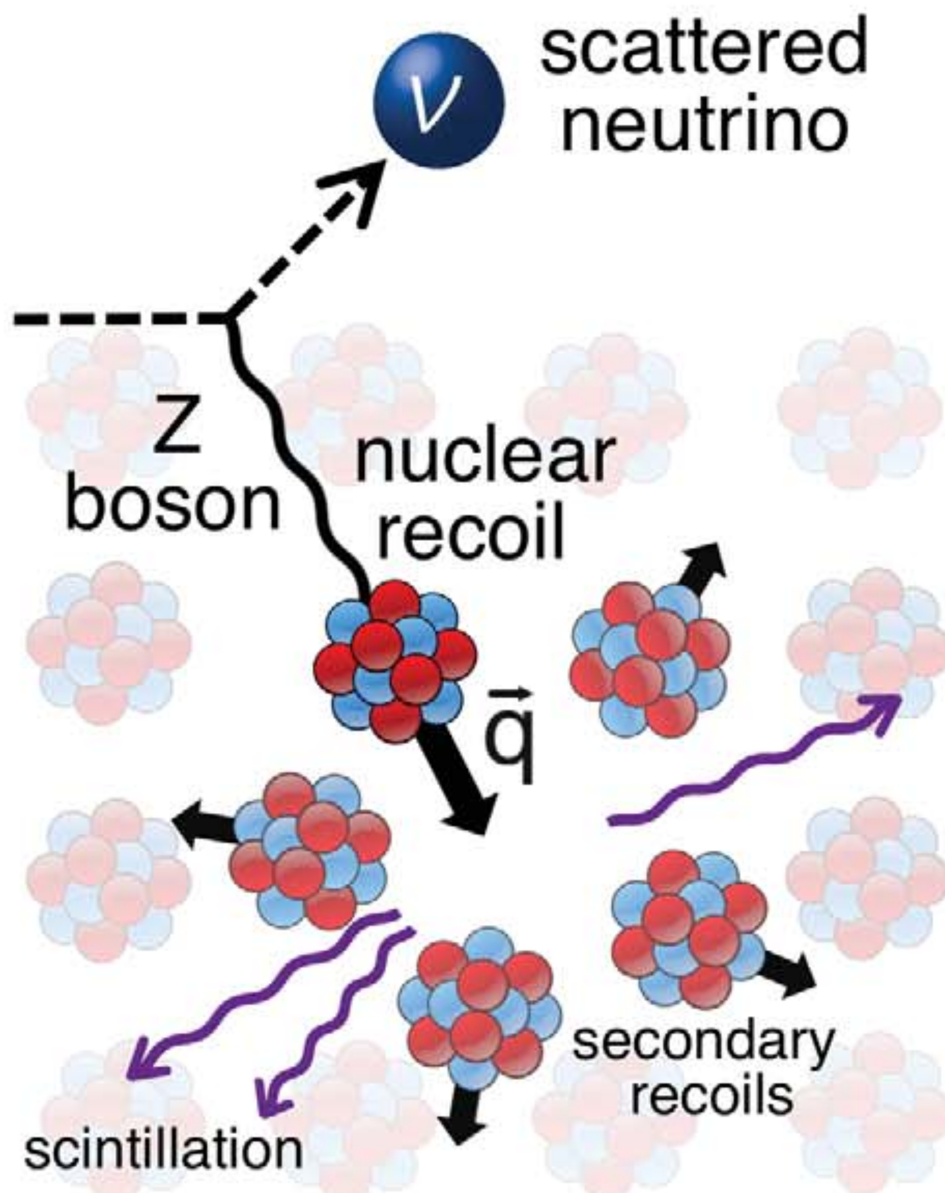
Neutrino-nucleus coherent scattering: new physics experiments applications.



Science 357 (2017) 1123

Marco Vignati,

INFN Roma

Pisa, 26/3/2019

Neutrino cross-sections

Inverse Beta Decay

$$\bar{\nu} + p \rightarrow n + e^+$$

$$\sigma^0_{\mathrm{IBD}} = \frac{G_F^2 \cos^2\theta_C}{\pi} \left(f^2 + 3g^2\right) E_e p_e$$

$$E_e = E_\nu - (M_N - M_p)$$

$$E_\nu > 1.806\ \mathrm{MeV}$$

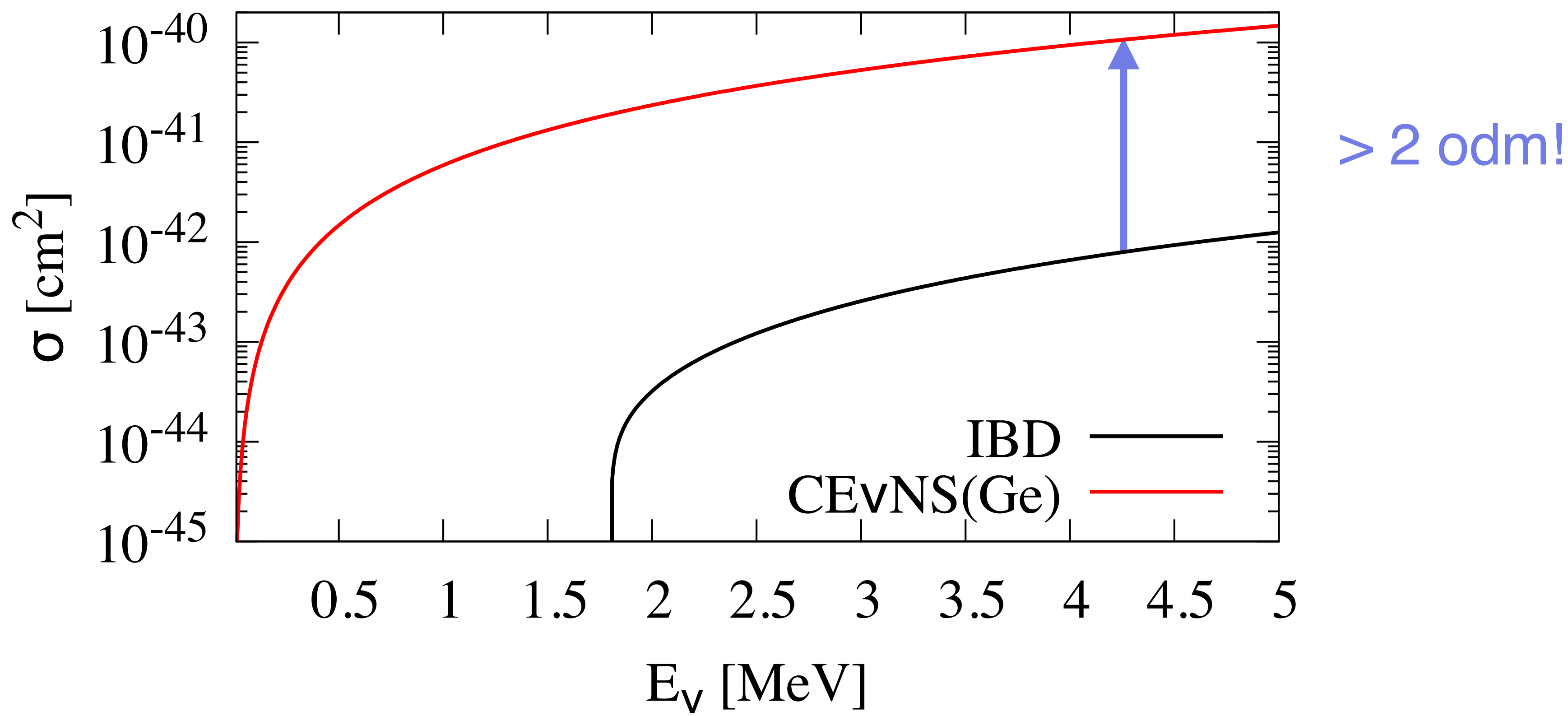
Coherent Elastic ν-Nucleus Scattering

$$\nu(\bar{\nu}) + A \rightarrow \nu(\bar{\nu}) + A$$

$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

$$Q_W = N - Z(1 - 4\sin^2\theta_W)$$

$$E_\nu < qR$$



Detectable energy

Inverse Beta Decay

$$\bar{\nu} + p \rightarrow n + e^{+}$$

Positron energy:

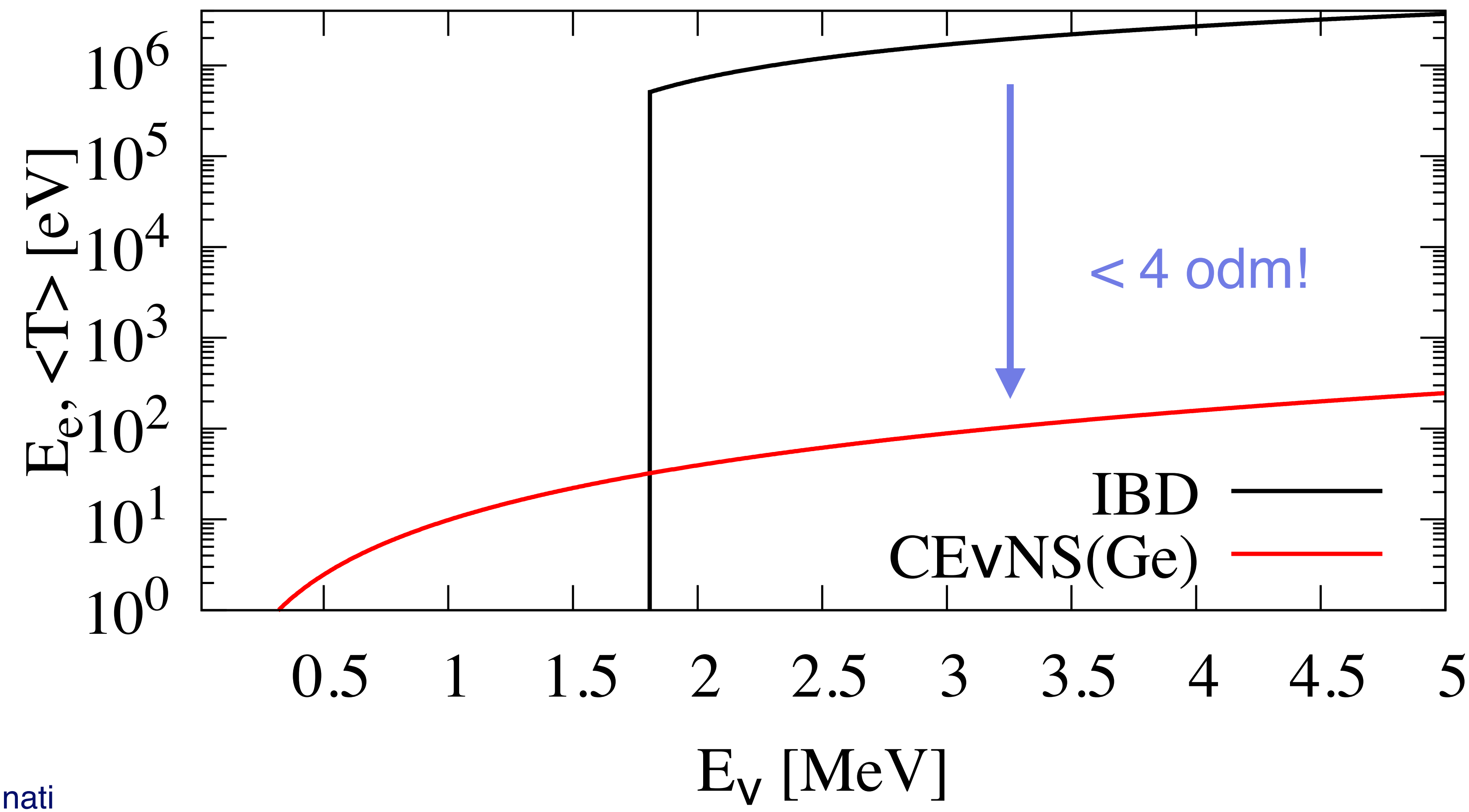
$$E_e = E_\nu - (M_N - M_p)$$

Coherent Elastic ν-Nucleus Scattering

$$\nu(\bar{\nu}) + A \rightarrow \nu(\bar{\nu}) + A$$

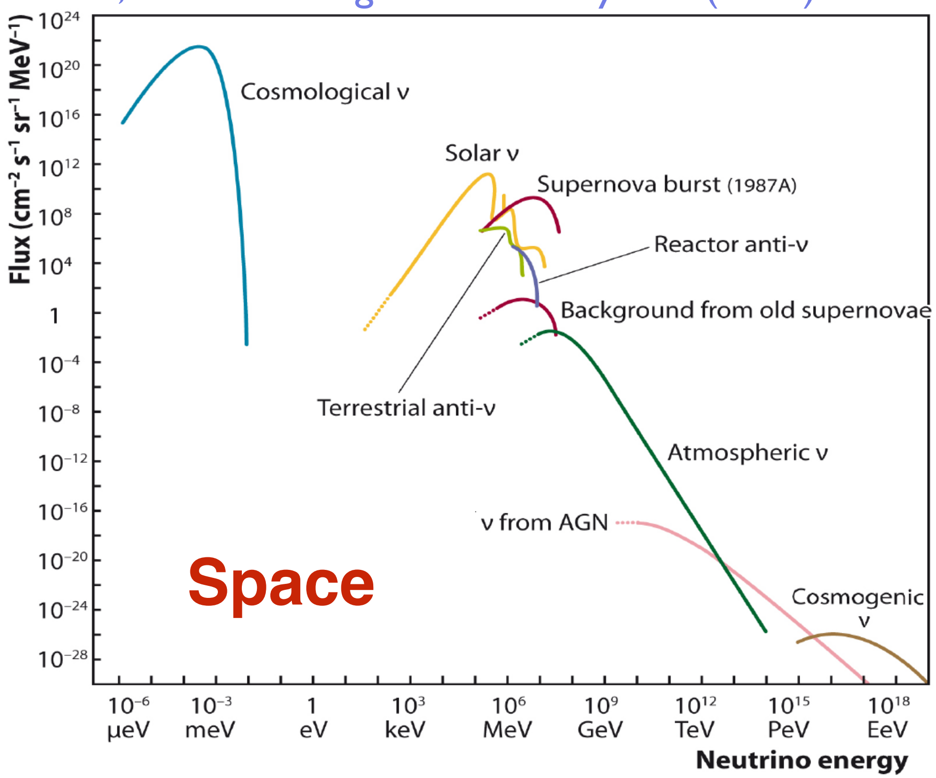
Average nuclear recoil energy:

