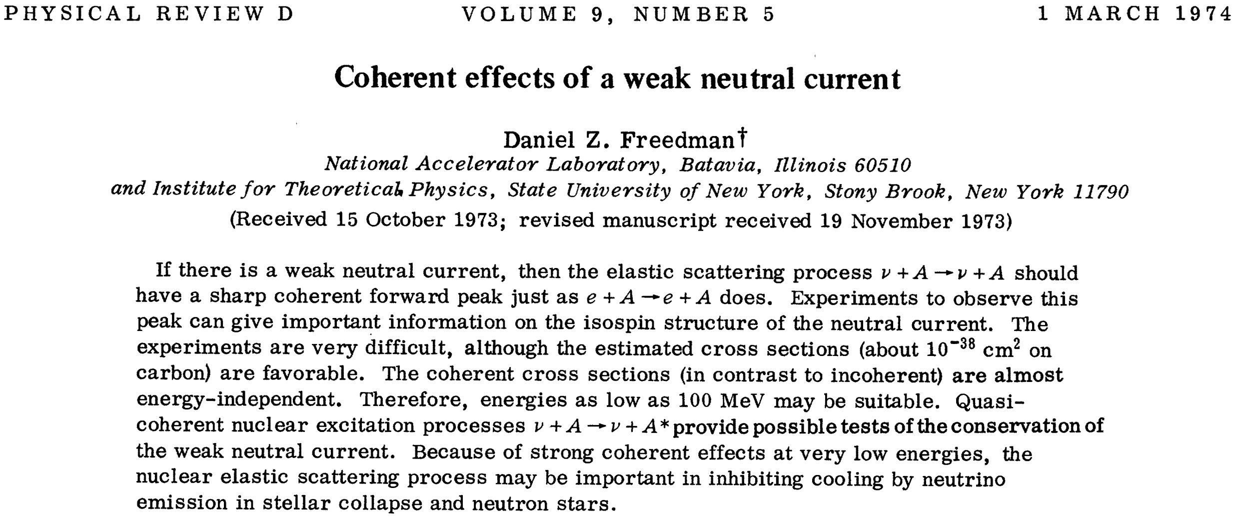


Near lab

Coherent elastic neutrino nucleus scattering

- Neutral current process, first predicted by Freedman (1974), still not observed yet
- Flavor insensitive (!)




PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

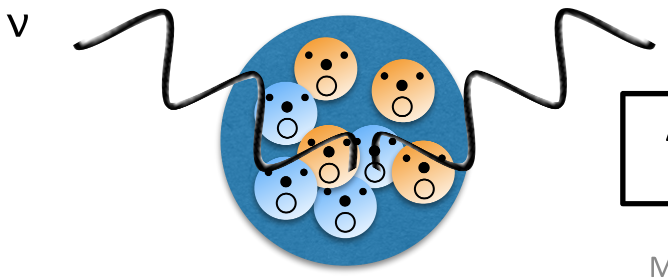
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ 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 $\nu + A \rightarrow \nu + A^*$ 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.

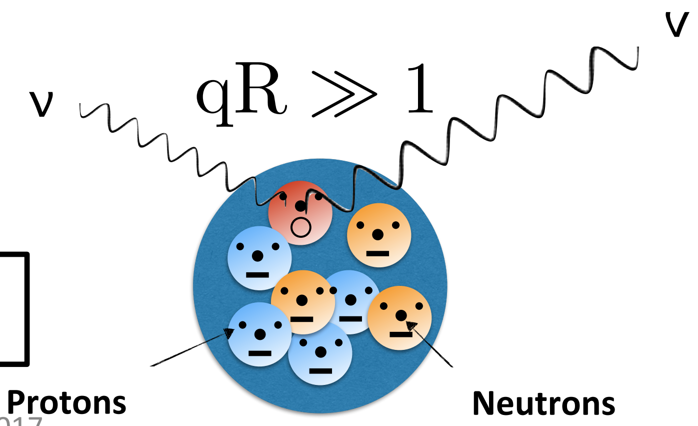
- “Coherence”:

$$qR \lesssim 1$$



q: momentum transfer
R: nucleus size

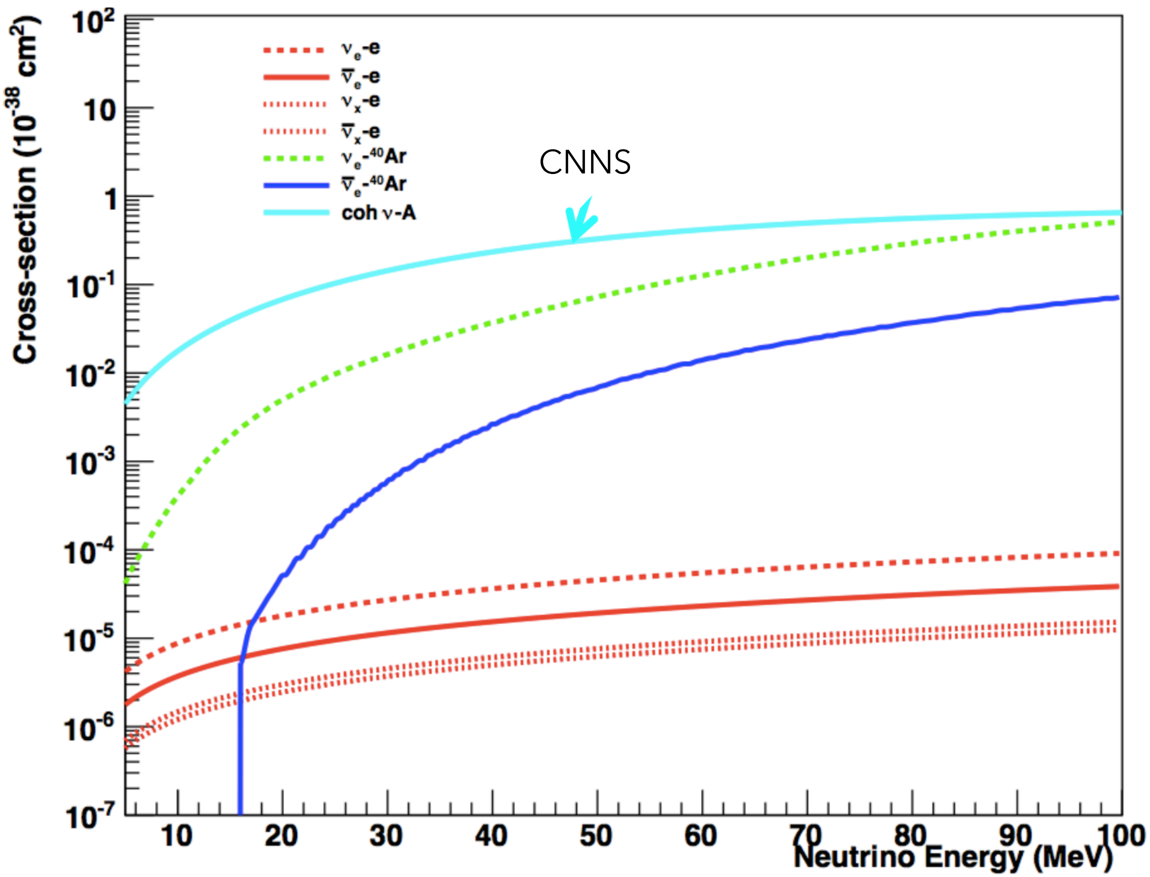
Aluminium: 1/R ≈ 60 MeV
Lead: 1/R ≈ 30 MeV


$$qR \gg 1$$

CEνNS cross-section

- Coherent scattering mostly caused by neutrons:

$$\sigma(\mathrm{E}_\nu) \simeq \frac{\mathrm{G}_\mathrm{F}^2 \boxed{\mathrm{N}^2}}{4\pi}\mathrm{E}_\nu^2 \simeq 0.42 \times 10^{-44}\,\mathrm{N}^2(\mathrm{E}/1\,\mathrm{MeV})^2\mathrm{cm}^2$$

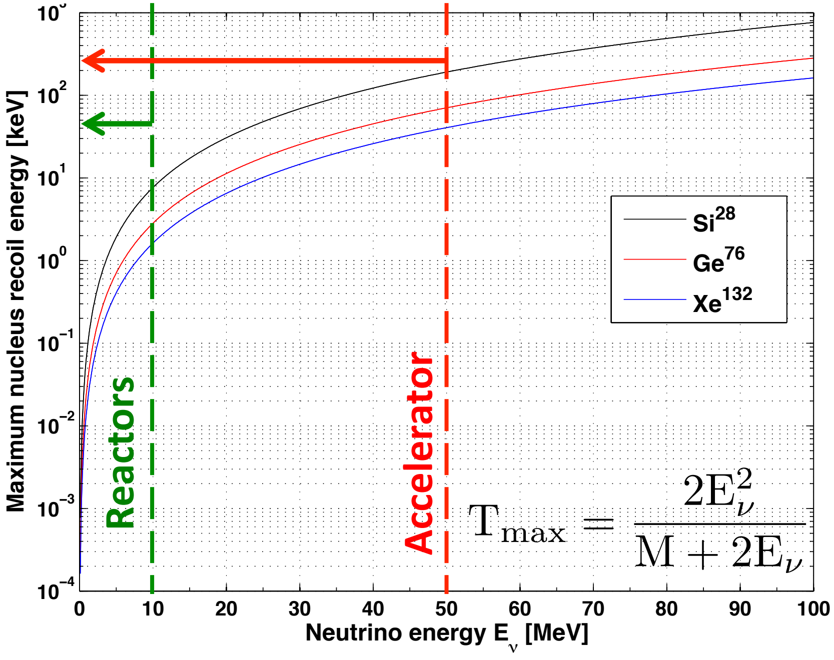


→ CEνNS on Ar

↑ **X 10^4 !**

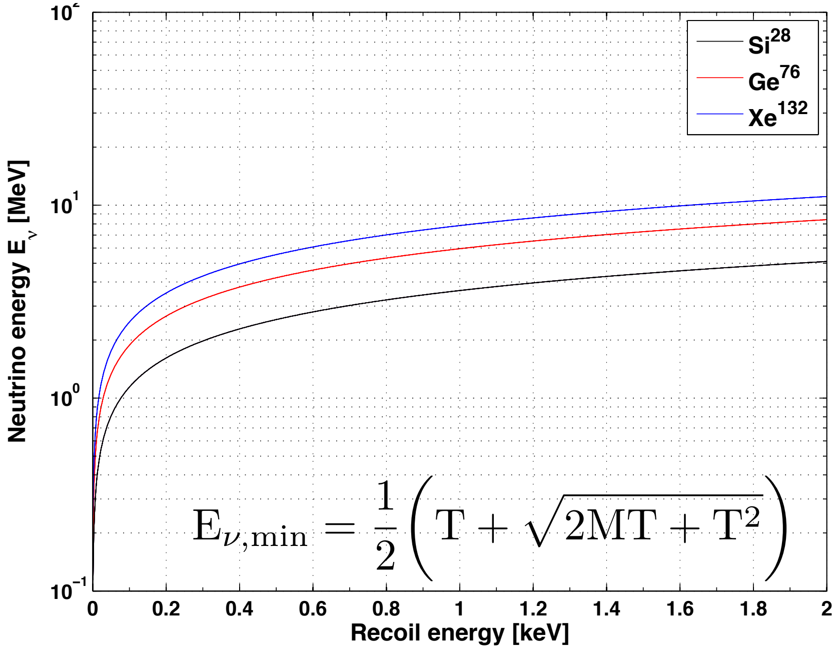
→ Solar ν detection in Borexino…

CEνNS kinematics



Maximum recoil energy produced by a neutrino of energy E

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



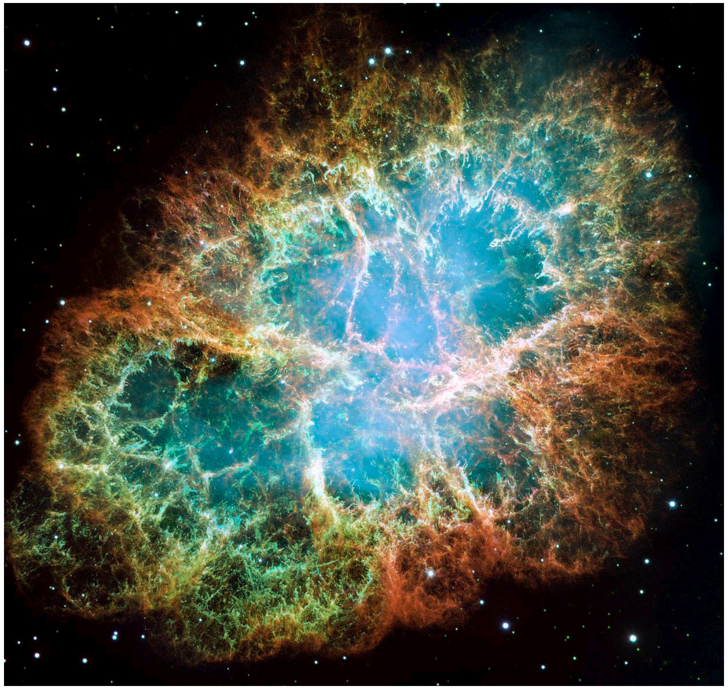
Minimum neutrino energy to produce a recoil of energy T

$$E_{\nu,\min} = \frac{1}{2}\left(T + \sqrt{2MT + T^2}\right)$$

- Extremely low recoil energies: hence very challenging to see…
- Reactor νs (≈ 3 MeV) typically produce on average 10-100 eV nucleus recoils, which can go up to a few keV, depending on target mass.
- Accelerator νs with E ≈ 10-50 MeV produce recoils generally above 1-10 keV.