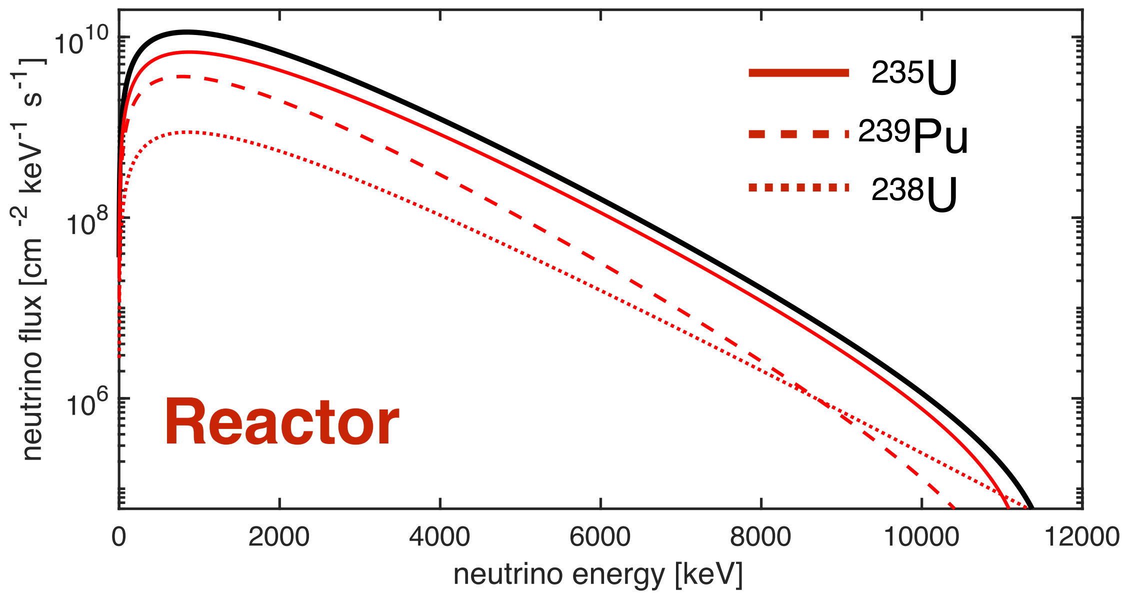
$$< T >= \frac{2}{3}\frac{E_\nu^2}{M_A}$$

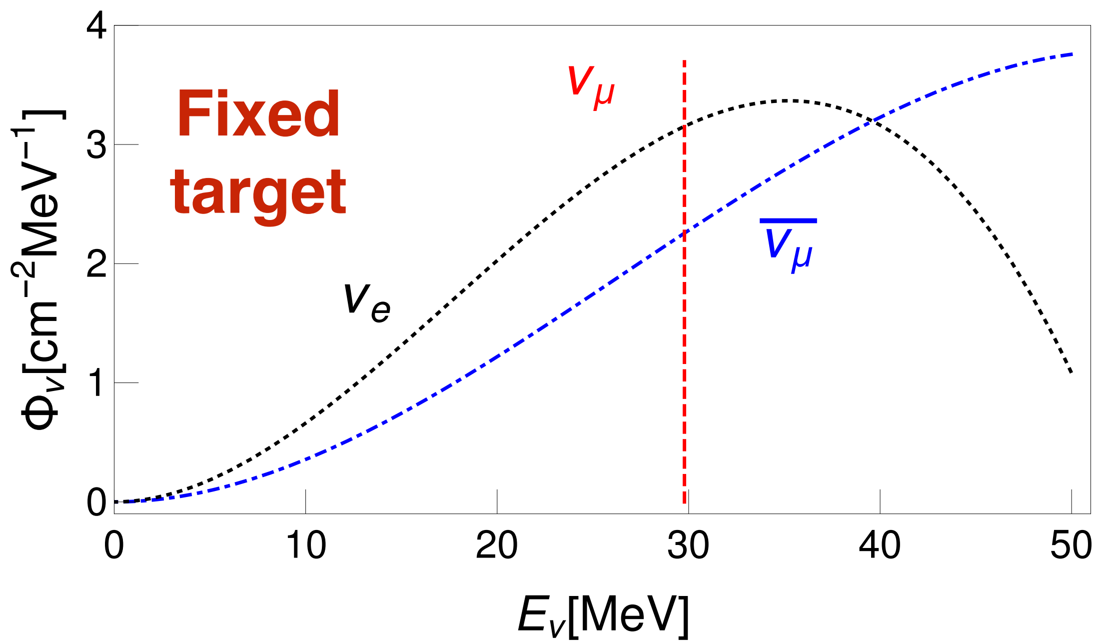


Neutrino sources

Katz, U.F. et al. Prog.Part.Nucl.Phys. 67 (2012) 651

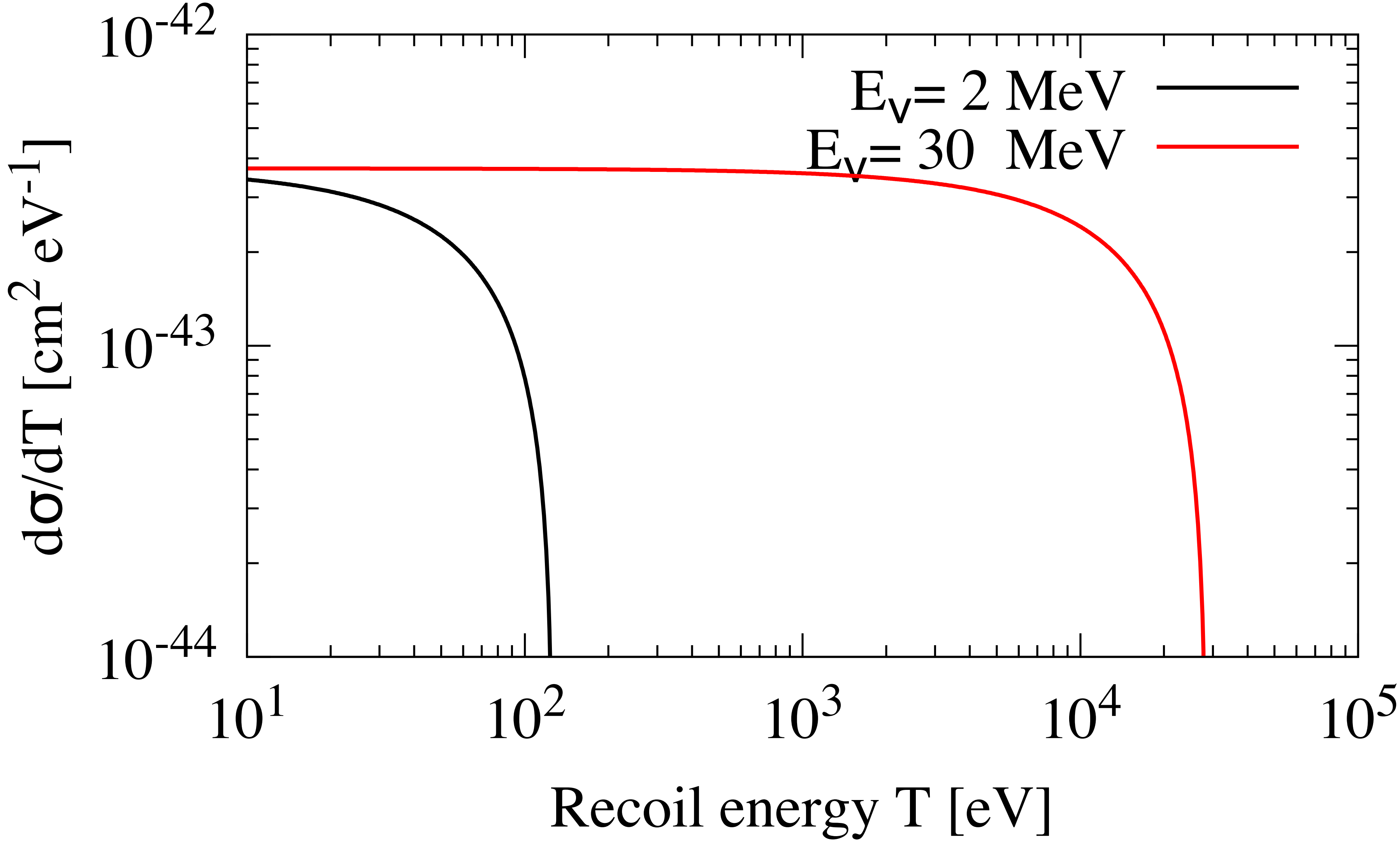






Energy spectrum

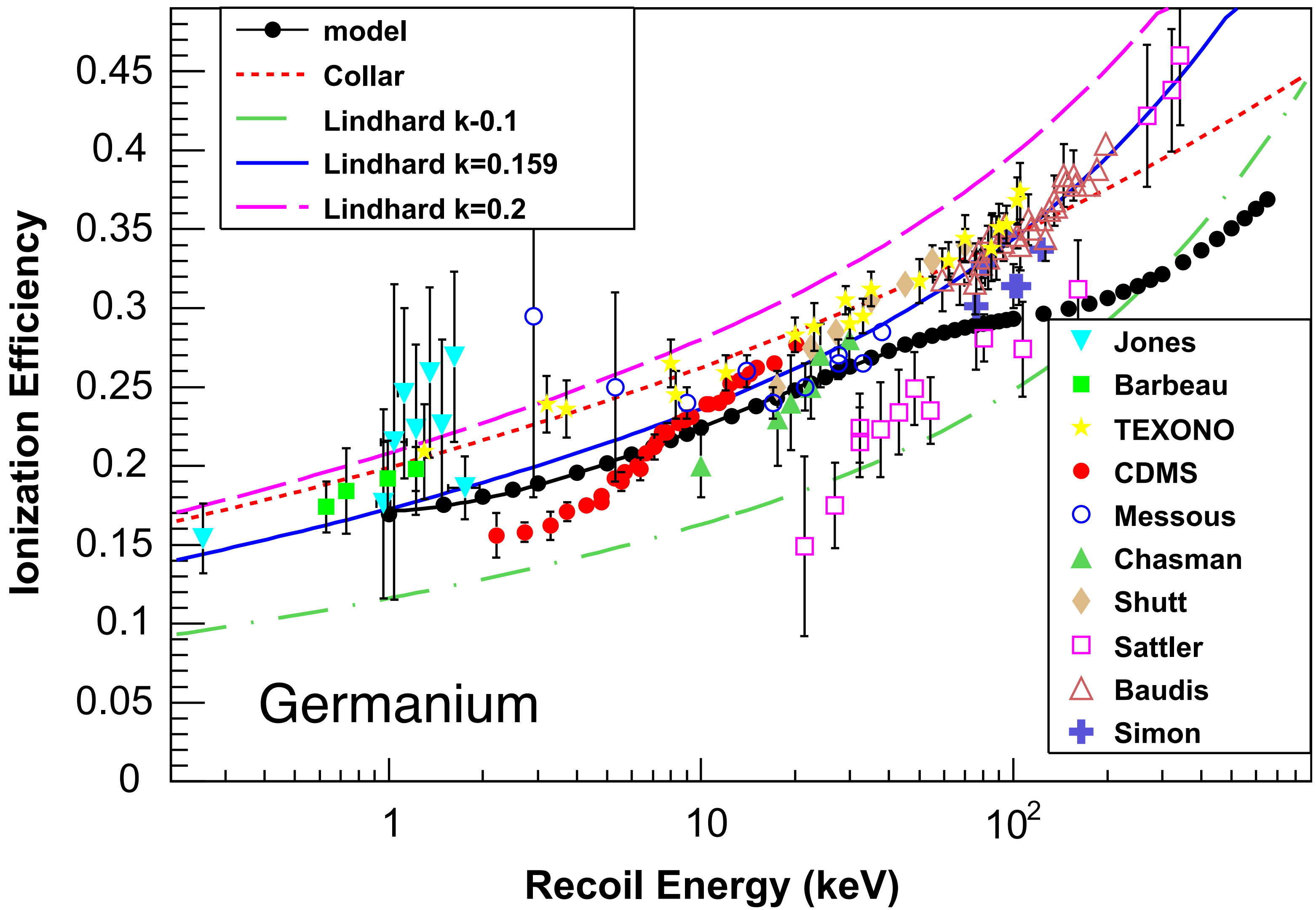
$$\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 \left(1 - \frac{M_A T}{2E_\nu^2}\right) \qquad T \leq \frac{2E_\nu^2}{M_A}$$



Another difficulty: quenching

Nuclear recoil energy is not fully converted to ionization or scintillation

D. Barker, D.-M. Mei / Astropart. Phys. 38 (2012) 1



43 years to be discovered

SICAL 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.

RESEARCH D. Akimov et al Science 357 (2017), 1123

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

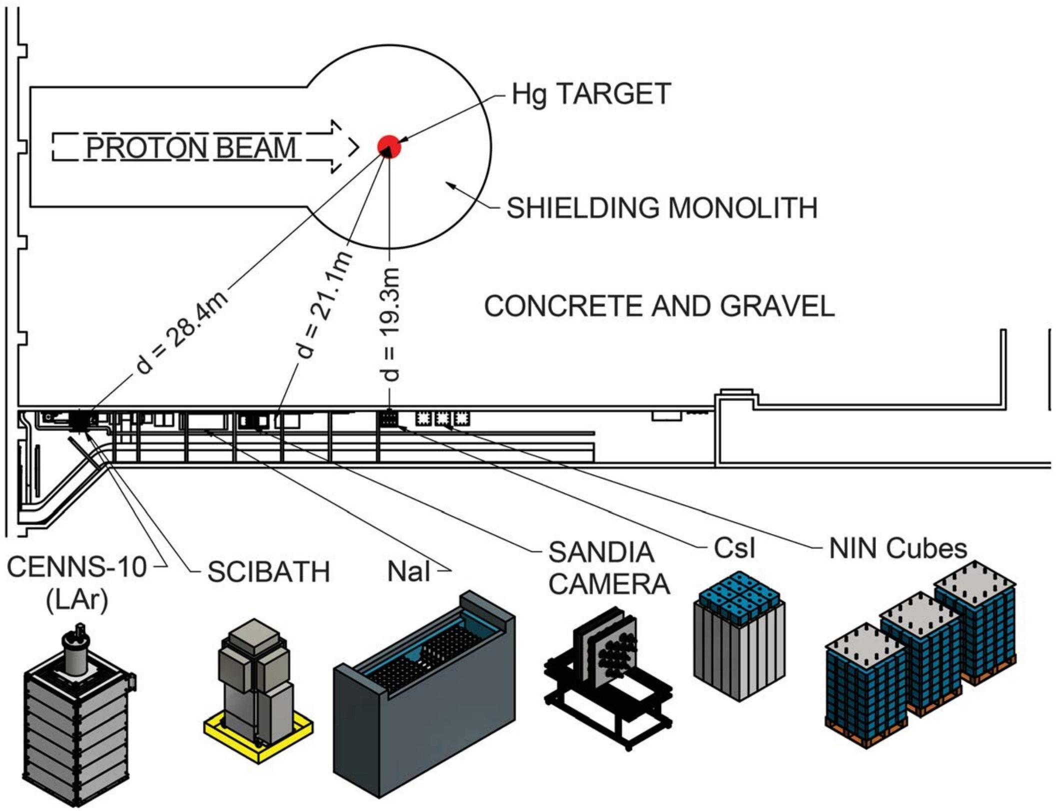
The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross section is by far the largest of all low-energy neutrino couplings. This mode of interaction offers new opportunities to study neutrino properties and leads to a miniaturization of detector size, with potential technological applications. We observed this process at a 6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the standard model for this process, were observed in high signal-to-background conditions. Improved constraints on nonstandard neutrino interactions with quarks are derived from this initial data set.

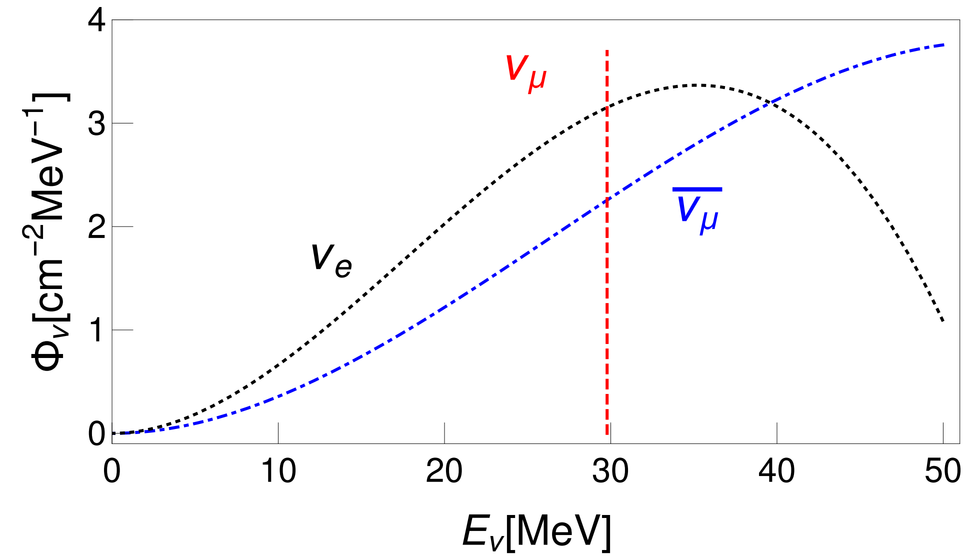
Coherent experiment

Spallation neutron source (SNS at Oakridge):

5×10^{20} POT/day, 0.08 ν_μ/p,

16-53 MeV, 60 Hz pulsed νs



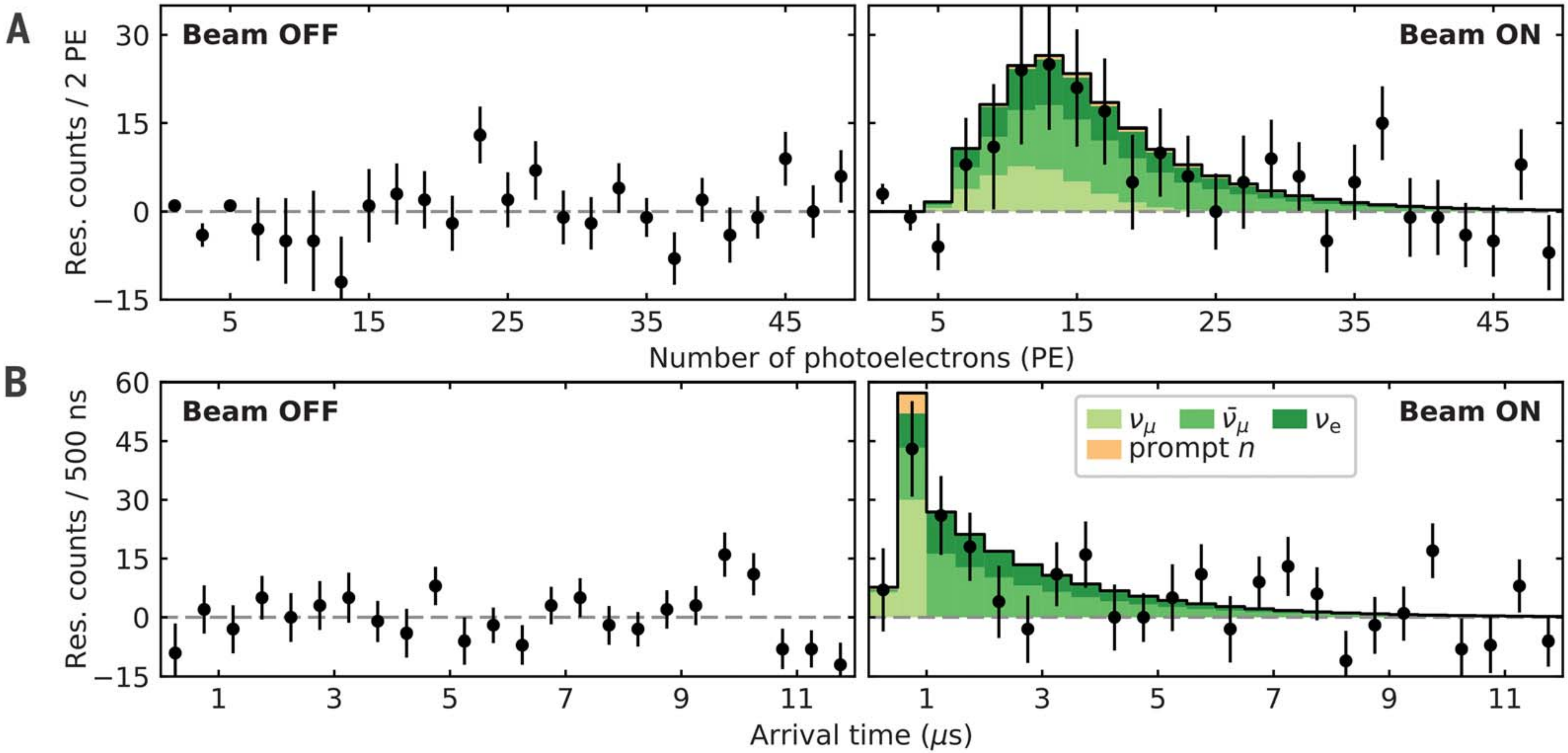


Instantaneous flux at detector during 1 μs pulse: 1.7×10^{11} $\nu_\mu/\mathrm{cm}^2/\mathrm{s}$

Signal observation

14.6 kg CsI[Na] scintillating crystal

153 days beam off
308 days beam on

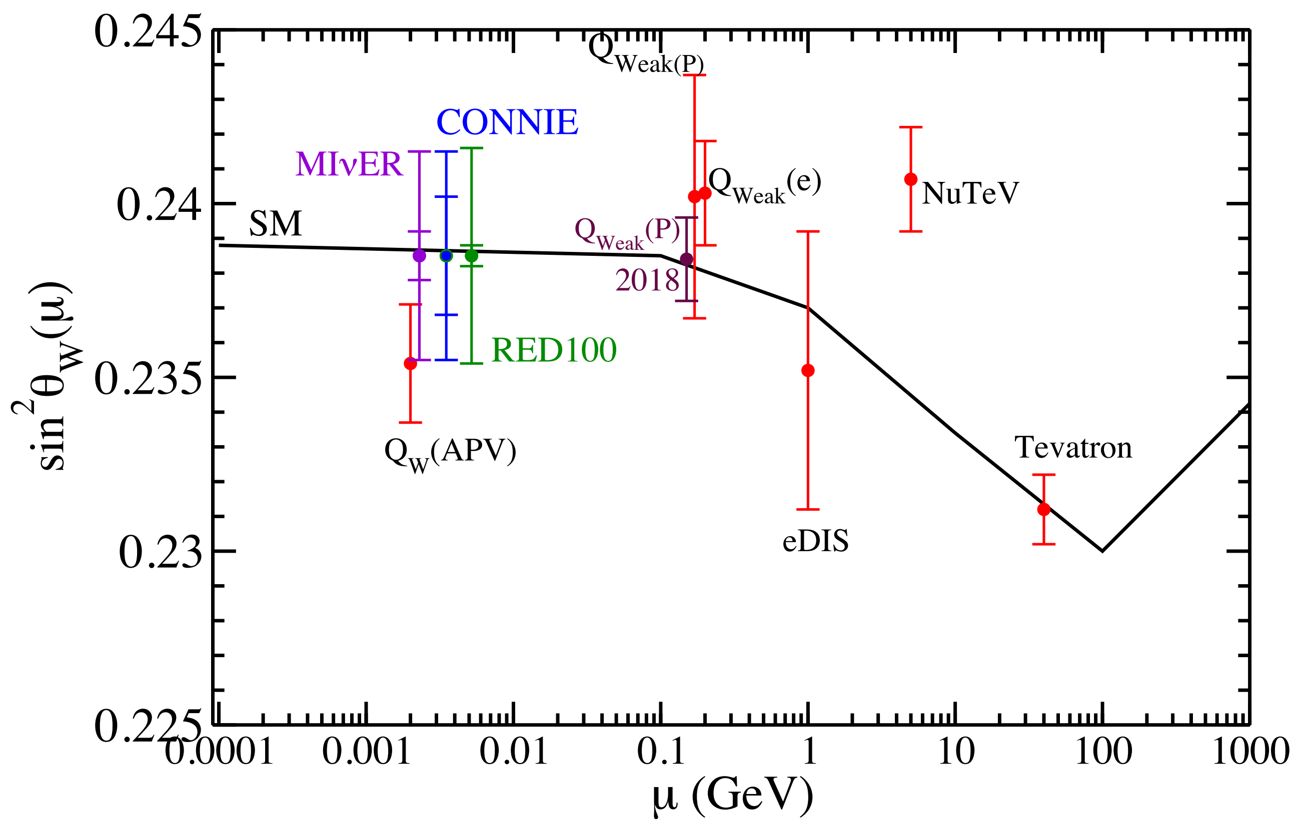


CEνNS opportunity

new physics with
compact detectors
sensitive to low energies

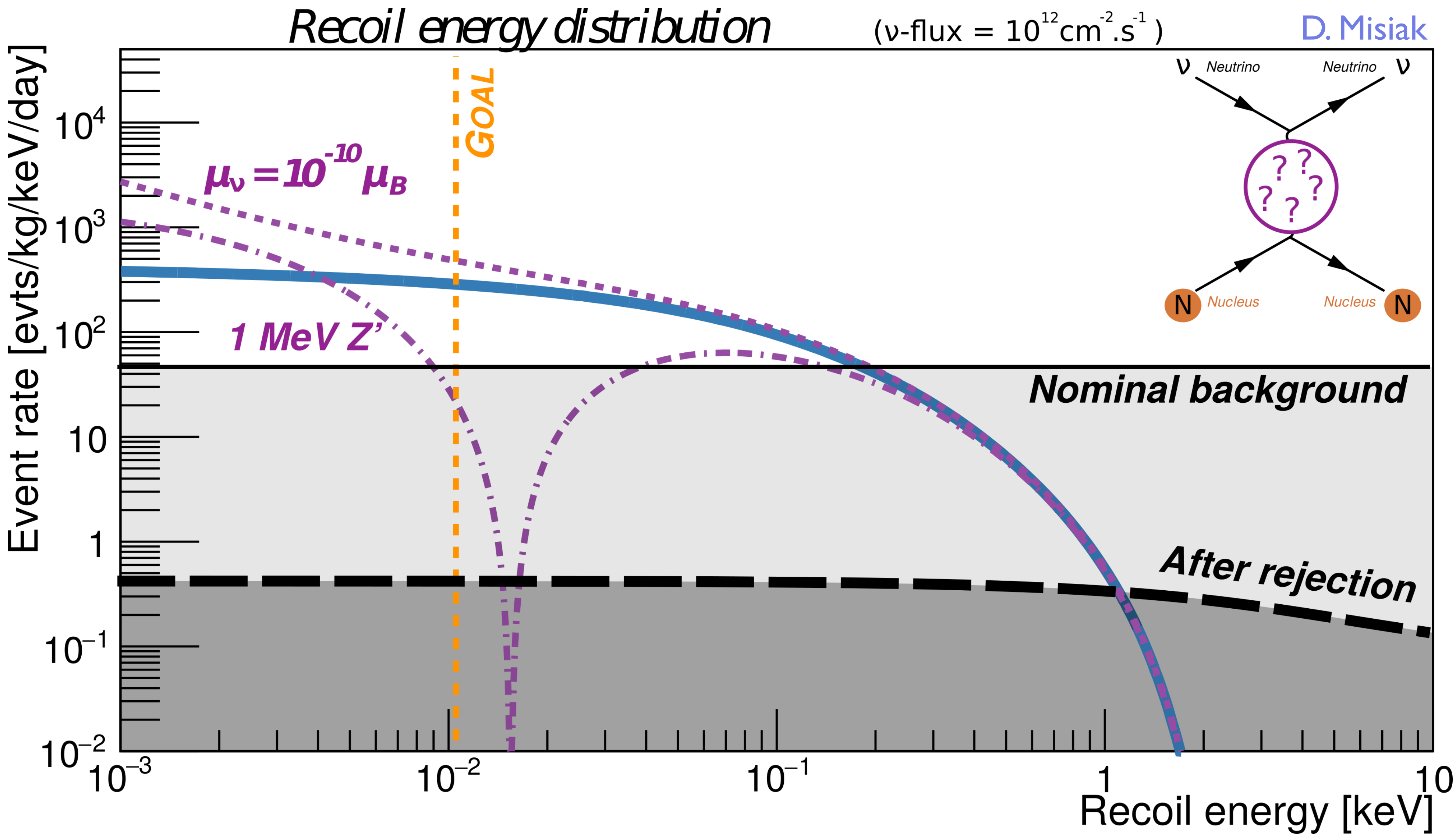
$\sin^2\vartheta_W$ at low Q

Miranda

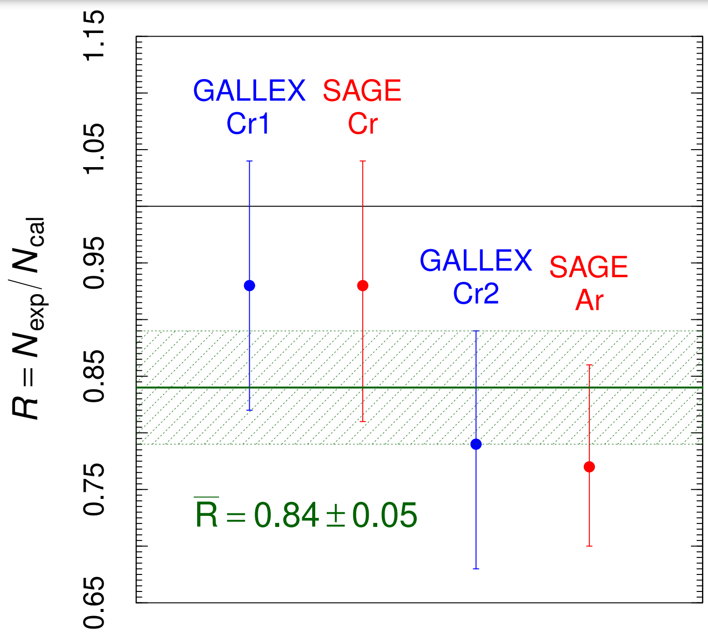


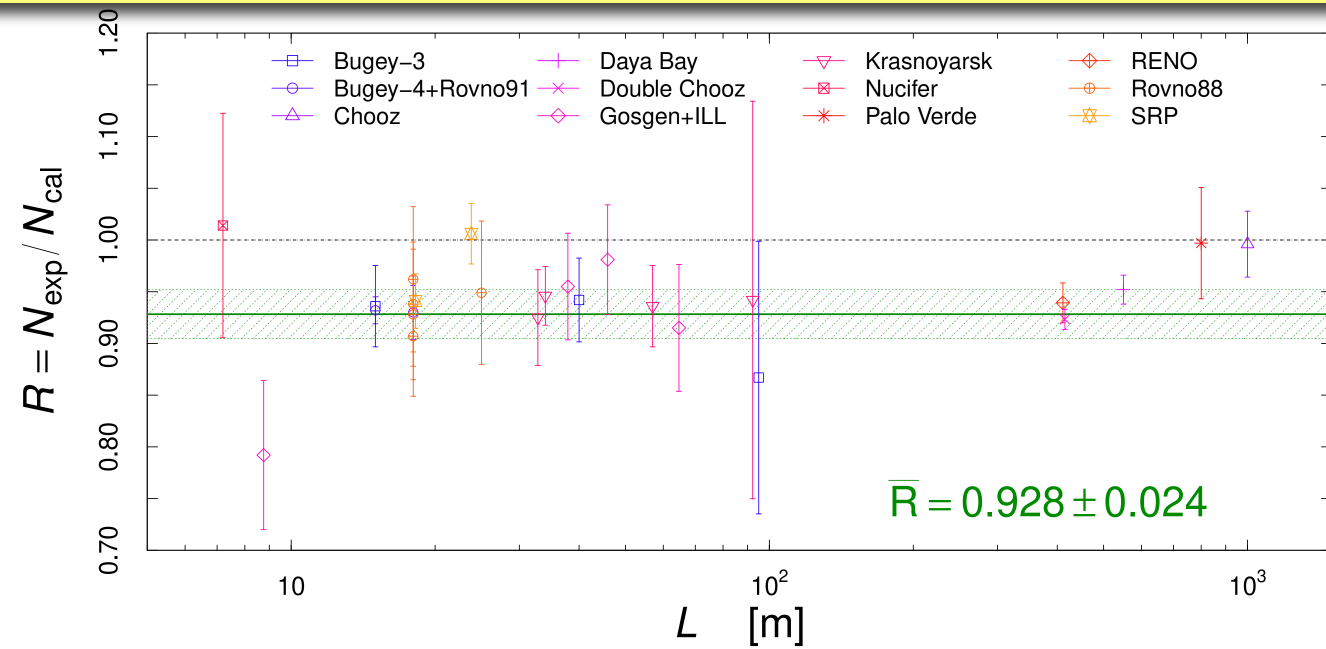
	T_{thres}	Baseline	Z/N	Det. Tec.	Fid. Mass
CONNIE	28 eV	30 m	1.0	CCD (Si)	1 kg
RED100	500 eV	19 m	0.70	Lq.Xe	100 kg
MINER	10 eV	1 m	0.81	^{72}Ge:^{28}Si (2:1)	30 kg
TEXONO	100 eV	28 m	0.79	HPGe	1 kg
CONUS	100 eV	10 m	0.79	HPGe	100 kg