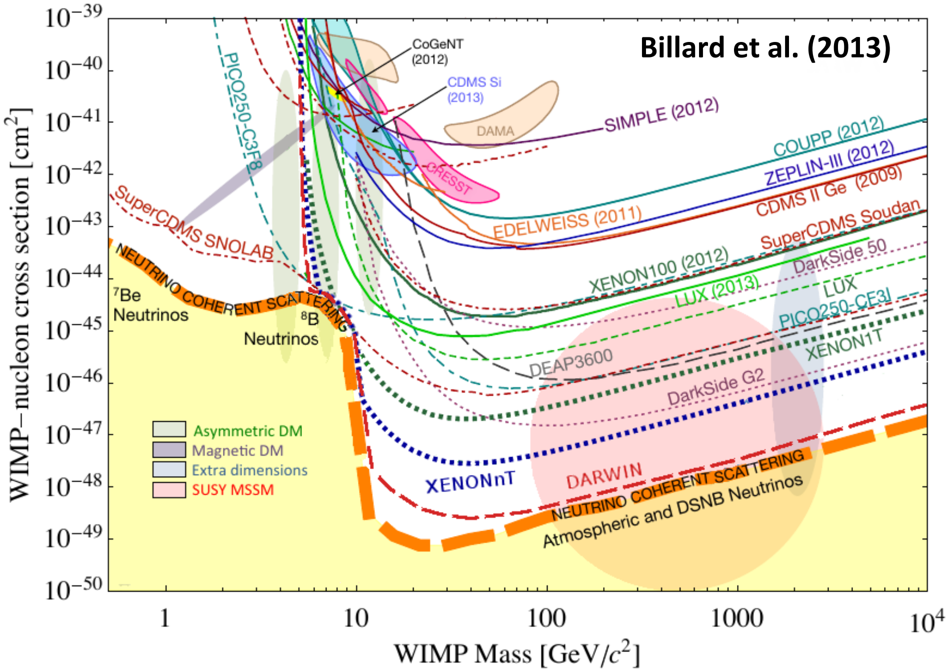
Astroparticle physics motivations

CEνNS is a relevant process for supernova dynamics…



Solar/Atmospheric/DSNB CEνNS could be soon an irreducible background for direct DM search experiments

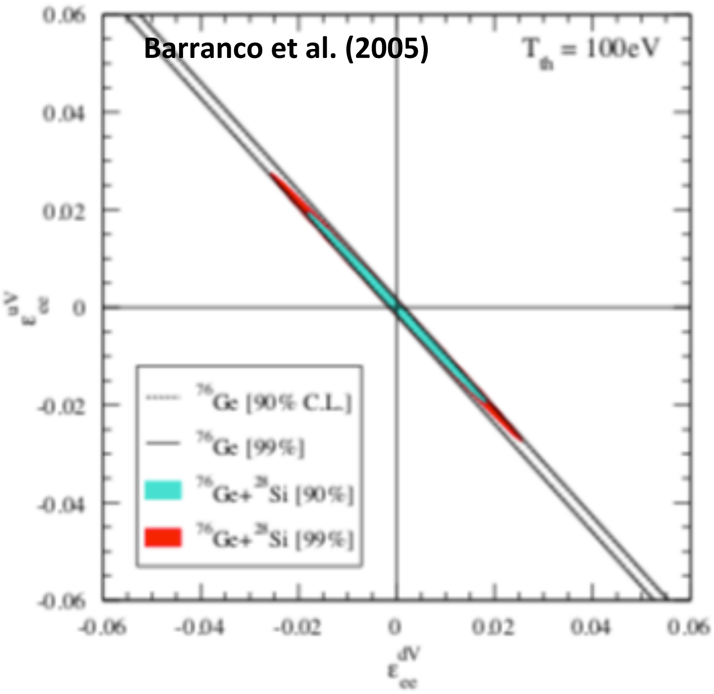
[see talk by M. Fairbairn this morning]


Billard et al. (2013)

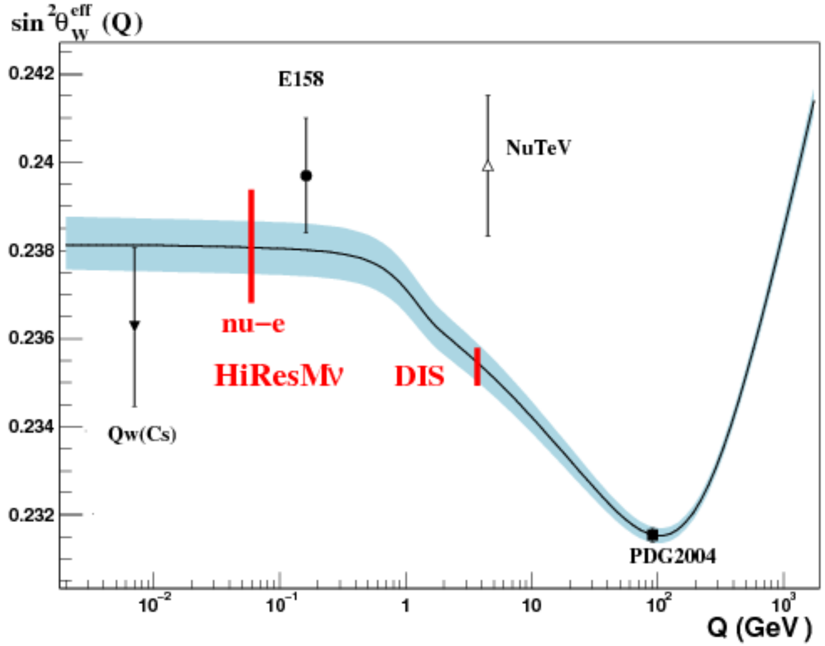
Would benefit from the measurement of $\sigma_{CE\nu NS}$…

Particle physics motivations

- Test of standard model – search for BSM physics
  - Measurement of Weinberg angle at low q
  - Possibility to explore the light sterile neutrino sector
  - Search for NSI interactions
  - Search for ν magnetic moment
  - …

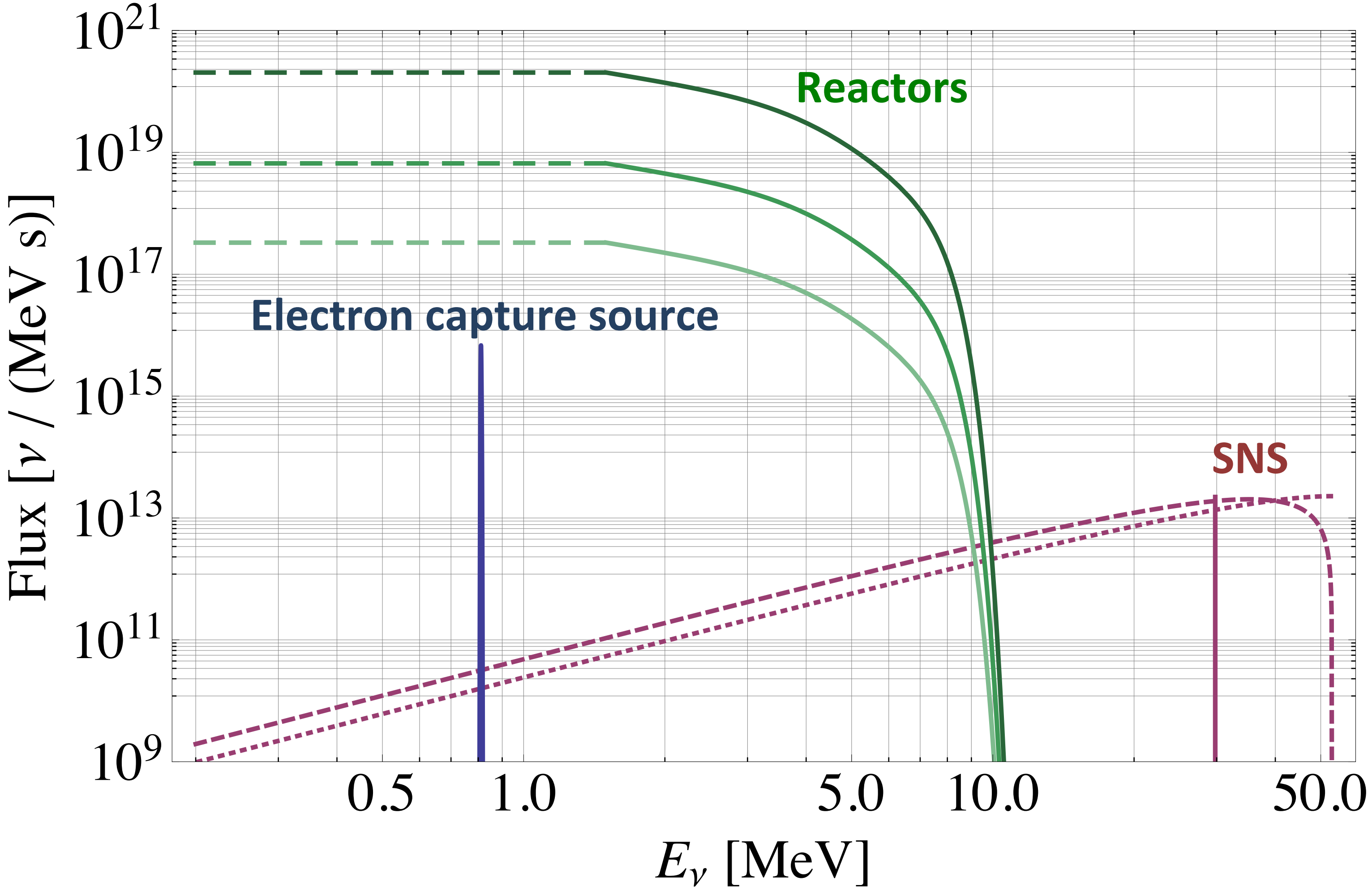


Barranco et al. (2005)



Relevant sources for CEνNS detection

- The variety of sources trade off flux, energy and knowledge of spectrum



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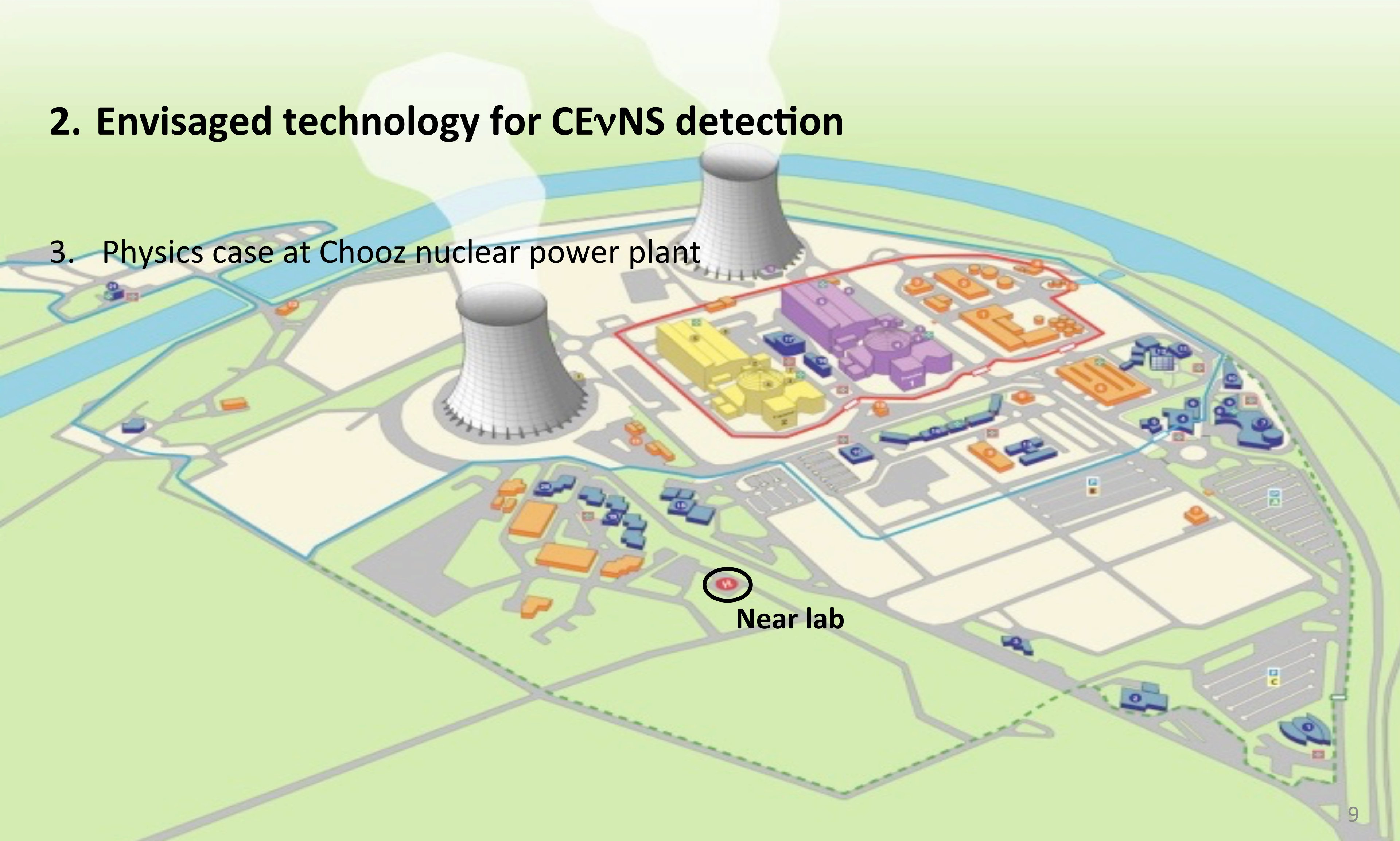
3. Physics case at Chooz nuclear power plant



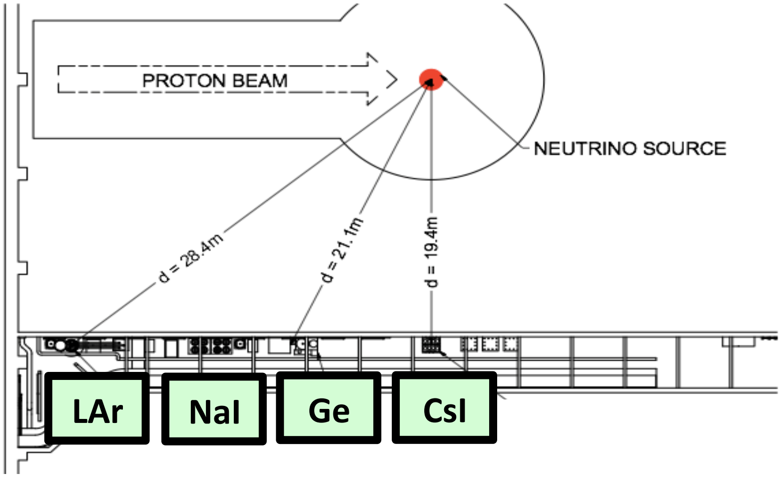
Near lab

CEνNS detection strategies

- **Using accelerators neutrinos:** larger E_ν → larger recoils → “easier” detection

CEνNS detection strategies

- **Using accelerators neutrinos:** larger E_ν ➔ larger recoils ➔ “easier” detection



- Multiple detectors placed 20-30 m away from neutrino source (10^7 cm^{-2} s^{-1} @ 20 m)
- Up to ≈ 100 events/yr expected
- Neutrons most dangerous source of backgrounds: from SNS itself & neutrinos induced neutrons on PB and Fe
- 10^{-4} neutron discrimination factor thanks to pulsed structure of beam

Target	Technology	Mass [kg]	Distance [m]	Recoil threshold [keVnr]	Data-taking start date/ CEnNS detection goal
CsI[Na]	Scintillator	14	20	6.5	Sept. 2015; 3σ in 2 yr
Ge	HPGe PPC	10	22	5	Early 2017
LAr	Single phase	35	29	20	Dec. 2016
NaI[Tl]	Scintillator	185	28	13	Summer 2016

CEνNS detection strategies

- **Using reactors neutrinos:** smaller E_ν ➔ smaller recoils ➔ “harder” detection

CEνNS detection strategies

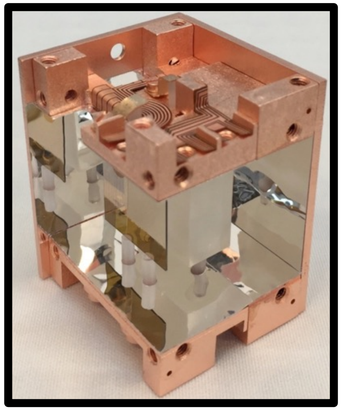
- **Using reactors neutrinos:** smaller E_ν ➔ smaller recoils ➔ “harder” detection.
- Smaller recoils ➔ lower thresholds ➔bolometry technique !

Repurposing DM detectors…

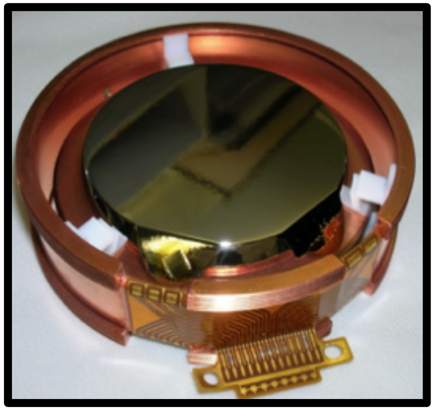
- **Using reactors neutrinos:** smaller E_ν → smaller recoils → “harder” detection.

- Performances achieved by bolometer detectors in direct DM and $0\nu\beta\beta$ experiments steadily improved over the past decades.

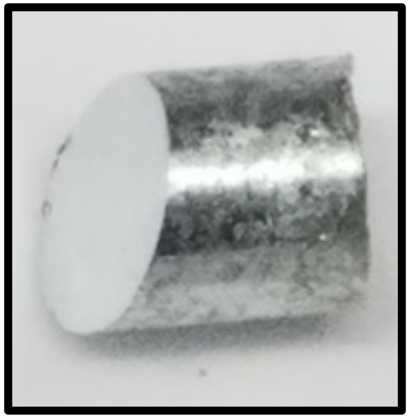
- **Idea: repurposing DM detectors…** Need to achieve recoil thresholds **below 100 eV** and low background rates to see the onset of reactor neutrinos from CEνNS.



CRESST $CaWO_4$ (TUM)



EDELWEISS Ge (CSNSM/IPNL/CEA)



Zn (MIT)

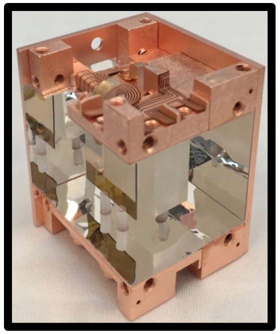
« ν-cleus »

RICOCHET

Repurposing DM detectors…

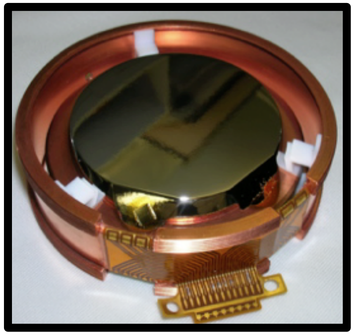
Strategy: reducing size of absorbers…

CRESST $CaWO_4$ (TUM)



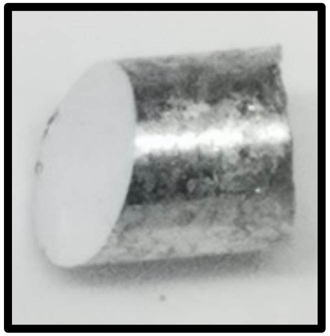
- Heat and scintillation signals
- New 24 g detectors reached 50-100 eV thresholds
- Low internal background: < 3.5 events/keV/kg/day

EDELWEISS Ge (CSNSM/IPNL/CEA)



- Heat and ionization signals
- New 25 gram-scale detectors projected to reach 50-100 eV thresholds
- Internal background contamination reduced down to ≈ 1 events/keV/kg/day

Zn (MIT)

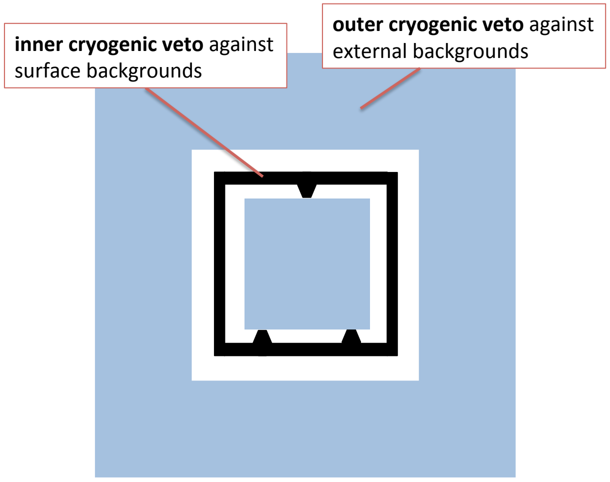


- High Debye temperature, low thermal capacitance
- Phonons and quasi-particles (breaking of cooper pairs) signals
- Potential separation of nuclear recoils from electromagnetic recoils using timing signatures of phonons vs QQs…

Further reducing the absorber mass…

ν-cleus concept (Strauss et al., arXiv:1704.04320)

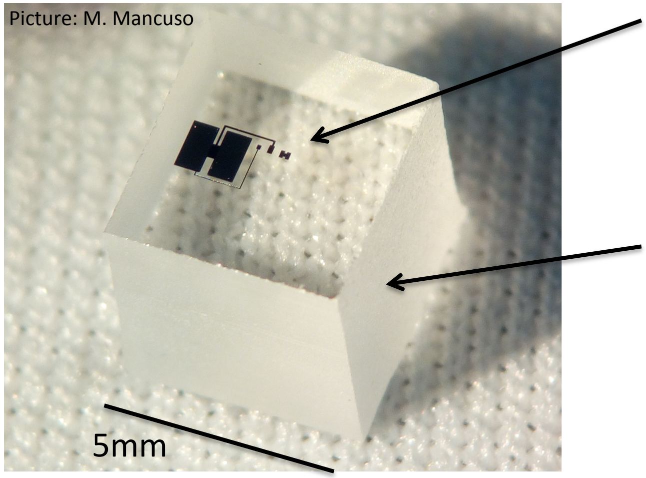
- Array of gram-scale (5x5x5) mm^3 $Al_2O_3/CaWO_4$ crystal cubes



inner cryogenic veto against surface backgrounds

outer cryogenic veto against external backgrounds

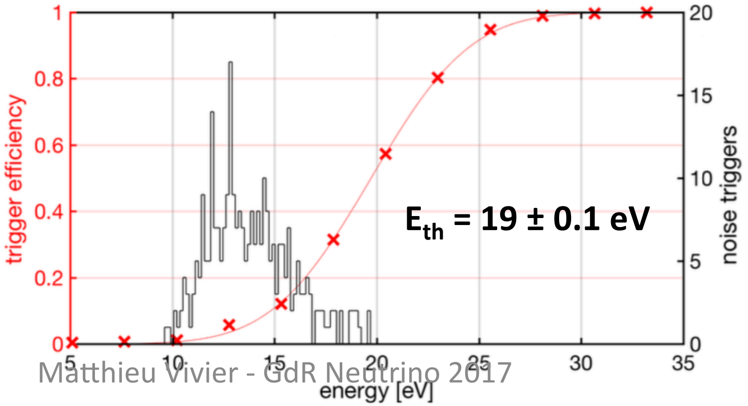
→ „Fiducial-volume“ cryogenic detector



Transition-edge-sensor

Sapphire crystal 0.5g

- Purposes:
    - Low thresholds
    - Encapsulation
    - Operability above ground