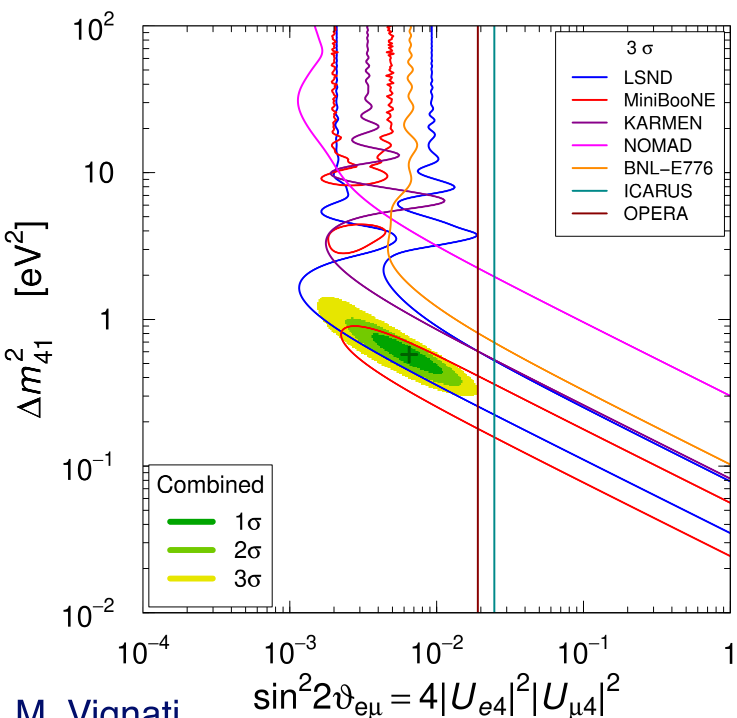
Non-standard interactions

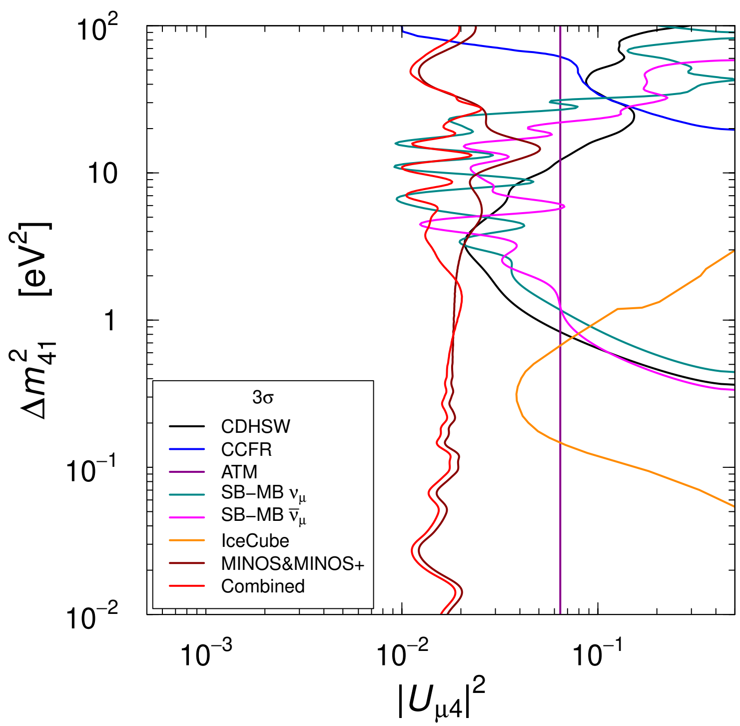


Sterile neutrinos







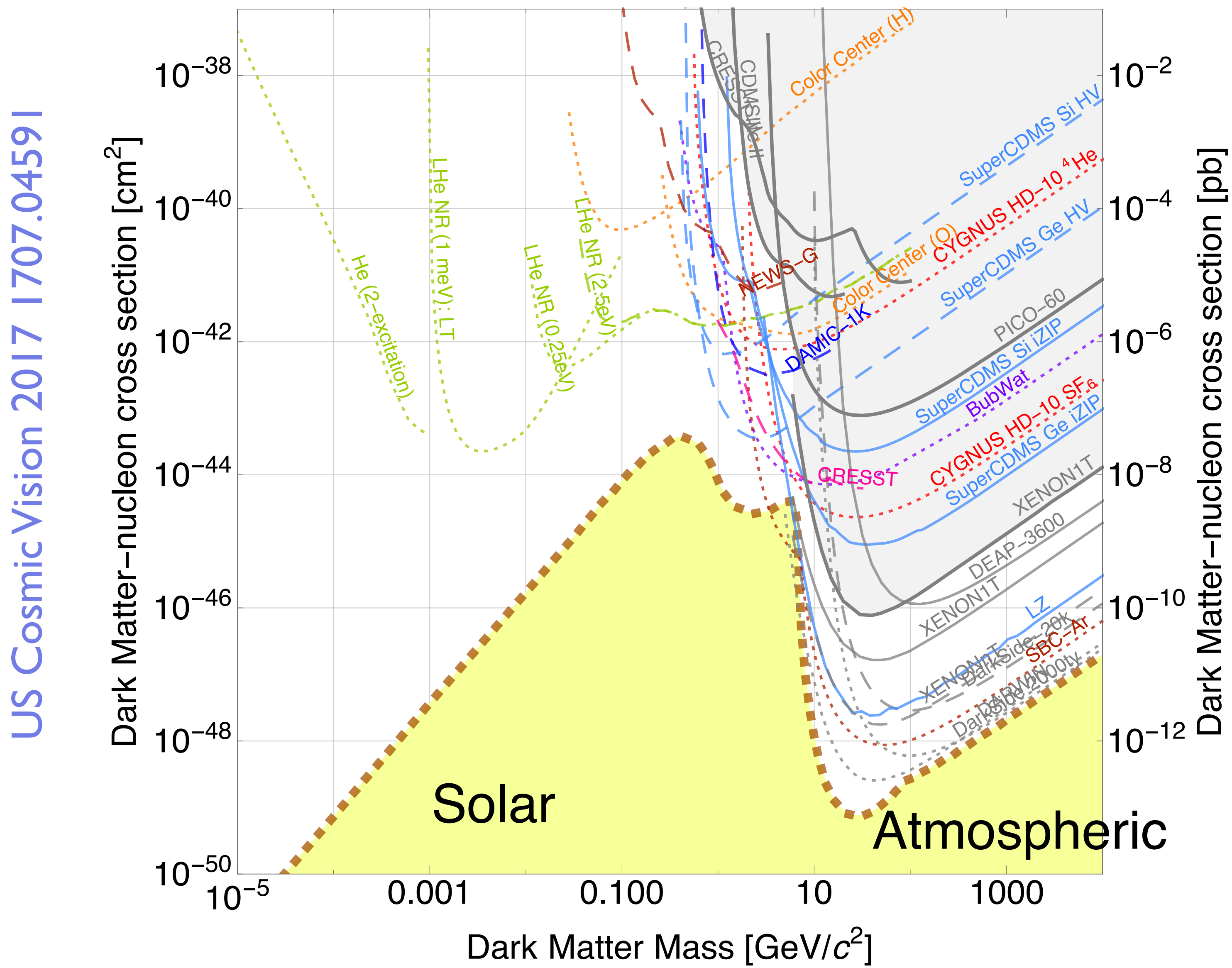


Puzzle
not yet solved

C. Giunti,
T. Lasserre
1901.08330

Implication for dark matter search

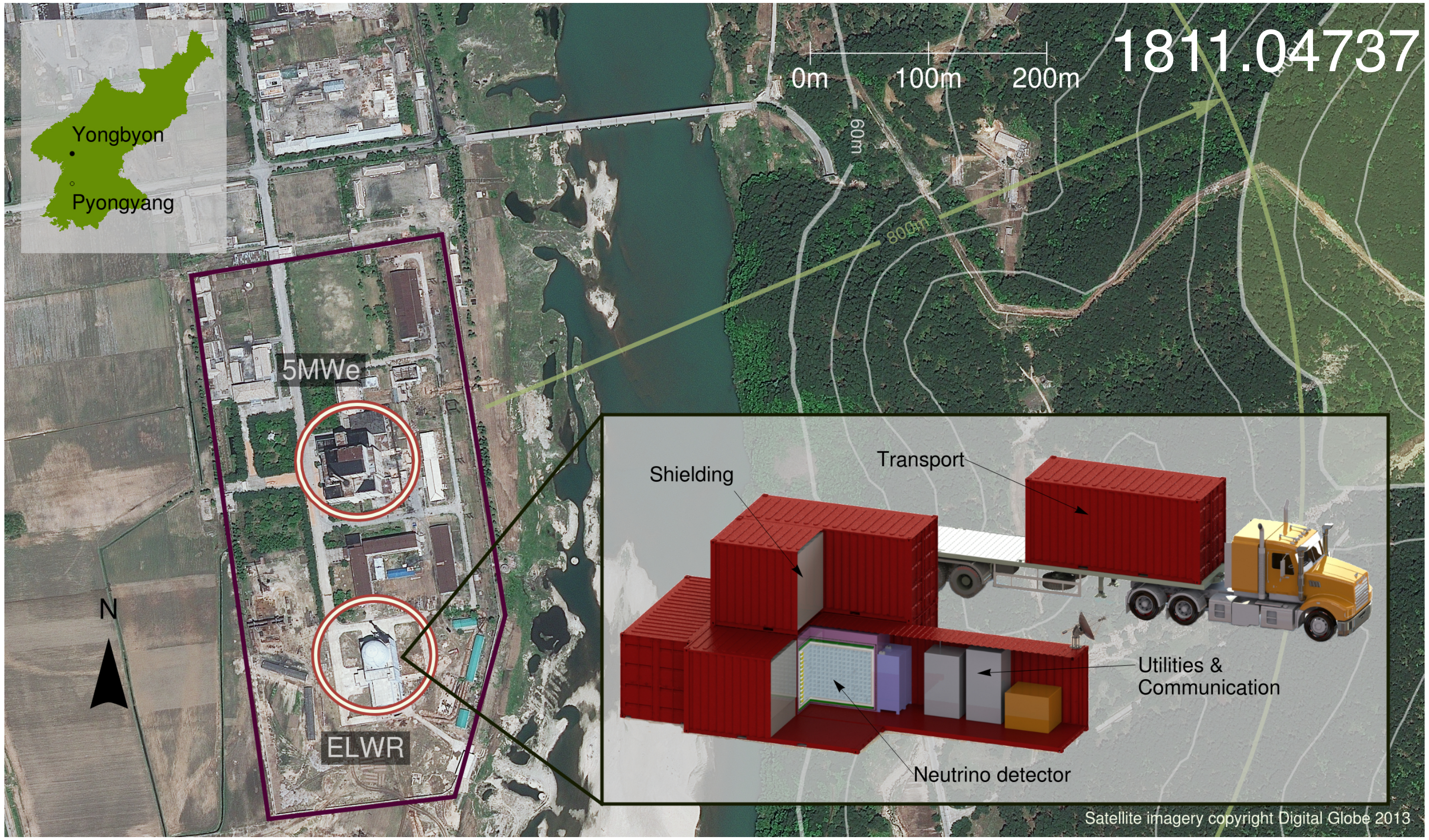
WIMPs are detected via nuclear recoils:
ultimate background from solar and atmospheric CEνNS



Non-proliferation

Neutrino-based tools for nuclear verification and diplomacy in North Korea

Rachel Carr,[1] Jonathon Coleman,[2] Mikhail Danilov,[3] Giorgio Gratta,[4] Karsten Heeger,[5] Patrick Huber,[6] YuenKeung Hor,[7] Takeo Kawasaki,[8] Soo-Bong Kim,[9] Yeongduk Kim,[10] John Learned,[11] Manfred Lindner,[12] Kyohei Nakajima,[13] James Nikkel,[5] Seon-Hee Seo,[10] Fumihiko Suekane,[14] Antonin Vacheret,[15] Wei Wang,[7] James Wilhelmi,[16] and Liang Zhan[17]



Can be sensitive to fuel diversion (e.g. Pu removal from core)

Experiments
(other than COHERENT)

Content from the Magnificent CEνNS workshop
November 2-3 2018, Chicago
My comments in Red

Coherent scattering at reactors

Strigari

The CONNIE experiment

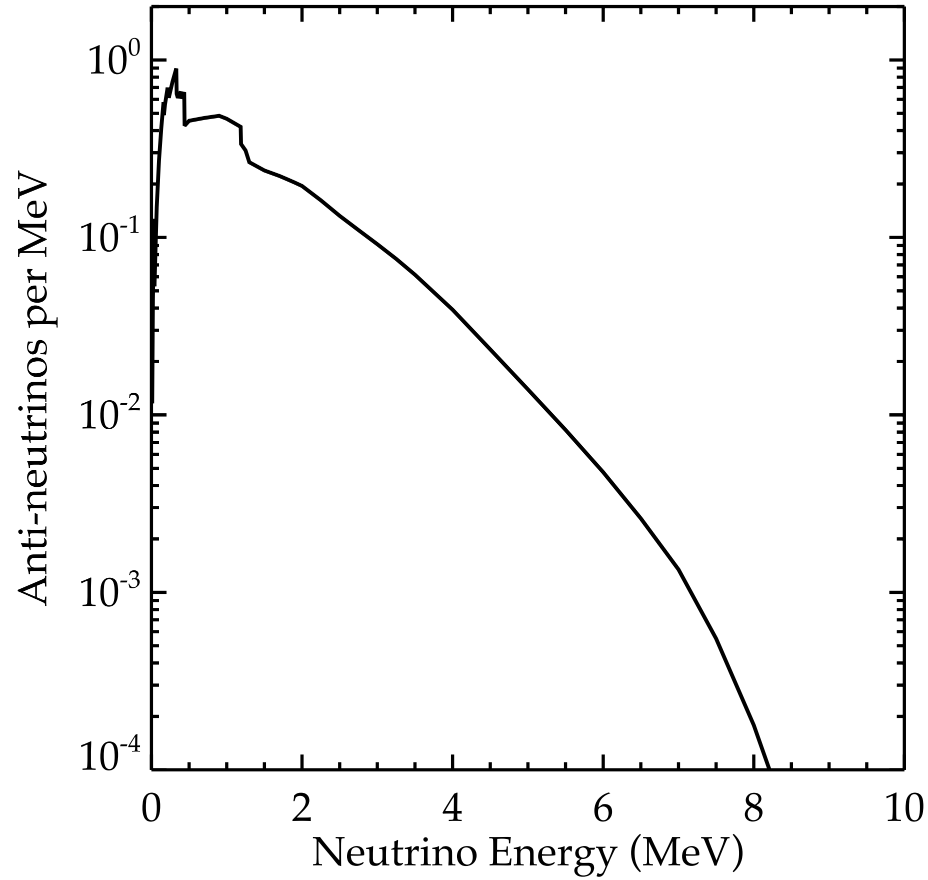
A. Aguilar-Arevalo[1], X. Bertou[2], C. Bonifazi[3], M. Butner[4], G. Cancelo[4], A. Castaneda Vazquez[1], B. Cervantes Vergara[1], C.R. Chavez[5], H. Da Motta[6], J.C. D'Olivo[1], J. Dos Anjos[6], J. Estrada[4], G. Fernandez Moroni[7,8], R. Ford[4], A. Foguel[3,6], K.P. Hernandez Torres[1], F. Izraelevitch[4], A. Kavner[9], B. Kilminster[10], K. Kuk[4], H.P. Lima Jr.[6], M. Makler[6], J. Molina[5], G. Moreno-Granados[1], J.M. Moro[11], E.E. Paolini[7,12], M. Sofo Haro[2], J. Tiffenberg[4], F. Trillaud[1], and S. Wagner[6,13]

Connie (CCD)

Coherent Neutrino Scattering with Low Temperature Bolometers at Chooz Reactor Complex

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]

Ricochet (NTD)



Research program towards observation of neutrino-nucleus coherent scattering

H T Wong[1,*], H B Li[1], S K Lin[1], S T Lin[1], D He[2], J Li[2], X Li[2], Q Yue[2], Z Y Zhou[3] and S K Kim[4]

[1] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan.
[2] Department of Engineering Physics, Tsing Hua University, Beijing 100084, China.
[3] Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China.
[4] Department of Physics, Seoul National University, Seoul 151-742, Korea.

Background Studies for the MINER Coherent Neutrino Scattering Reactor Experiment

G. Agnolet[a], W. Baker[a], D. Barker[b], R. Beck[a], T.J. Carroll[c], J. Cesar[c], P. Cushman[b], J.B. Dent[d], S. De Rijck[c], B. Dutta[a], W. Flanagan[c], M. Fritts[b], Y. Gao[a,e], H.R. Harris[a], C.C. Hays[a], V. Iyer[f], A. Jastram[a], F. Kadribasic[a], A. Kennedy[b], A. Kubik[a], I. Ogawa[g], K. Lang[c], R. Mahapatra[a], V. Mandic[b], R.D. Martin[h], N. Mast[b], S. McDeavitt[i], N. Mirabolfathi[a], B. Mohanty[f], K. Nakajima[g], J. Newhouse[i], J.L. Newstead[j], D. Phan[c], M. Proga[c], A. Roberts[k], G. Rogachev[l], R. Salazar[c], J. Sander[k], K. Senapati[f], M. Shimada[g], L. Strigari[a], Y. Tamagawa[g], W. Teizer[a], J.I.C. Vermaak[i], A.N. Villano[b], J. Walker[m], B. Webb[a], Z. Wetzel[a], S.A. Yadavalli[c]

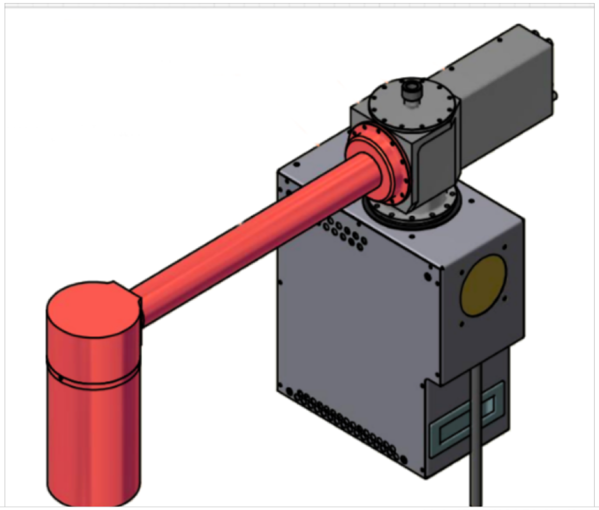
Miner (iZIP)

CONUS 2.4 sigma measurement— Neutrino 2018

CONUS (HPGe)

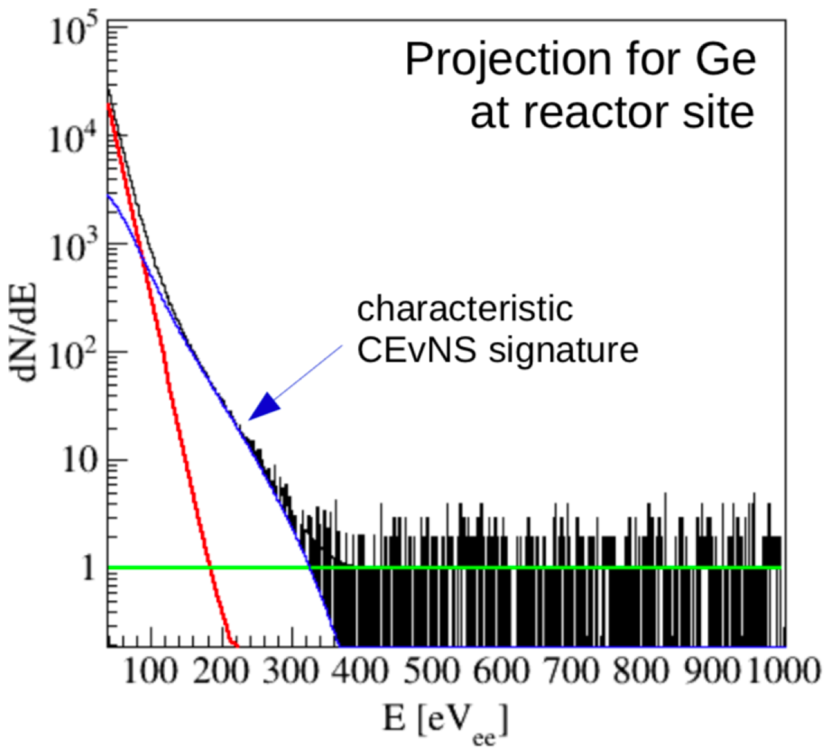
CONUS

- p-type point contact HPGe
- 4x 1kg – **active mass 3.85kg**
- Spec. for pulser res. (FWHM) ≤ 85eV
  → noise threshold ≤ 300eV
- electrical PT-cryocoolers
- ultra low background components
- close collaboration with Canberra



Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

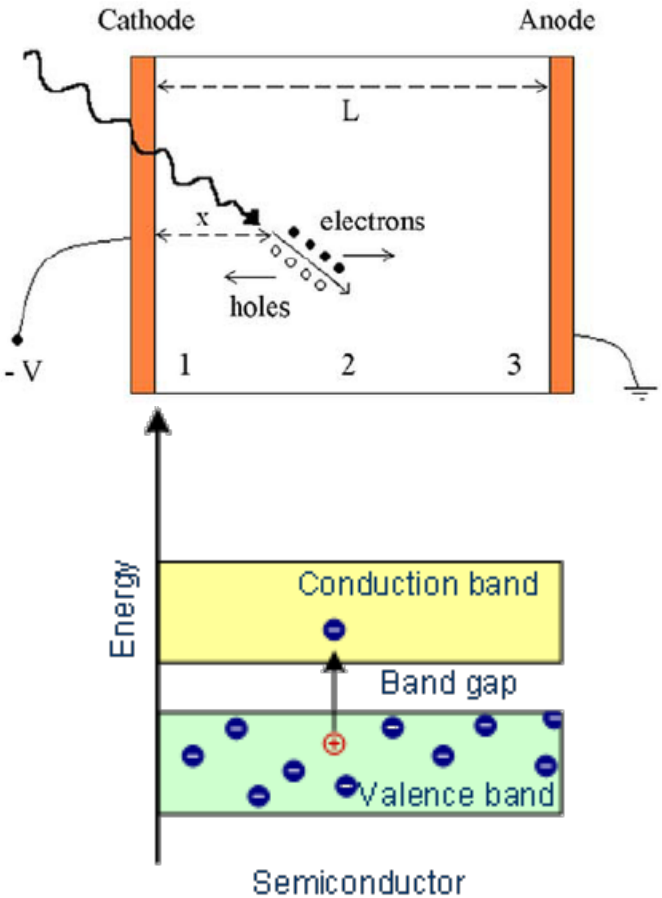
Taking data at the Brokdorf 3.9 GWth reactor



Ionization detector: quenching factor can be an issue

Cryogenics: when sensitivity matters

Semiconductor detectors

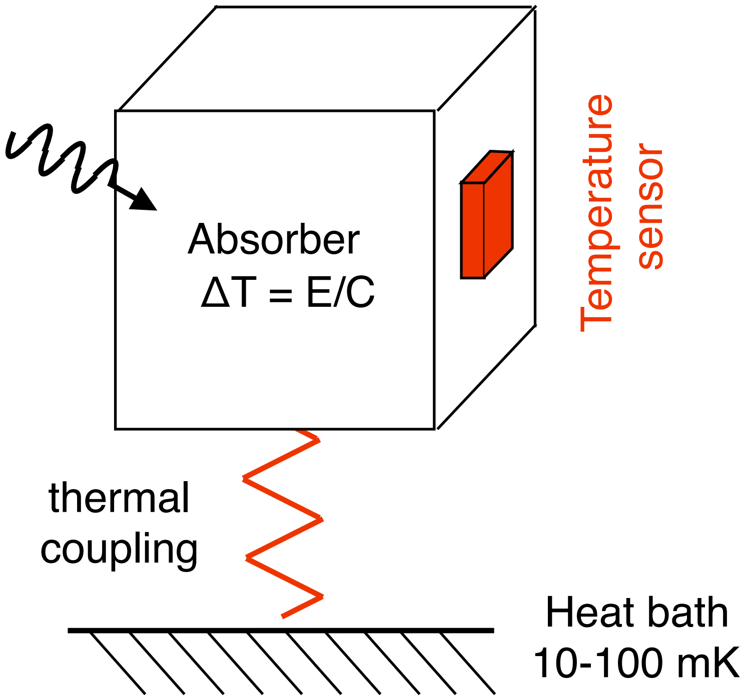


$\epsilon \sim 1\,\mathrm{eV}$

$w > \varepsilon$, quenching

$\Delta E \propto \sqrt{\epsilon E}$

Cryogenic detectors



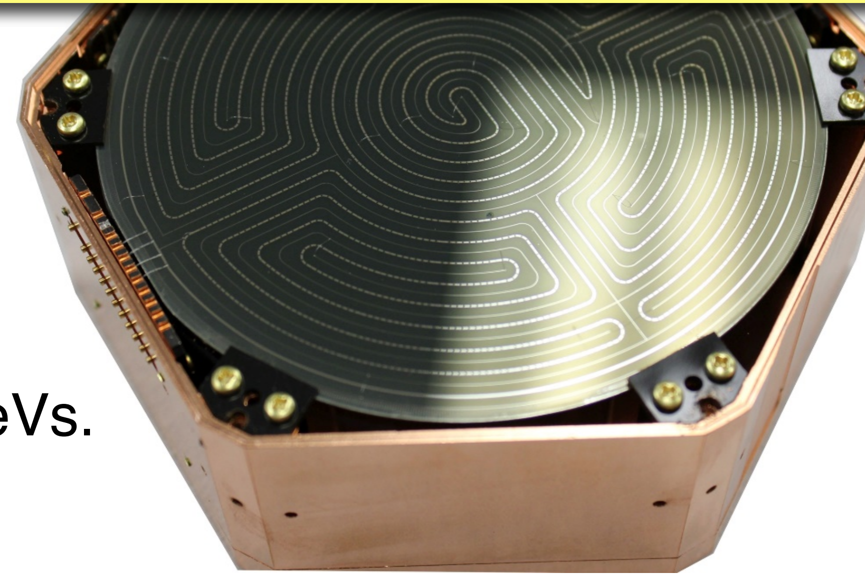
Quanta are phonons

$\epsilon = k_B T(100\mathrm{mK}) \sim 10\,\mu\mathrm{eV}$

no quenching

Miner (CDMS)

Mohapatra

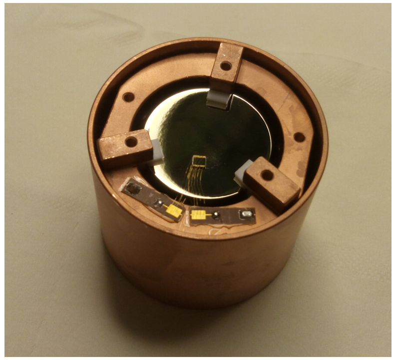


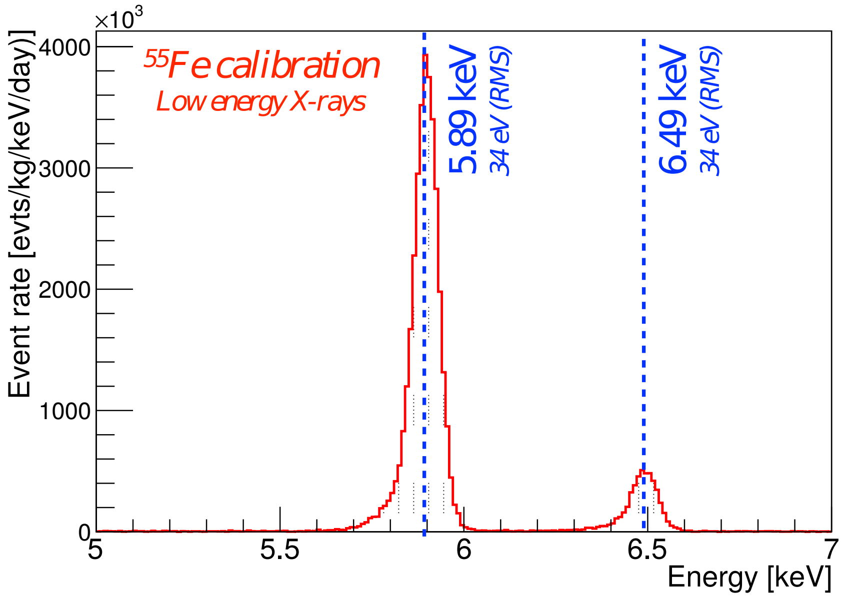
- IZIP TES with HV Luke amplification
- HV Amplification implies that the primary signal is due to ionisation
- Not clear the Quenching Factor at 10s of eVs. it might be zero.