First results of a Al_2O_3 0.5 g crystal operated above ground

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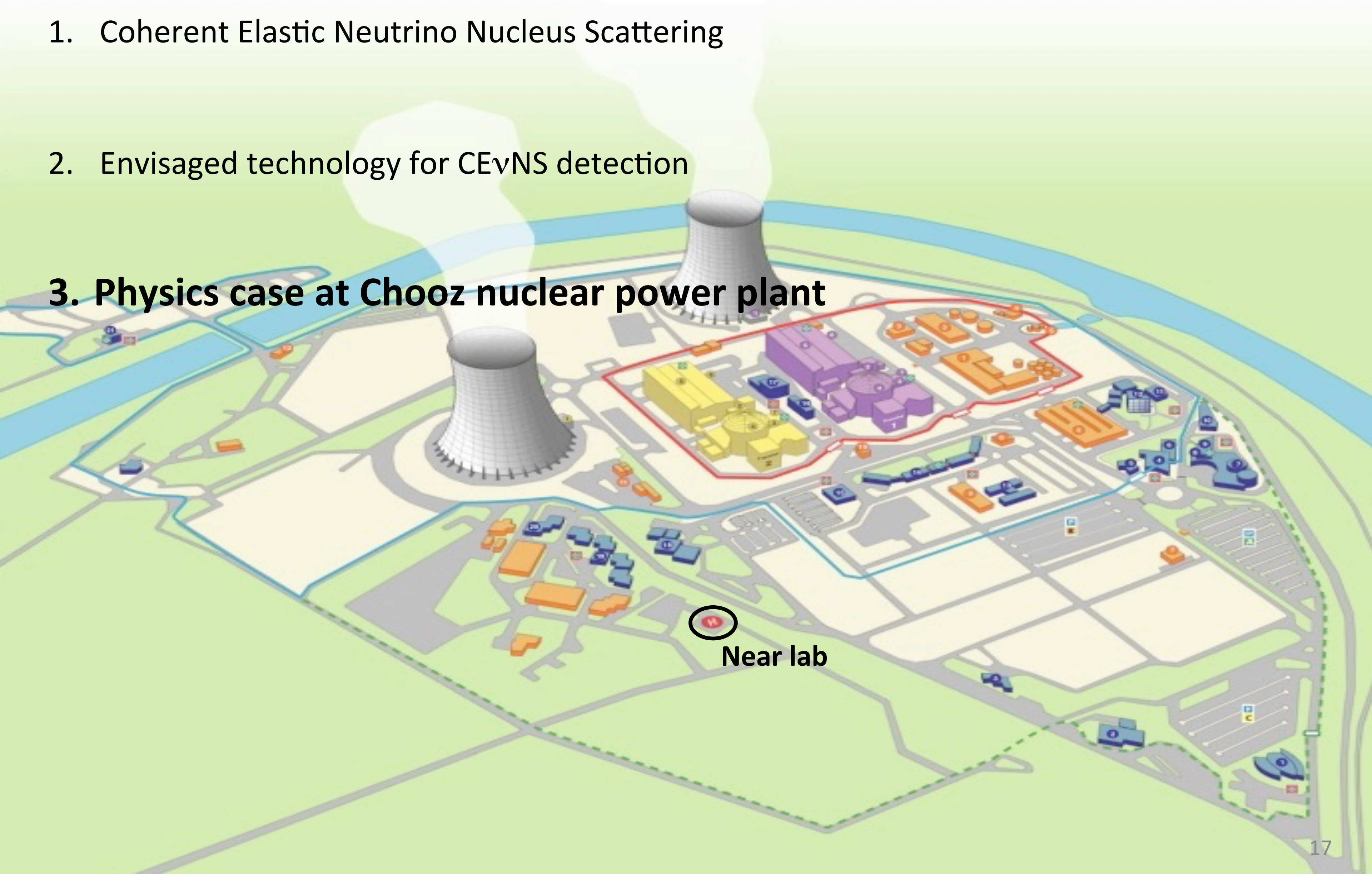
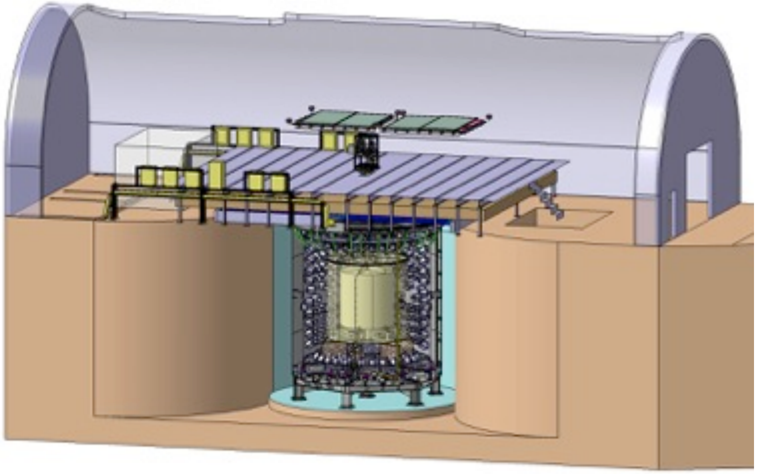


CEνNs at DC near laboratory

- Double Chooz
  - Will end operation by the end of 2017, and be dismantled by 2018/2019
  - Full infrastructure at the near laboratory could be reused

400 m – 120 m.w.e – Flat overburden

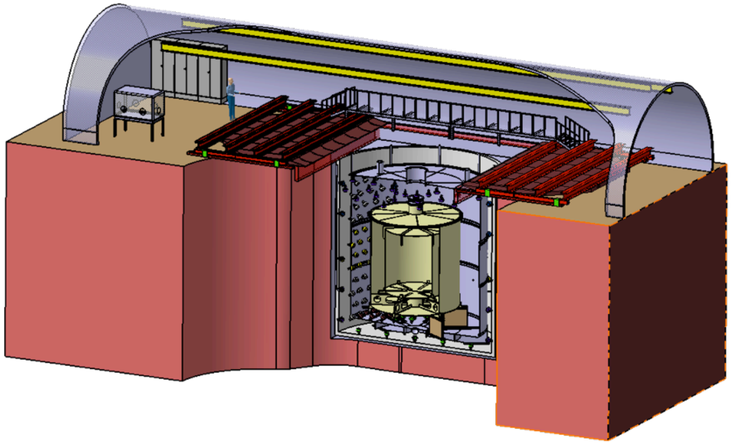
Data Taking since December 2014



≈300 neutrinos/day

1050 m – 300 m.w.e – Hill overburden

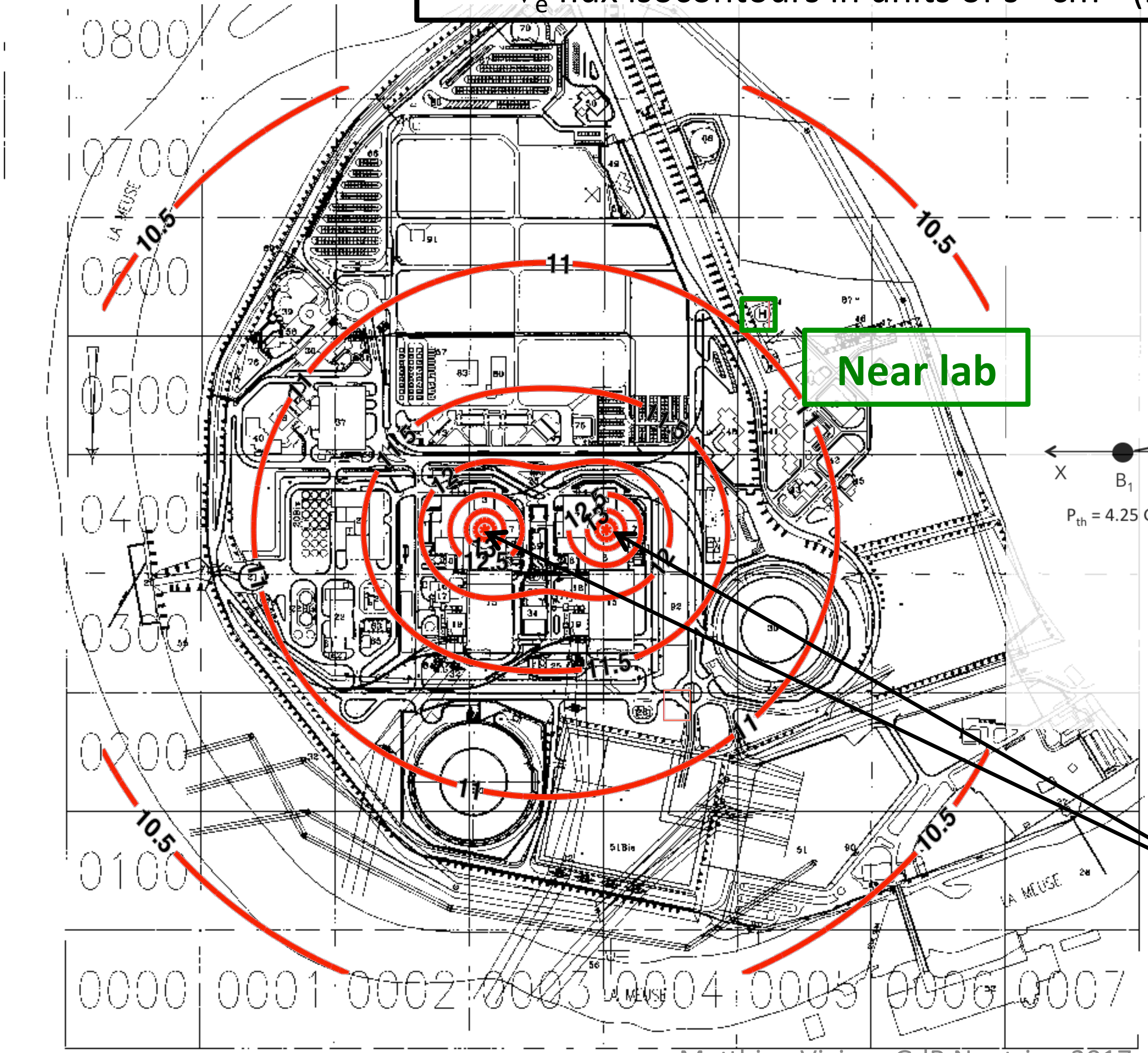
Data Taking since December 2010



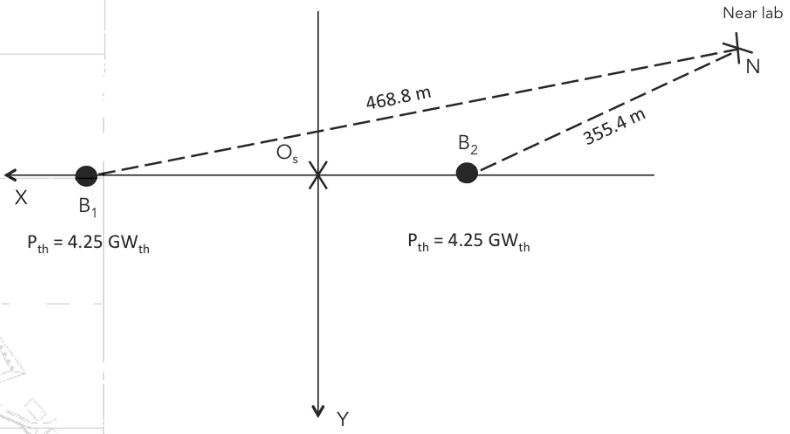
≈50 neutrinos/day

Near lab at Chooz power plant

ν_e flux isocontours in units of s^{-1} cm^{-2} (log scale)



≈ 7 x 10^{10} ν_e s^{-1} cm^{-2} @ near lab



Both reactor cores at full power (4.25 GW_{th})

Integral count rates at near lab

$$N_{\mathrm{CE\nu NS}}(T \geq T_{\mathrm{th}}) = \frac{t}{4\pi D^2} \times \frac{P_{\mathrm{th}}}{\sum_k \alpha_k E_{f,k}} \times \sum_i \frac{M_{\mathrm{det}}}{m_i} A_i \times \int_0^\infty dE\, \phi(E_\nu) \int_{T_{\mathrm{th}}}^{T_{\mathrm{max}}(m_i, E_\nu)} dT \frac{d\sigma}{dT}(m_i, T, E_\nu)$$

- **Fission rate**
- **Isotope natural abundance**
- **Reactor ν spectrum**
- **CEνNS recoil spectrum**

Rates [$\mathrm{kg}^{-1}\ \mathrm{d}^{-1}$] above energy threshold with $B_{1,2}$ operating at full power