Parameters	Phase-1 (current phase	Phase-2 (Larger phase with
Max payload	4 kg	30 kg
Baseline	~7 eVee	~5 eVee
Lindhard	~1/6-1/5 (Ge) and ~1/20?	~1/6-1/5 for Ge ~1/20? (Si)
NR threshold	~100 eVNR* in Ge/Si HV	100 eVnr* in HV in Ge/Si HV
Background	~1000 DRU	~100 DRU
Neutrino Flux	10^{12}/cm^2.sec	10^{12}/cm^2.sec
Distance from	~4 m – 10 m	~2m – 10 m

Edelweiss technology: NTD thermistor on HPGE at 10 mK

Early Demonstrator: RED20, heat channel only

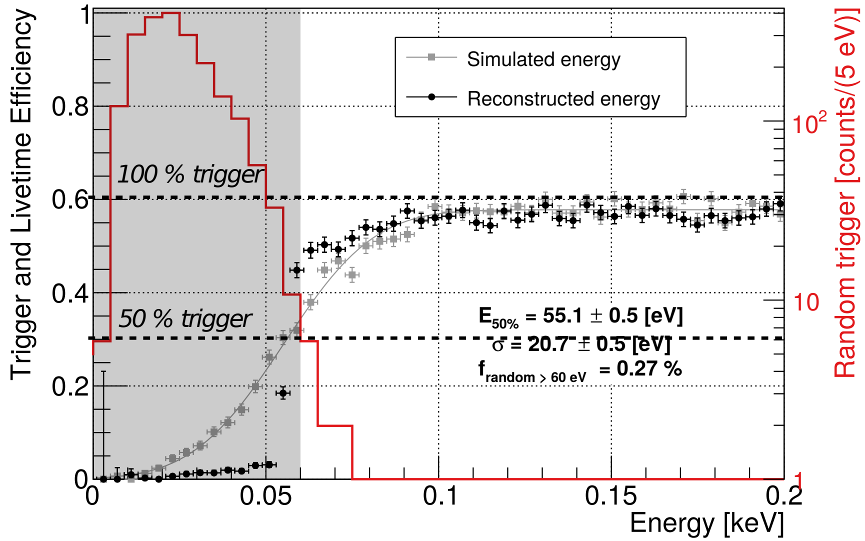




Groundbreaking results:

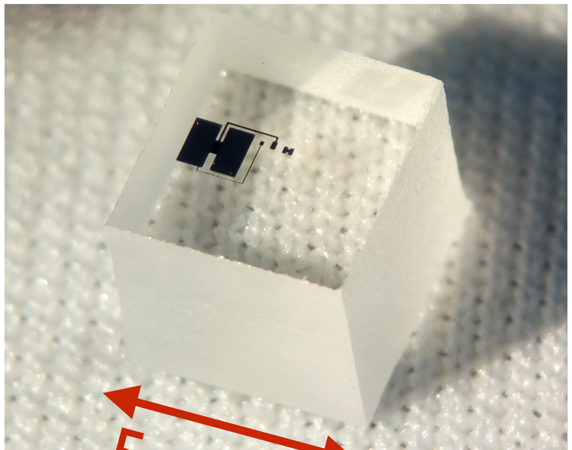
- 18 eV energy resolution (RMS)
- 55 eV energy threshold
- with a 32g Ge Detector

Phonon detector: no quenching

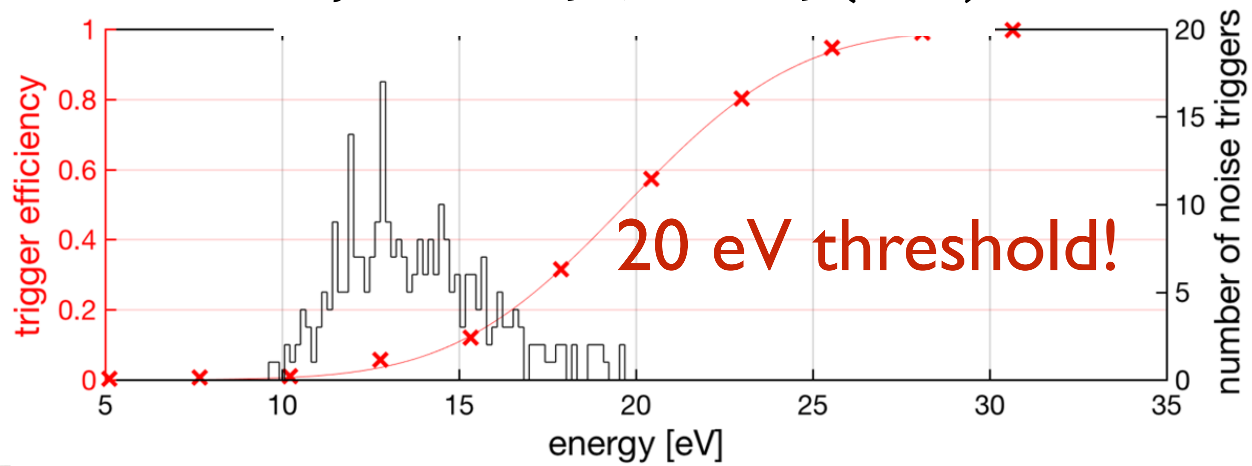


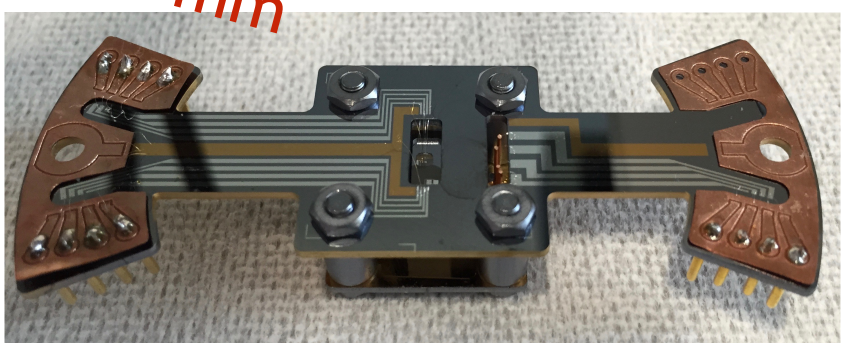
ν-cleus

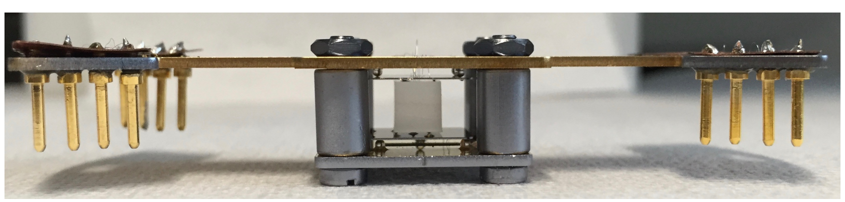
CRESST technology: TES on $CaWO_4$ or Al_2O_3 at 10 mK



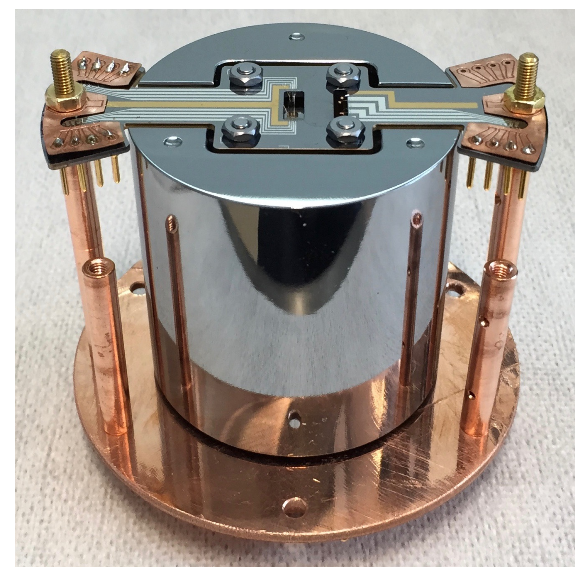
Phys. Rev. D **96**, 022009 (2017)







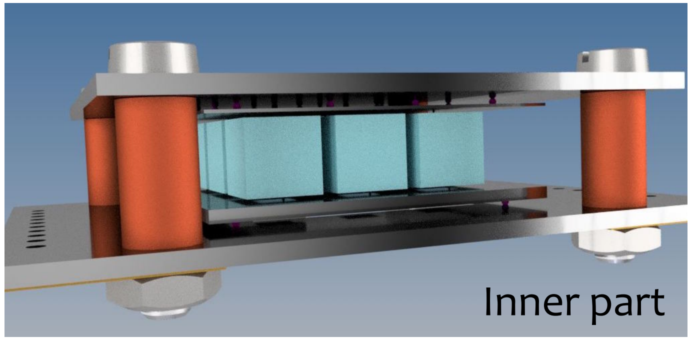
- Sapphire and $CaWO_4$ crystals
- Flexible Si wafers as inner veto detectors

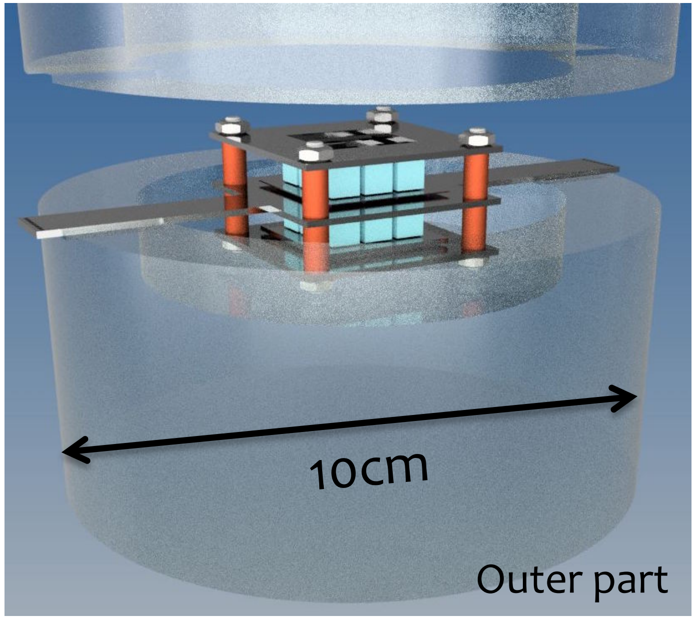


Si outer veto prototype

ν-cleus: 2-phase approach

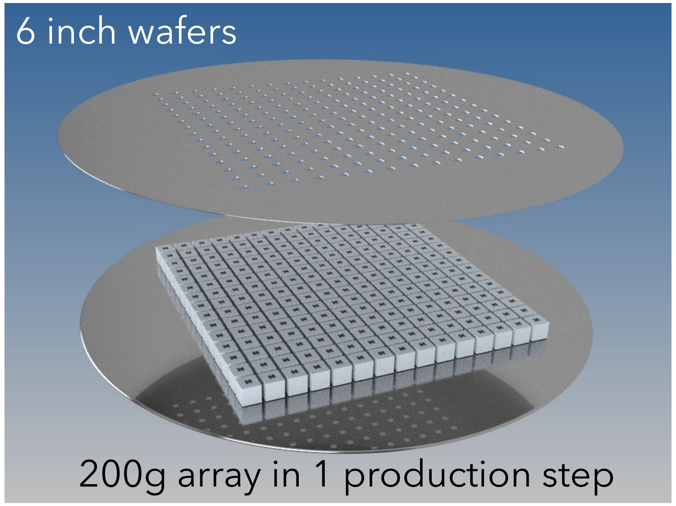
NU-CLEUS 10g





NU-CLEUS 1kg

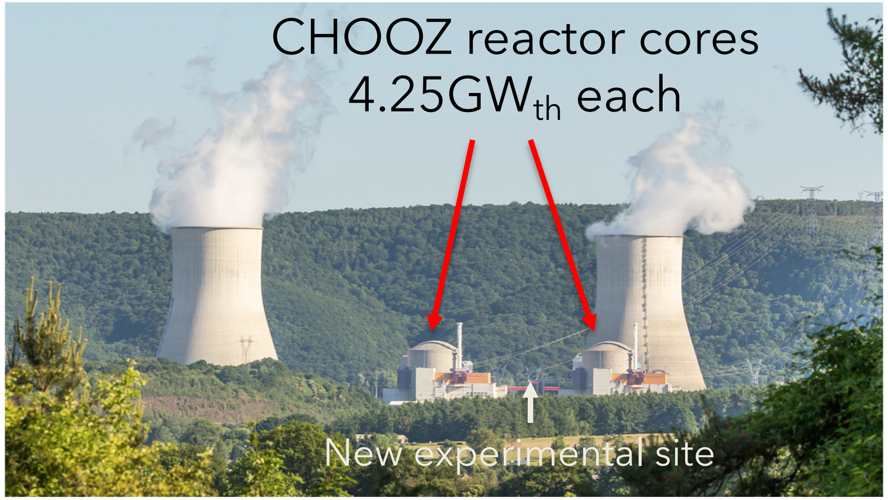
A scalable cryogenic detector



- Exploit semiconductor technology
- SQUID multiplexing

Breakthrough for the NU-CLEUS physics program!
Impact for other cryogenic experiments!

The CHOOZ Power Plant in France



Th. Lasserre (CEA)
M. Vivier (CEA)
V. Wagner (CEA)
G. Munch (EDF)
J. Molina (EDF)
R. Strauss (MPP)
A. Langenkämper (TUM)

Established relation to reactor company (EDF)

Since March 2018:

- Full access to inner zone of power plant
- Support from engineers on-site for infrastructure and safety
- Permission for background measurements on-site
- Convention (CEA-EDF) for NU-CLEUS in preparation

See Victoria's talk

ν-cleus collaboration

TECHNISCHE UNIVERSITÄT MÜNCHEN

erc

SFB 1258 Neutrinos Dark Matter Messengers

cea

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Tobias Ortmann
Elizabeth Mondragon-Cortes
Lothar Oberauer
Franz v. Feilitzsch

PD
(PhD)
PhD with CEA (50/50)

Thierry Lasserre
Matthieu Vivier
Victoria Wagner
Florence Adellier-Desage
Loris Scola

Claudia Nones

+PhDs...

NU-CLEUS

Kick-Off Meeting
Munich Nov7-9 2018
~30 people
Steering committee!