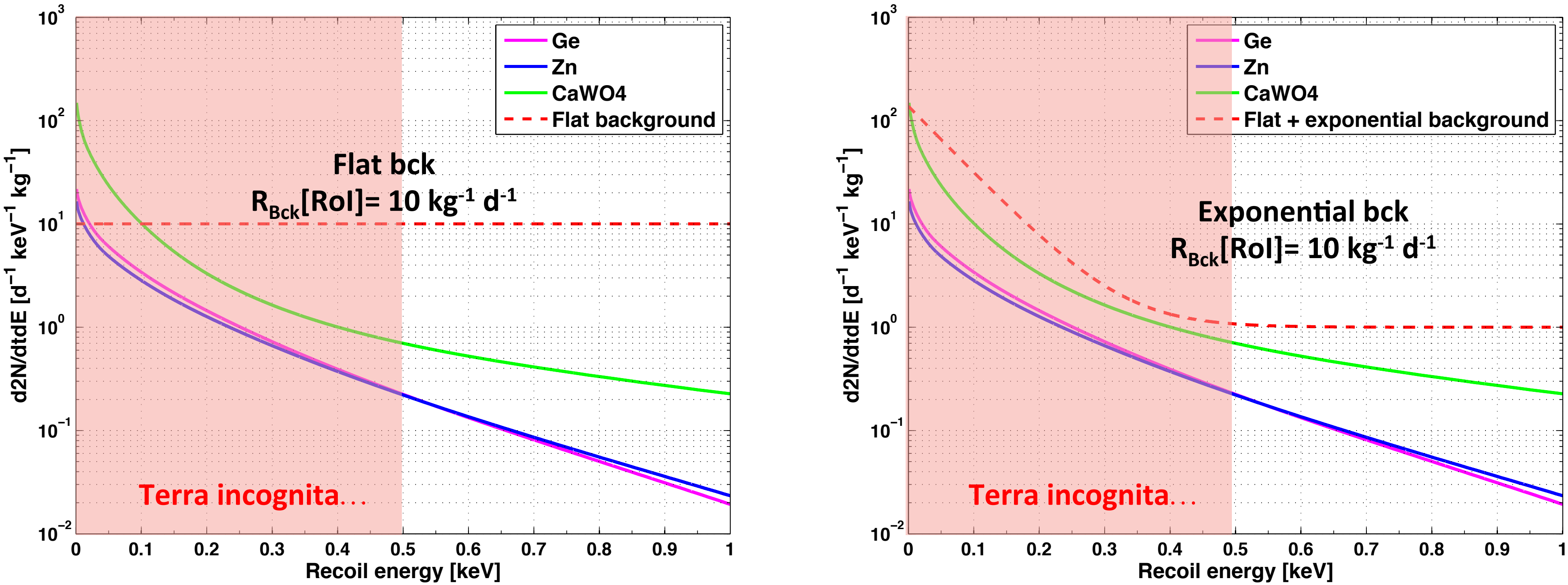
T_{th}	Zn	Ge	$CaWO_4$
10 eV	0.87	1.03	3.79
20 eV	0.78	0.92	3.19
50 eV	**0.60**	**0.68**	**2.16**
100 eV	0.41	0.46	1.38
200 eV	0.22	0.23	0.80

Need a few kilograms of material to get a couple of events per day

Recoil spectra @ Chooz near lab

- A simple (but unrealistic) baseline scenario:
  - Single detector with mass 1 kg
  - Region of interest for signal detection: recoil events from T_{th} up to 1 keV
  - Two kinds of background “modeling” in the RoI: **flat** or **exponential**

Differential recoil spectra [kg^{-1} d^{-1} keV^{-1}] @ Chooz near lab

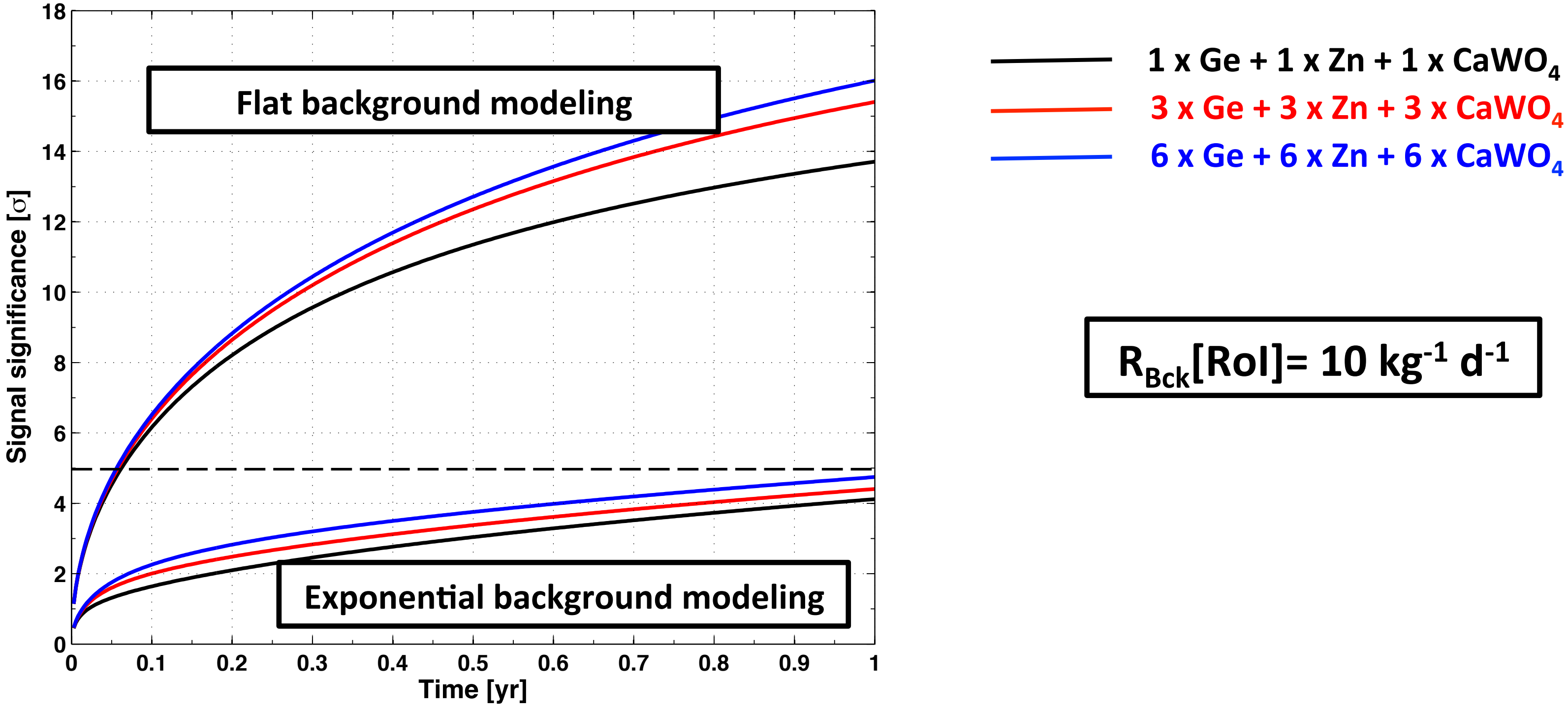


$$B(x) = A + B\exp(-\Gamma x)$$

Simplistic sensitivity projections @ Chooz near lab

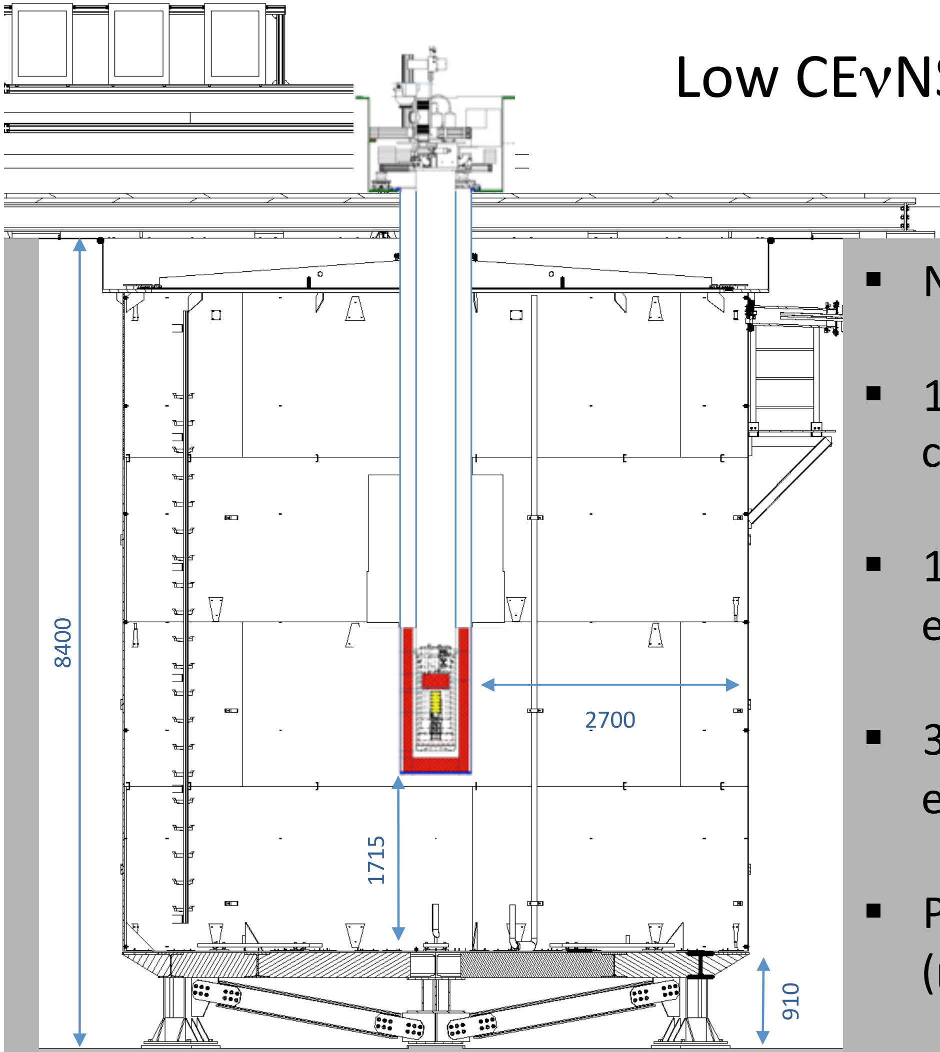
- **Combining** three envisaged technologies:
    - Total payload mass: **1 kg (Ge + Zn + CaWO$_4$)**
    - Region of interest for signal detection: recoil events from **T_{th}= 50 eV up to 2 keV**
    - Two kinds of background "modeling" in the RoI: **flat** or **exponential**
    - Background rate is assigned a 20% uncertainty
    - Detection efficiency is assigned a 5% uncertainty
    - Reactor and ν_e spectra uncertainty embedded in an additional 5% signal normalization uncertainty

Rate + shape significance



R_{Bck}[RoI]= 10 kg^{-1} d^{-1}

A possible detector configuration…



Low CEνNS rate @ near lab but…

- No reactor induced backgrounds
- 120 mwe → strong reduction of cosmogenic induced backgrounds
- 1 m ultra pure copper pit for an easier cryostat/detector handling
- 3.5 m of water shielding to reduced external background
- Possibility to install active shielding (muon veto, etc…)

Ricochet @ Chooz (J. Billard et al.)

Combination of Ge/Zn detectors – 10 kg

Edelweiss backgrounds

Recoil thresholds = 100 eV

J. Billard[1], R. Carr[2], J. Dawson[3], E. Figueroa-Feliciano[4], J. A. Formaggio[2], J. Gascon[1], M. De Jesus[1], J. Johnston[2], T. Lasserre[5,6], A. Leder[2], K. J. Palladino[7], S. H. Trowbridge[2], M. Vivier[5], and L. Winslow[2]

[1] *Univ Lyon, Universite Claude Bernard Lyon 1, CNRS/IN2P3, Institut de Physique nucleaire de Lyon, 4 rue Enrico Fermi, F-69622 France*

[2] *Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA*

[3] *AstroParticule et Cosmologie, Universite Paris Diderot, Paris, France*

[4] *Department of Physics, Northwestern University, Evanston, IL, USA*

[5] *Commissariat à l'énergie atomique et aux énergies alternatives, Centre de Saclay, DRF/Irfu, 91191 Gif-sur-Yvette, France*

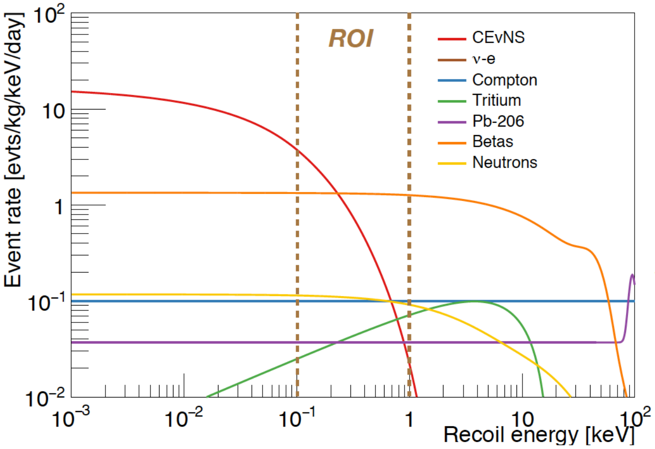
[6] *AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France*

[7] *Department of Physics, University of Wisconsin, Madison, WI, USA*

E-mail: `lwinslow@mit.edu`

30 December 2016

Abstract. We present the potential sensitivity of a future recoil detector for a first detection of the process of coherent elastic neutrino nucleus scattering (CEνNS). We use the Chooz reactor complex in France as our luminous source of reactor neutrinos. Leveraging the ability to cleanly separate the rate correlated with the reactor thermal power against (uncorrelated) backgrounds, we show that a 10 kilogram cryogenic bolometric array with 100 eV threshold should be able to extract a CEνNS signal



Event rate [/kg/day]

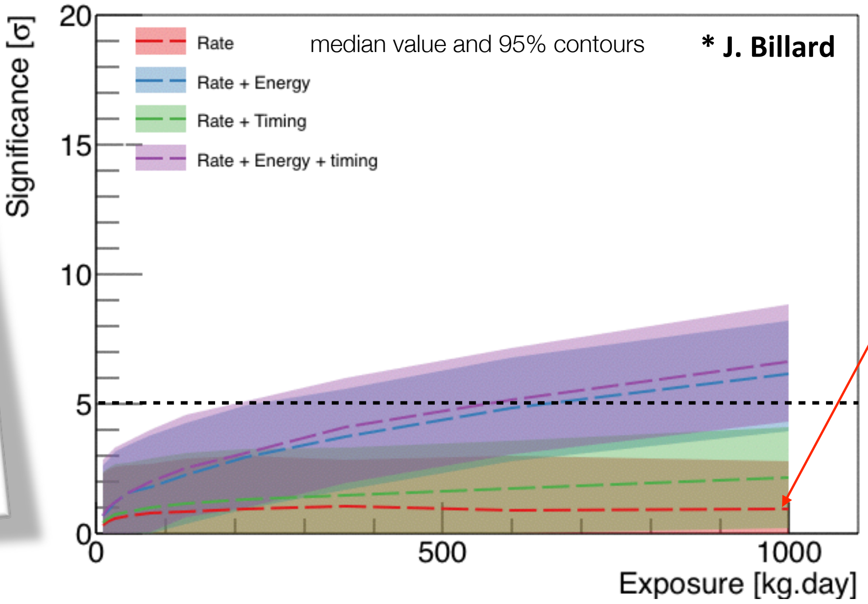
CEvNS: 0.51 (both ON)

Compton: 0.09
Tritium: 0.0480258
Betas: 1.16872
Lead: 0.0333
Neutron: 0.0919413
nu-e: 1e-6 (not considered)
Tot. Back.: 1.43

Systematic uncertainty [%]

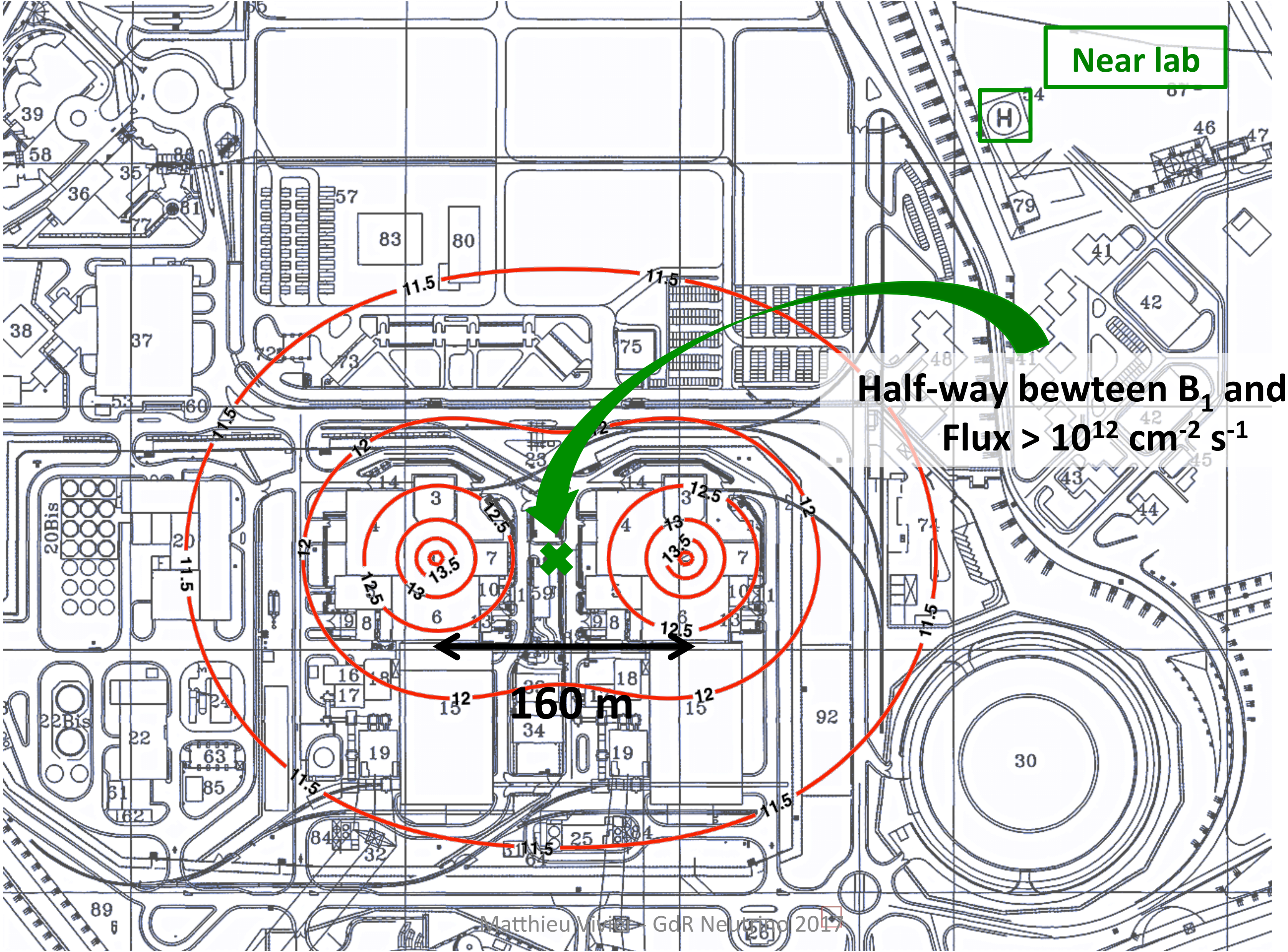
Sig. Eff.: 5

Compton: 10
Tritium: 10
Betas: 20
Lead: 10
Neutron: 10



Saturation due to systematics

CEνNS at a very near site (< 100m)



Half-way bewteen B_1 and B_2

Flux > 10^{12} cm^{-2} s^{-1}

Integral count rates at a very near site

$$N_{\mathrm{CE}\nu\mathrm{NS}}(T \geq T_{\mathrm{th}}) = \frac{t}{4\pi D^2} \times \frac{P_{\mathrm{th}}}{\sum_k \alpha_k E_{f,k}} \times \sum_i \frac{M_{\mathrm{det}}}{m_i} A_i \times \int_0^\infty dE\, \phi(E_\nu) \int_{T_{\mathrm{th}}}^{T_{\mathrm{max}}(m_i,E_\nu)} dT\, \frac{d\sigma}{dT}(m_i, T, E_\nu)$$

- **Fission rate**
- **Isotope natural abundance**
- **Reactor ν spectrum**
- **CEνNS recoil spectrum**

Rates [kg^{-1} d^{-1}] above energy threshold at **80 m** from $B_{1,2}$ operating at full power

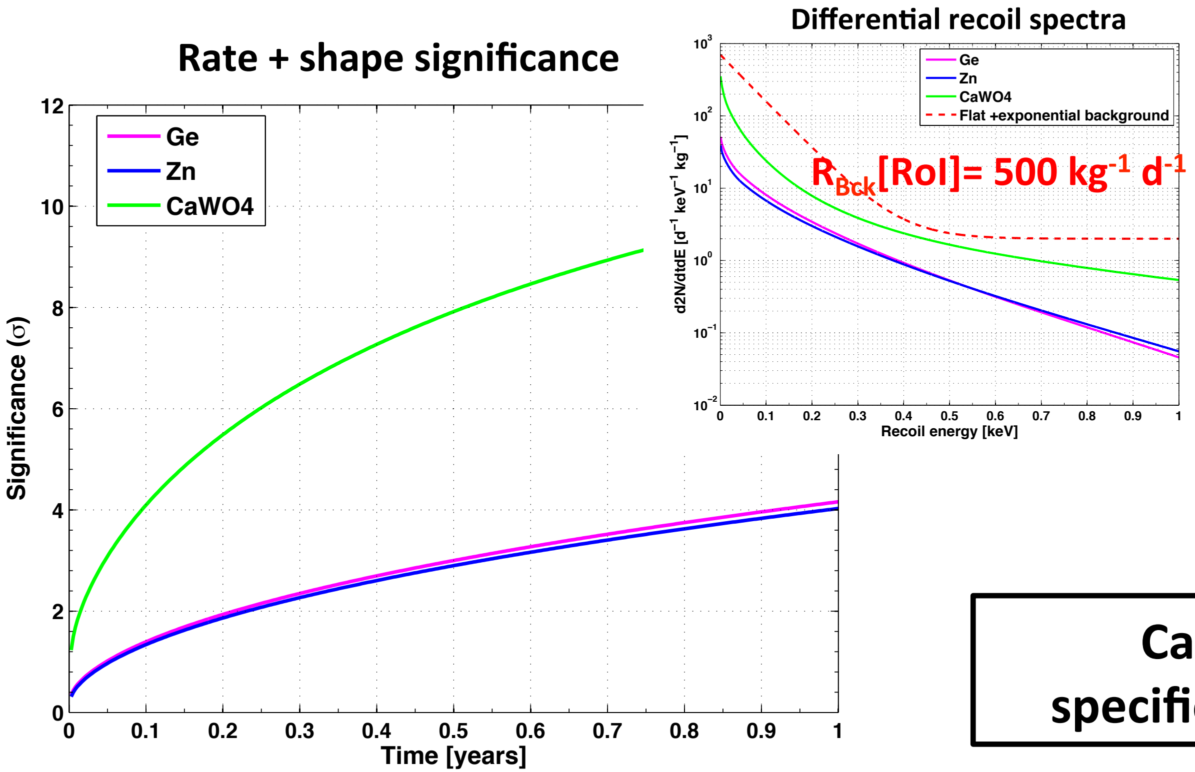
T_{th}	Zn	Ge	$CaWO_4$
10 eV	20.68	24.46	89.67
20 eV	18.50	21.68	75.42
50 eV	14.12	16.18	51.05
100 eV	9.72	10.80	32.66
200 eV	5.19	5.49	18.86

Rates x 30 with respect to Double Chooz near lab

Need a few 10 to 100 grams of material to get a couple of events per day

Sensitivity at a very near site

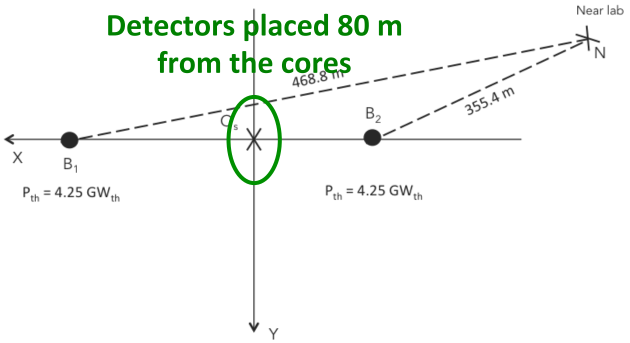
- A simple (but unrealistic) baseline scenario:
  - Single detector with mass **0.1 kg**
  - Region of interest for signal detection: recoil events from **T_{th}= 50 eV up to 2 keV**
  - Two kinds of background “modeling” in the RoI: **flat** or **exponential**
  - Background rate is assigned a 20% uncertainty
  - Detection efficiency is assigned a 5% uncertainty
  - Reactor and ν_e spectra uncertainty embedded in an additional 5% signal normalization uncertainty