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Federica Petricca
Johannes Rothe
Franz Pröbst
Dieter Hauff

Michele Mancuso
Lucia Canonica
Antonio Bento
Leo Stodolsky
Gode Angloher

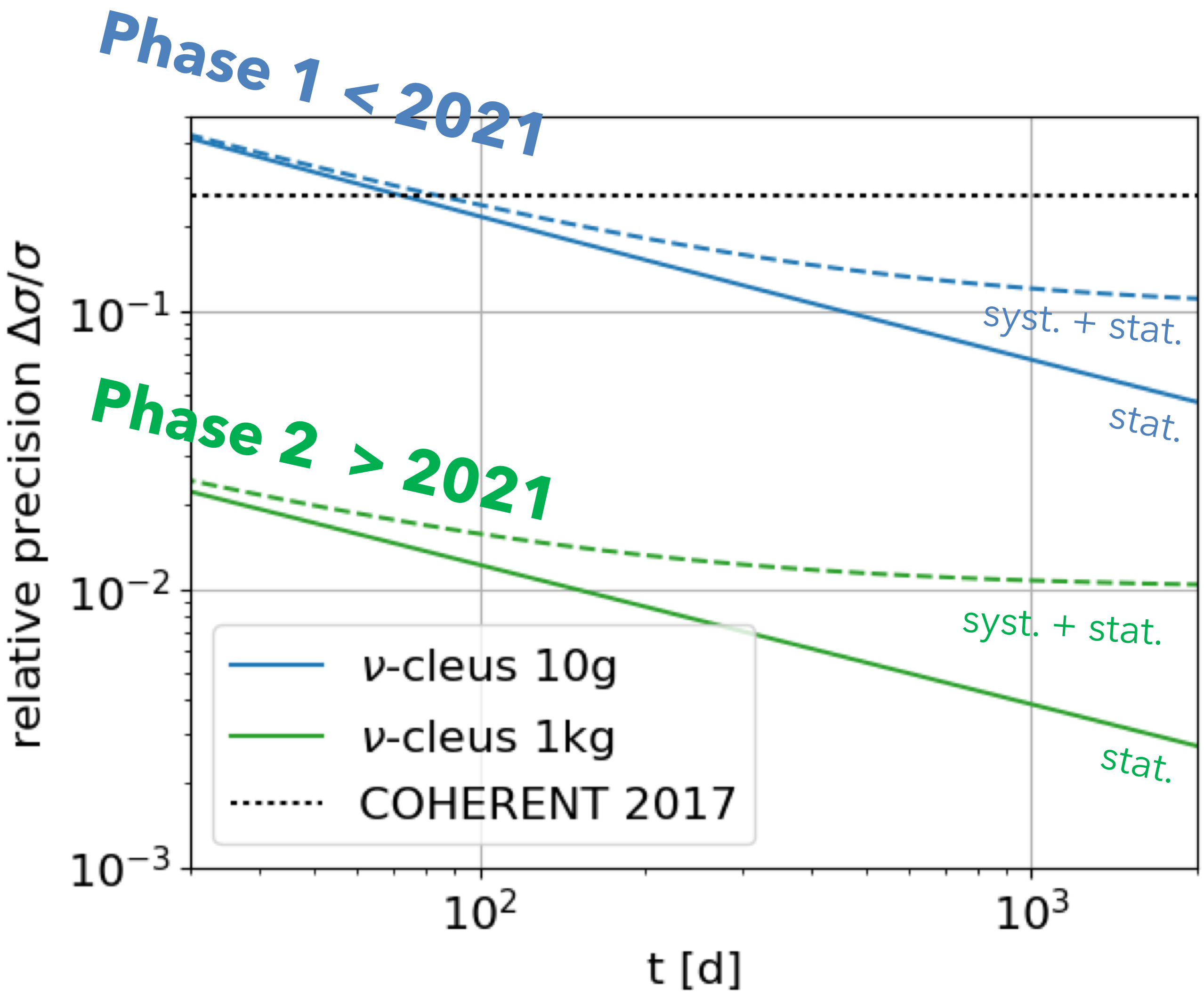
Intersted insitutions:

- INFN, Sapienza
- IBS Korea??
- TU Vienna

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

Jochen Schieck
Holger Kluck
Florian Reindl
Christoph Schwertner
Vasile Ghete

ν-cleus sensitivity



COHERENT 2017

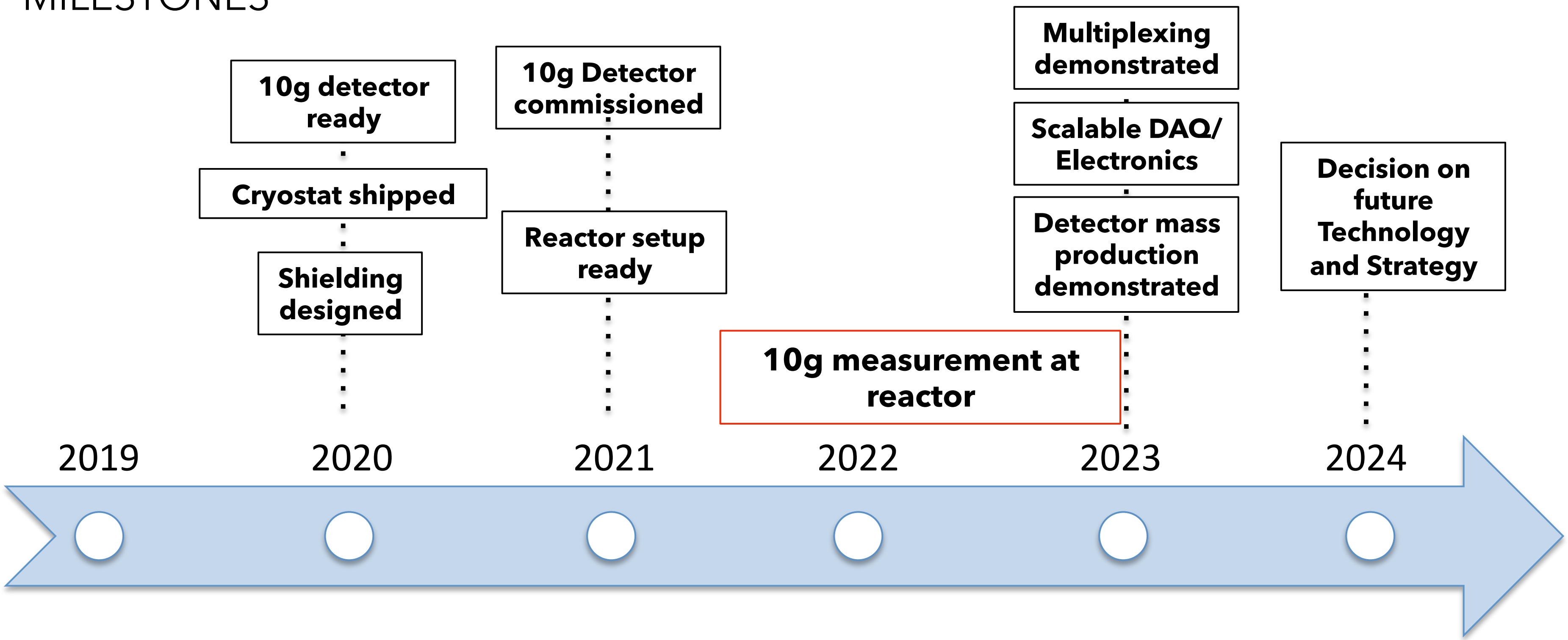
Present uncertainty of low-E neutrino flux ~10%

Future (estimated) uncertainty of low-E neutrino flux ~1%

Magnificent CEvNS, Raimund Strauss

ν-cleus milestones

MILESTONES



ERC grant 1.65M€ (TUM)

SFB funds + proposal for large equipment

SFB follow up (TUM)

ANR proposal by CEA (Matthieu)

FWF proposal in preparation by HEPHY (Holger)

+ MPP, CEA, HEPHY, TUM core funds **++ new collaborators**

FUNDING

ν-cleus activities

IT / computing

Reactor-site management

Shielding

Muon veto

Setup integration

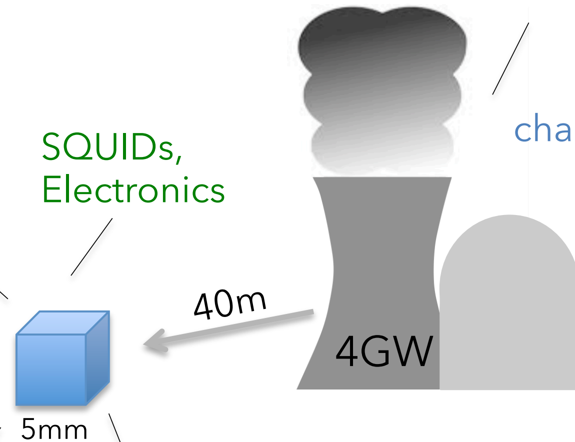
Background characterization

Slow control

Cryogenic detectors

SQUIDs, Electronics

Dry Cryostat



Data acquisition

Calibration

Acquisition software

Analysis software framework

Phenomenology

Analysis

Simulations

Readout software

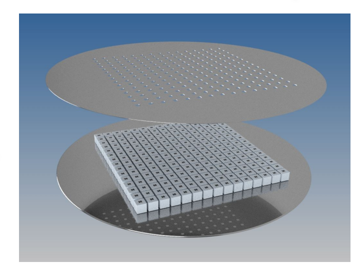
Multiplexing electronics

SQUID Multiplexing

Sensor production on large wafers

Detector mass production

New technology: KIDs ?



Scalable DAQ

Scalable Electronics

ν-cleus: INFN interested people

Roma1: F. Cappella, L. Cardani, N. Casali, I. Colantoni, A. Cruciani, C. Tomei and M. Vignati

Roma2: R. Cerulli

LNGS: L. Pattavina

Ferrara: V. Guidi and A. Mazzolari

Other INFN collaborators welcomed!

Next ν-cleus collaboration meeting, 21-22 May in Paris.

Another INFN opportunity: ^{51}Cr

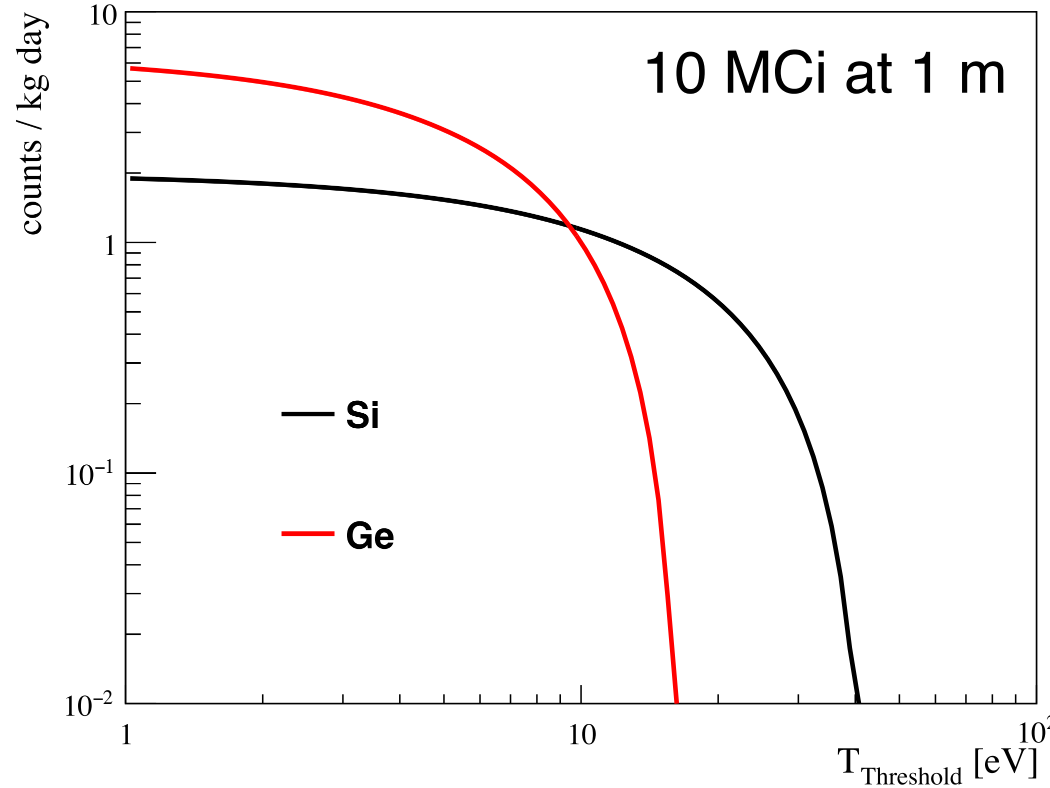
- 36 kg of ^{50}Cr owned by INFN (GALLEX experiment)
- ^{50}Cr need to be converted to ^{51}Cr at nuclear reactors

+ known spectrum (750 keV line)

+ known flux (0.3% heat monitor from SOX)

– Low neutrino energy.

– Half-life (27.7 days).



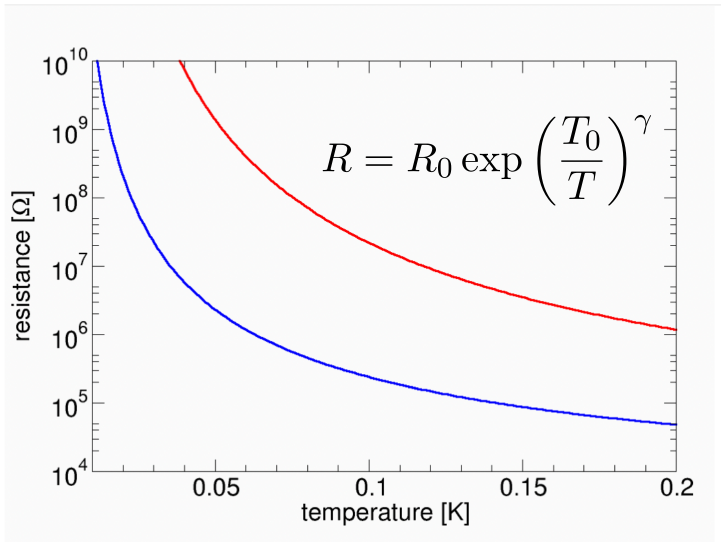
Ongoing feasibility study

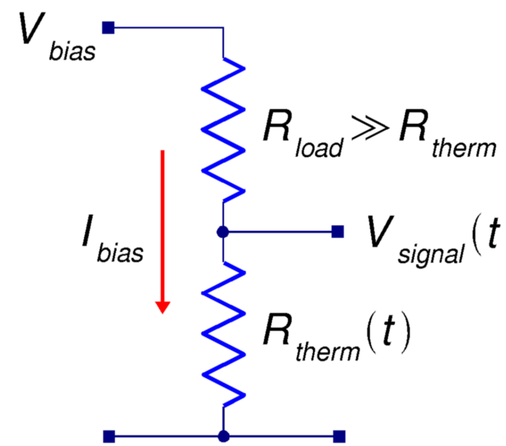
C. Bellenghi, D. Chiesa , L. di Noto, M. Pallavicini, E. Previtali and M. Vignati