Rate + shape significance

Differential recoil spectra

R_{Bck}[RoI]= 500 kg^{-1} d^{-1}

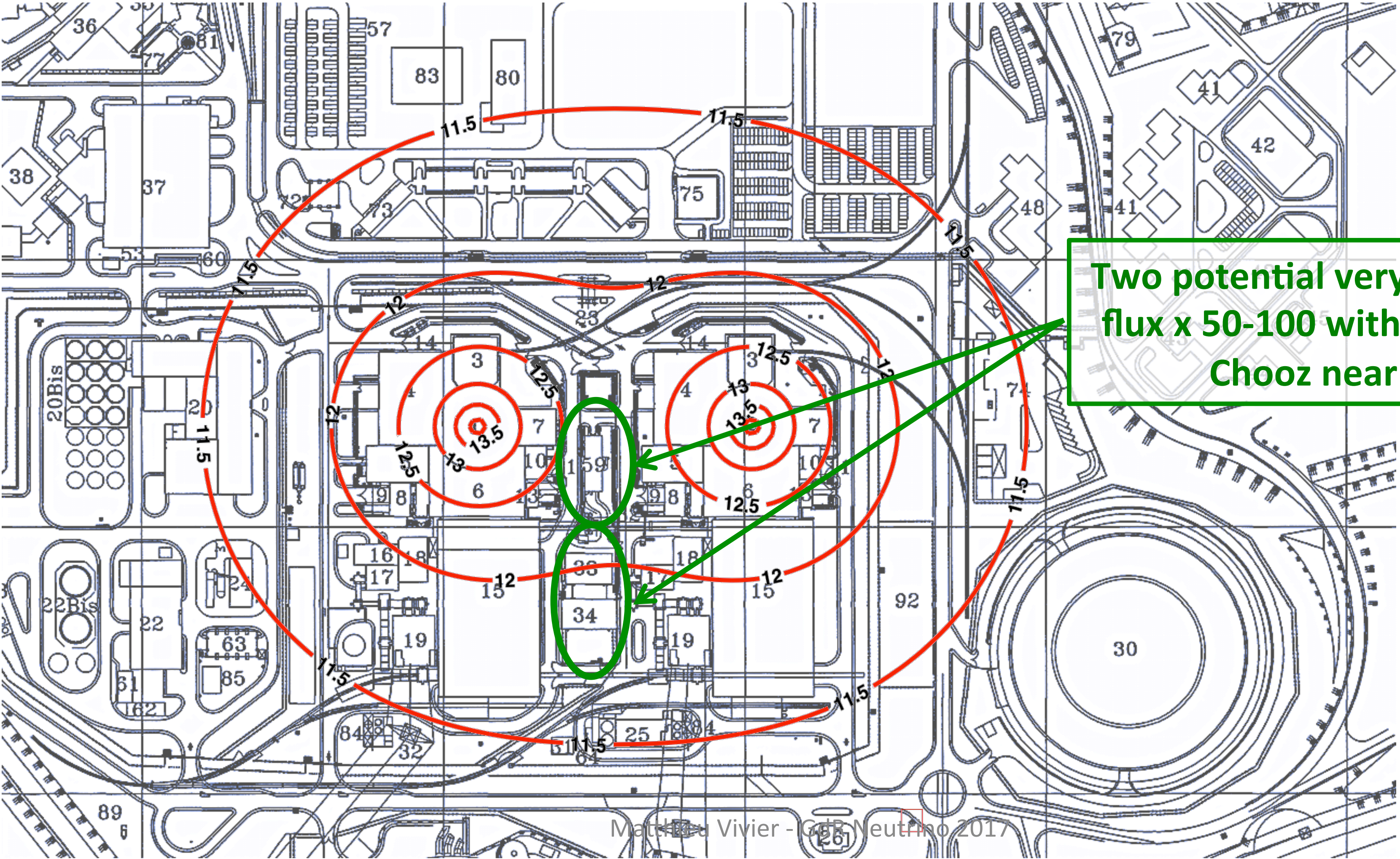


Detectors placed 80 m from the cores

Can relax background specifications by a factor 50…

Looking for a very near site…

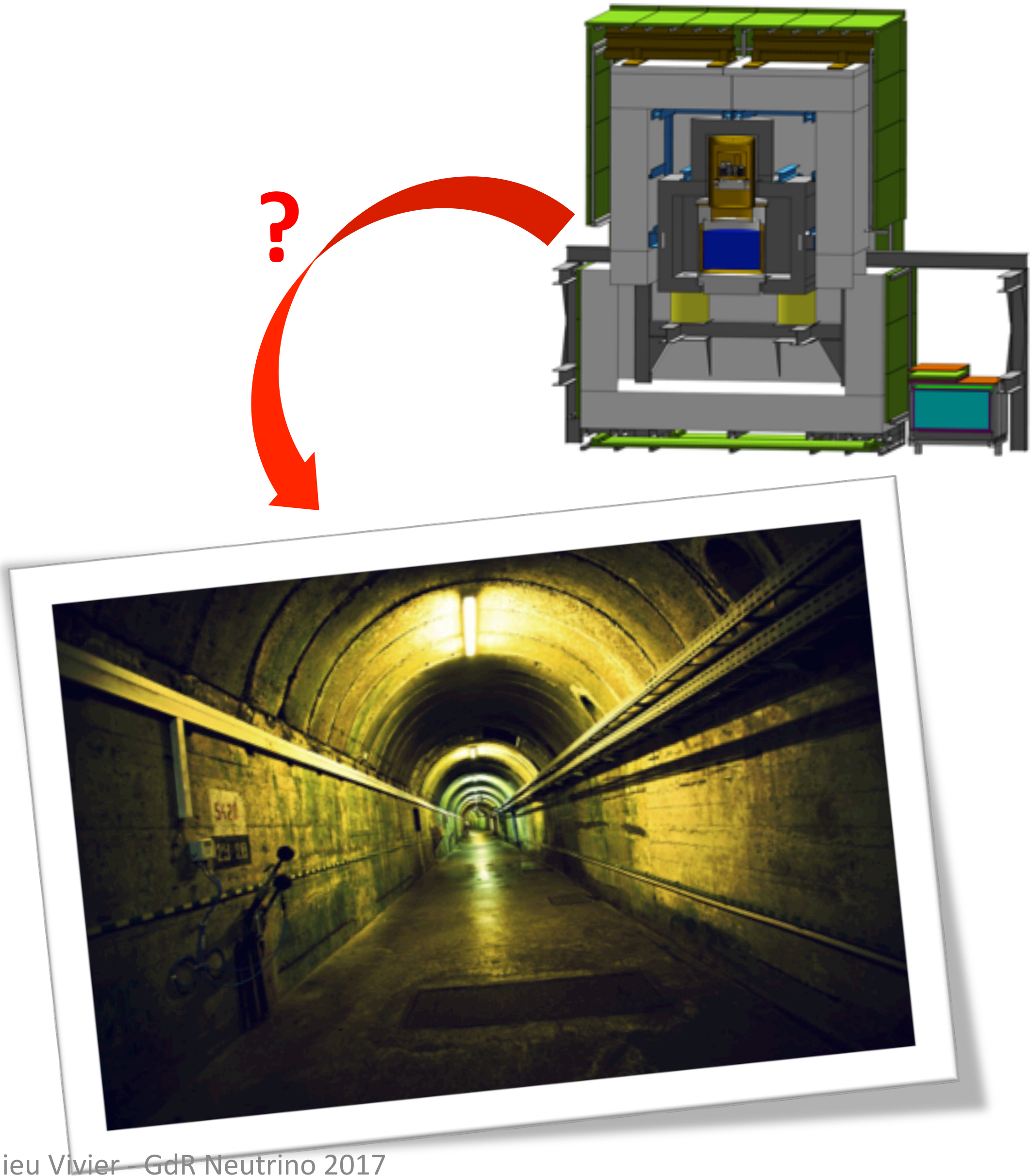
- Contact established with Chooz engineers
- An ‘EDF coordinator’ has been associated to our project
- Two potential sites have been identified by EDF engineers. They are located in the basement of the administrative buildings between the two reactors.



Two potential very near sites: flux x 50-100 with respect to Chooz near lab!

Casemate: contact with CNPE @ Chooz

- Discussions on:
  - Locations
  - Overburden
  - Other possible backgrounds (spent nuclear fuel pools, …)
  - Active/passive shieldings
  - Casemate Size
  - Integration constraints
  - Access (restricted)
  - Ventilation
  - Water line?
  - Electrical Power?



A growing interest…

🇺🇸

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

🇩🇪

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

MPI, Munich
Michele Mancuso Frederica Petricca
Raimund Strauss

🇫🇷

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

APC, Paris
Jaime Dawson

Conclusions

- CEνNS soon to be measured, thanks to improvements in DM direct detection experiments achieved over the past decades

- Attractive process: offers a wide variety of science applications (test of standard model, search for BSM, astroparticle physics implications)

- Two basic approaches: either using accelerator neutrinos (E_ν < 50 MeV, low flux) or reactor neutrinos (E_ν < 10 MeV, higher flux)

- Concept presented here aims at repurposing bolometric DM detectors for detecting CEνNS at the Chooz power plant

- Three envisaged bolometric technologies:
  - Ge [EDELWEISS style]
  - $CaWO_4$ [CRESST style]
  - Superconducting metal (Zn)

- First sensitivity studies showed that:
  - At least 1 kg of material with a recoil threshold less than 100 eV is necessary for a 5 σ detection @ Chooz near lab (400m) in less than a year, with $R_{bck} < 10\ kg^{-1}\ d^{-1}$
  - 10-100 g of material with E_{th} < 50 eV are enough to detect CEνNS in a few weeks at a very near site (< 100 m from B_1 and B_2 cores)

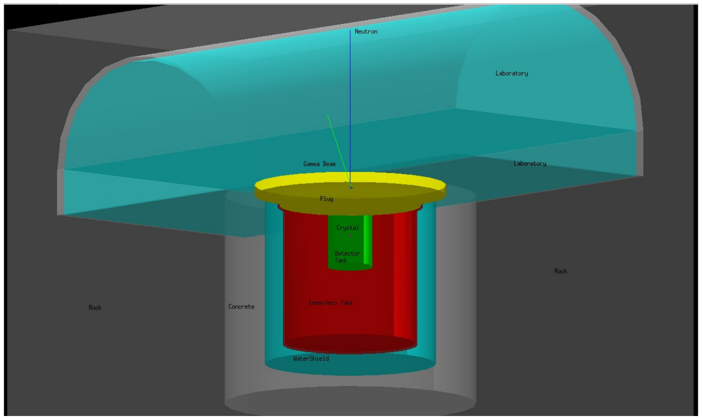
Future

- The idea of installing low threshold bolometer devices at Chooz shows a growing interest: collaborative work between American, French & German groups is on-going

- Dedicated background simulations are on-going at DC near hall and at a low overburden very near site
    - Estimate cosmogenic and radiogenic neutron backgrounds
    - Estimate γ/β backgrounds
    - Optimize shielding configuration

- A realistic scenario is being worked out to install a cryostat in the Double Chooz near detector pit

- A letter of intent is in preparation…

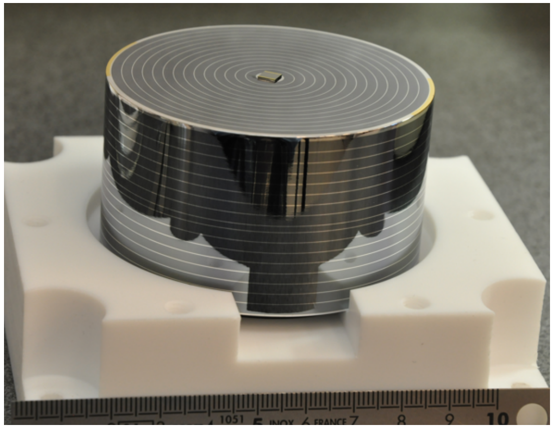


Global Geometry Visualization

First meeting at Chooz, January 2017

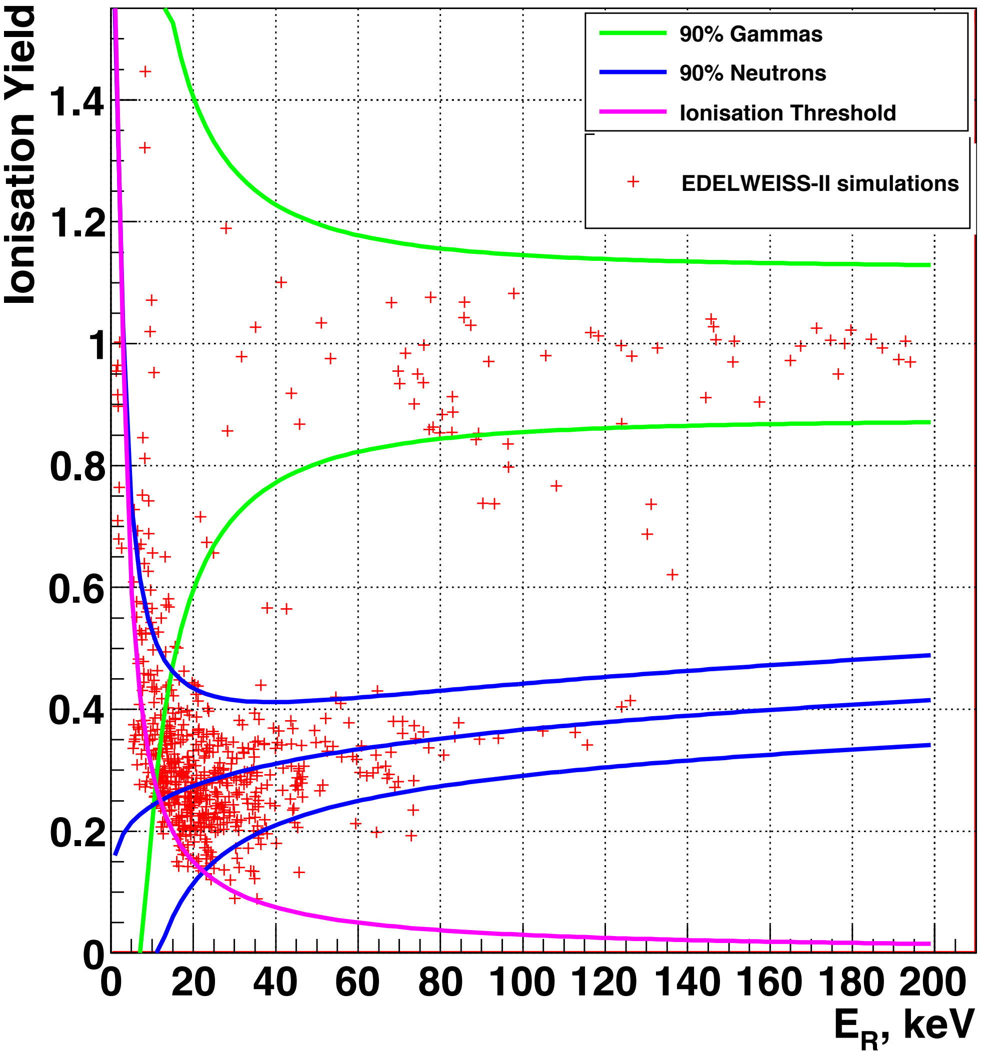
Backup slides

Repurposing DM detectors…

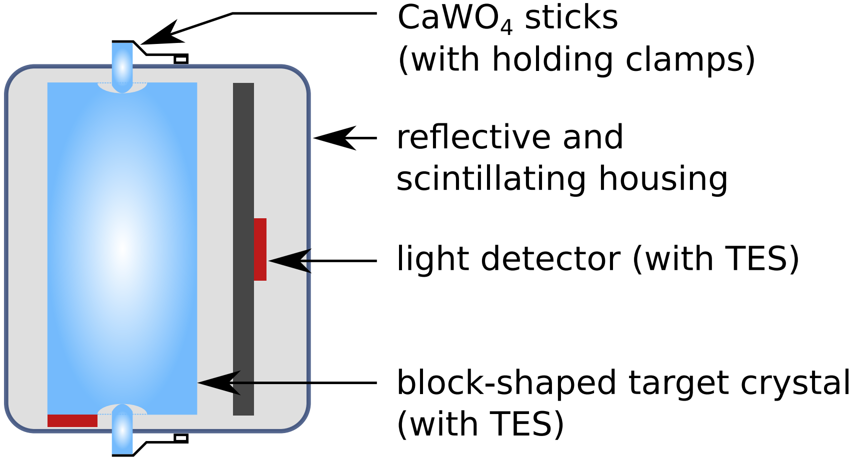


EDELWEISS detectors

- Separation of nuclear recoils from e^- recoils using heat and ionization signals
- New 25 gram-scale detectors projected to reach 50-100 eV thresholds (Ricochet project)
- Internal background contamination reduced down to ≈ 1 events/keV/kg/day



Repurposing DM detectors…



$CaWO_4$ sticks
(with holding clamps)

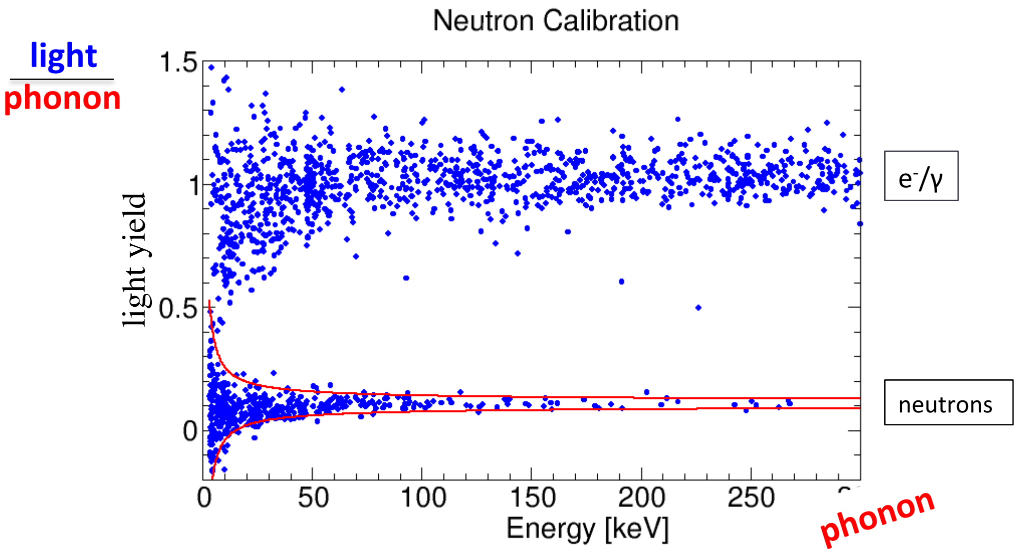
reflective and
scintillating housing

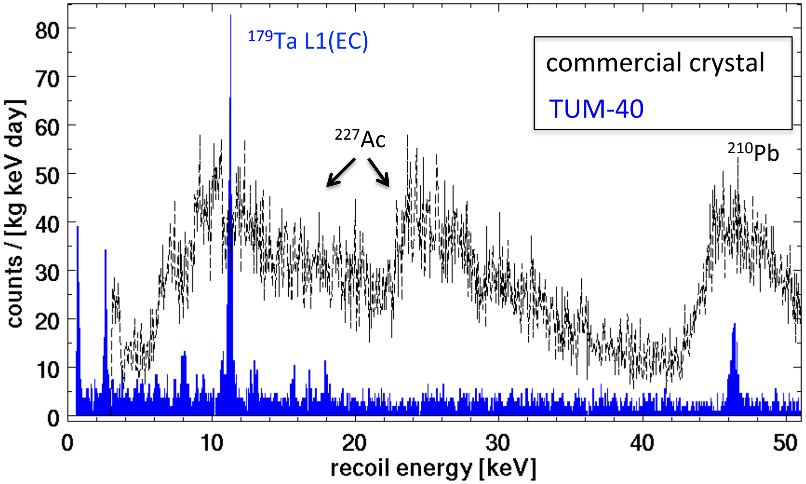
light detector (with TES)

block-shaped target crystal
(with TES)

CRESST (type 3) detectors

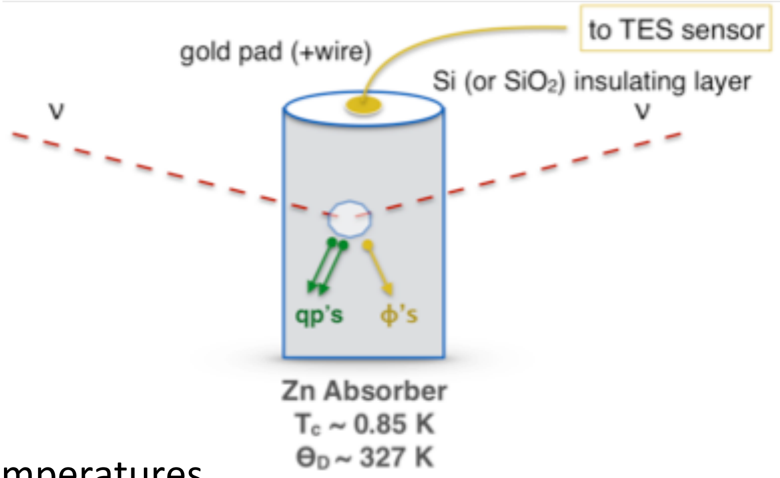
- CaWO4 crystals with TES readout
- Separation of nuclear recoils from e^- recoils using heat and scintillation signals
- New 24 g detectors reached 50-100 eV thresholds
- Low internal background contamination (< 3.5 events/keV/kg/day)



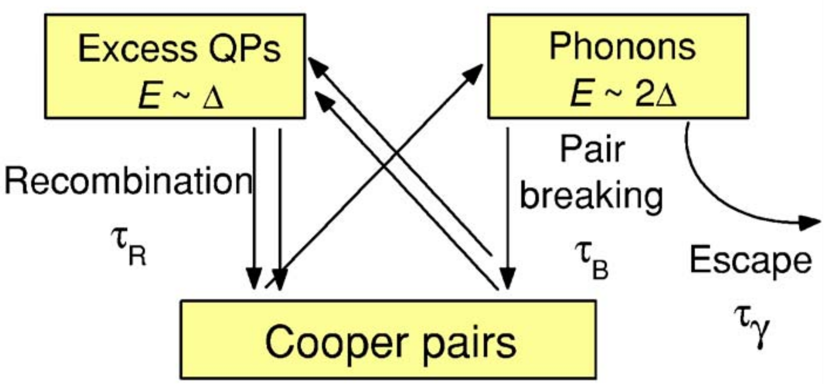


Using superconducting metals…

- R&D strategy pursued by MIT group of J. Formaggio (Ricochet project)
- Metallic Zn absorber coupled to TES
- High Debye temperature, low thermal capacitance
- In a superconducting state, competition between production of phonons and quasi-particles (breaking of cooper pairs)



- Recombination time for QQs extremely long at low temperatures, while (a)thermal phonons operates at much faster time scales: separation of nuclear recoils from electromagnetic recoils might be possible using timing signatures of phonons vs QQs…



Excess QPs $E \sim \Delta$

Phonons $E \sim 2\Delta$

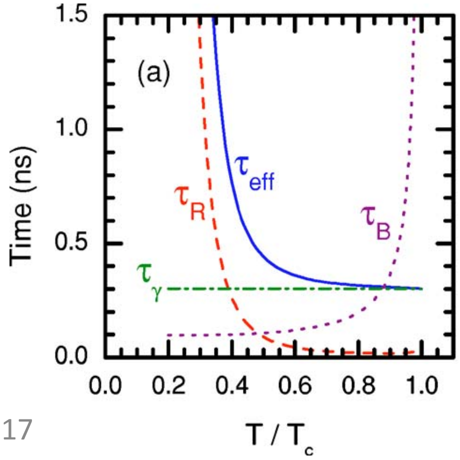
Recombination τ_R

Pair breaking τ_B

Escape τ_γ

Cooper pairs

Lobo et al.
Phys. Rev. B 72, 024510 (2005)



Statistical method

- Compute following χ^2 function to perform hypothesis tests and estimate signal significance versus time:

Unc. on bck normalization

$$\chi^2(y|H_{0,1}) = \sum_{k=1}^{N_{det}} \left[\sum_{j=1}^{N} \frac{(y_j^k - M_j^k(H_{0,1}))^2}{M_j^k(H_{0,1})} + \left(\frac{a^k}{\sigma_{a^k}}\right)^2 + \left(\frac{b^k}{\sigma_{b^k}}\right)^2 \right] + \left(\frac{\alpha}{\sigma_\alpha}\right)^2$$

Uncorrelated unc. on signal normalization (e.g. detector efficiencies)

Correlated unc. on signal normalization (e.g. reactor unc.)

- Model:
  - H_0: no signal $$M_j^k(H_0) = (a^k + \alpha)\, N_{0,i}^{CE\nu NS}(t) + (1 + b^k)\, B_{0,i}(t)$$
  - H_1: signal $$M_j^k(H_1) = (1 + a^k + \alpha)\, N_{0,i}^{CE\nu NS}(t) + (1 + b^k)\, B_{0,i}(t)$$

- χ^2 functions are minimized with respect to the $(2N_{det}+1)$ parameters (a_k, b_k, α) to compute $\Delta\chi^2$ between H_0 & H_1 hypothesis, and hence estimate the significance of a CEνNS signal