BULLKID: Kinetic Inductance Detectors for coherent scattering

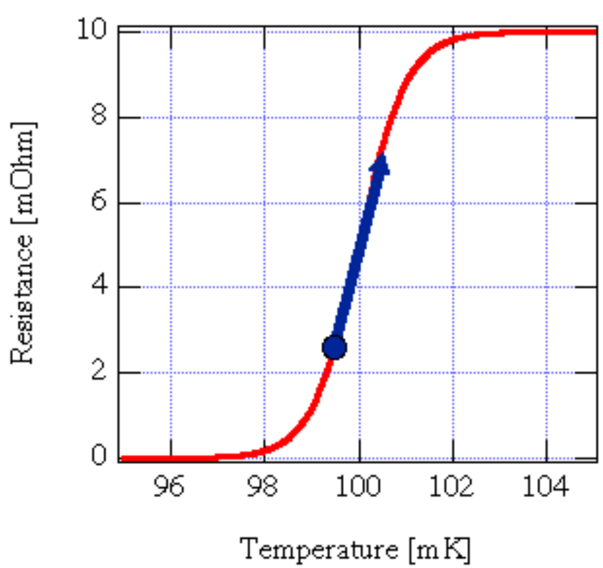
Cryogenic sensors

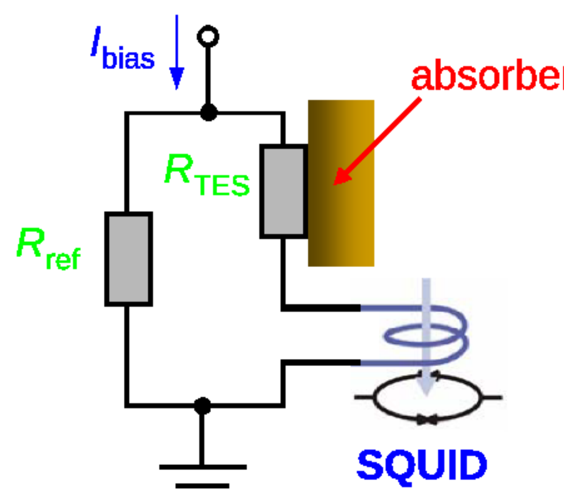
Thermistor: semiconductor with high-resistivity (e.g. Ricochet)





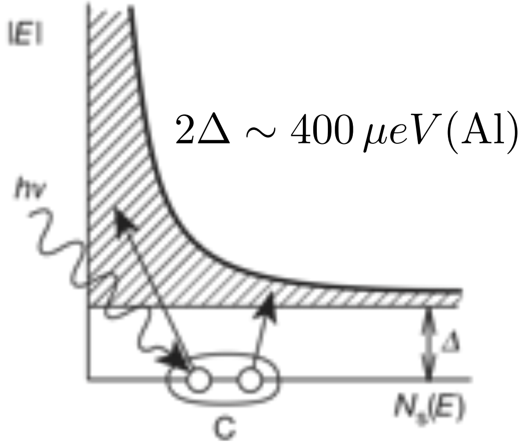
Transition edge sensor: superconductor at the transition (e.g. ν-cleus)

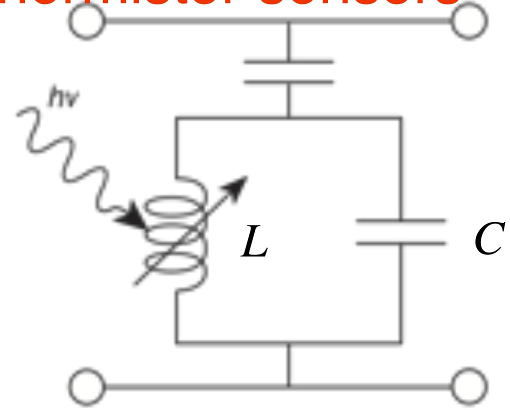




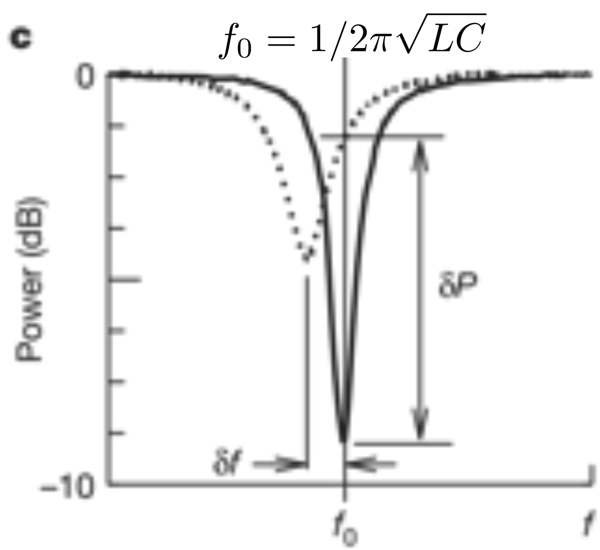
Kinetic Inductance Detectors (KIDs)

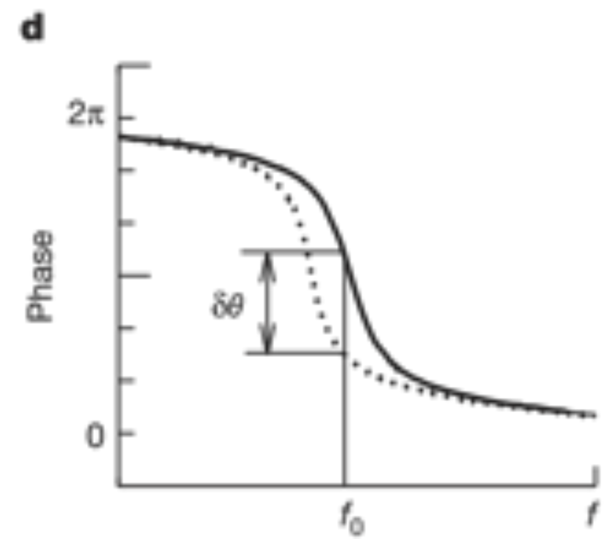
BULLKID (Grant INFN 2019-20) proposes
KIDs as an alternative to TES and thermistor sensors





Cooper pairs (cp) in a superconductor act as an inductance (*L*).
Absorbed photons or phonons change cp density and *L*.



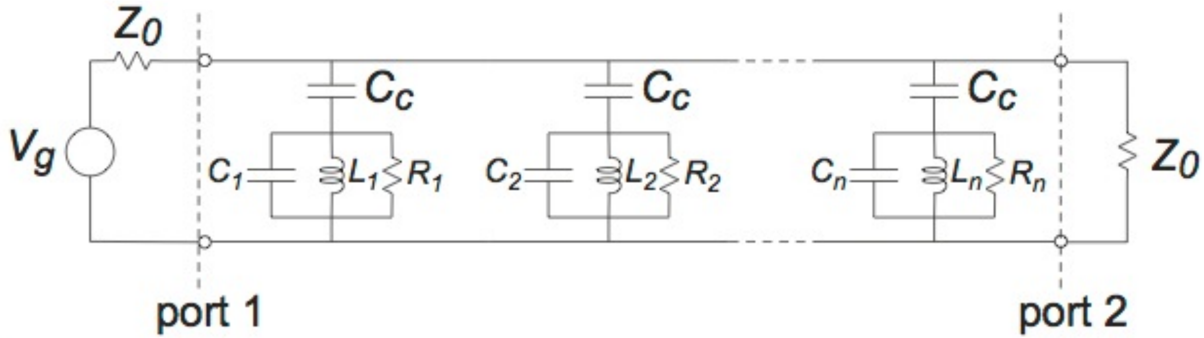


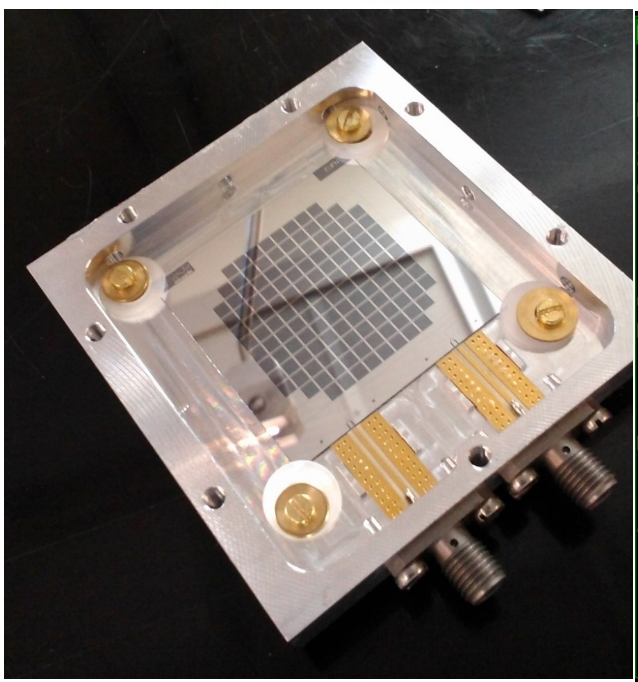
Day et al., Nature 425 (2003) 817

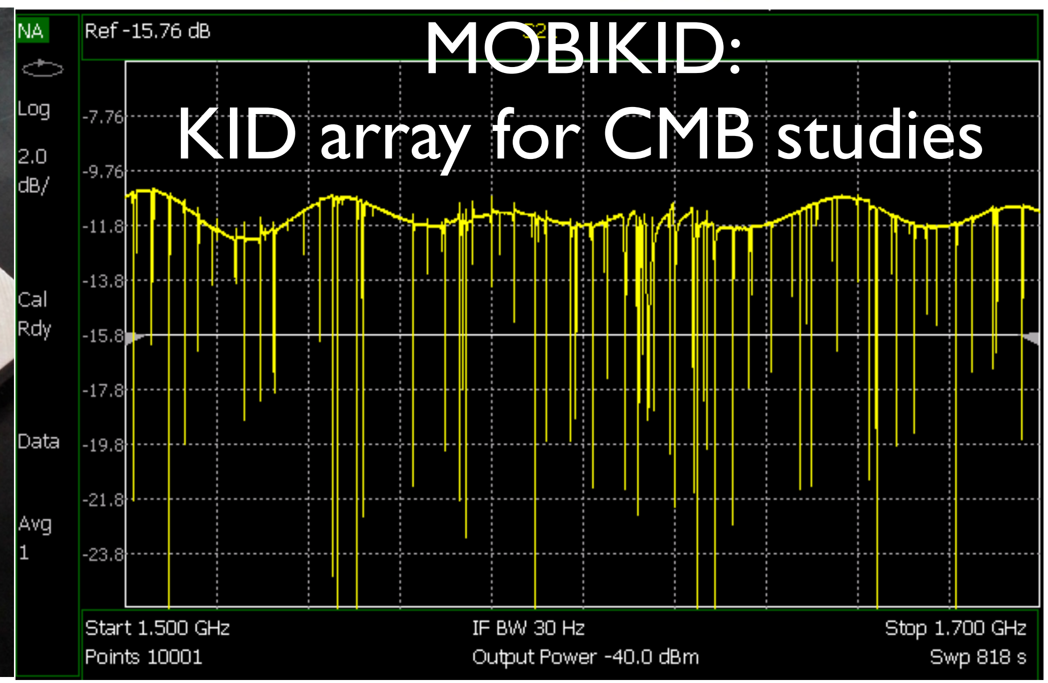
High quality factor (*Q*) resonant circuit biased with a microwave (GHz):
signal from amplitude and phase shift.

KID Multiplexing

Different resonators can be coupled to the same feedline
with slightly different resonant frequencies.
Resonant frequency modified via the capacitor (C) pattern of the circuit.





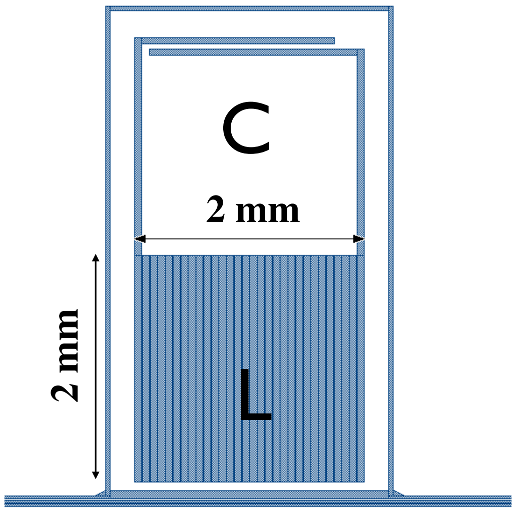


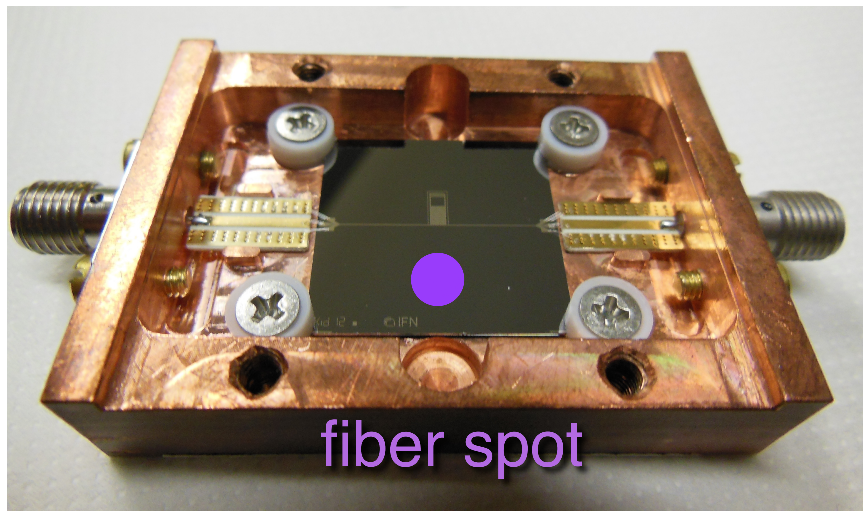
MOBIKID:
KID array for CMB studies

Multiplexing of 1000 KIDs with a single cryogenic amplifier demonstrated

CALDER result

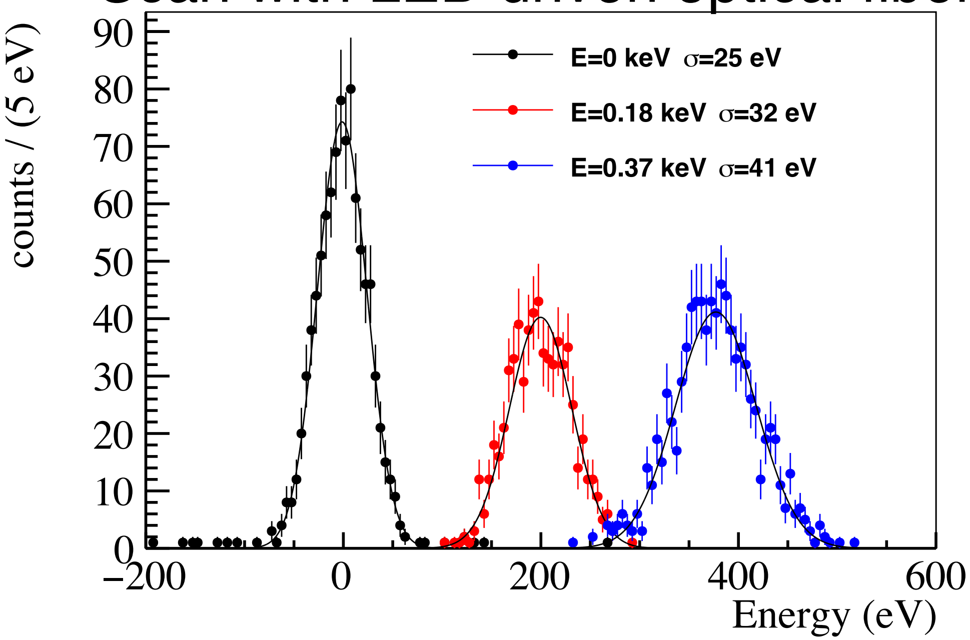
L. Cardani, et al, SUST (2018)



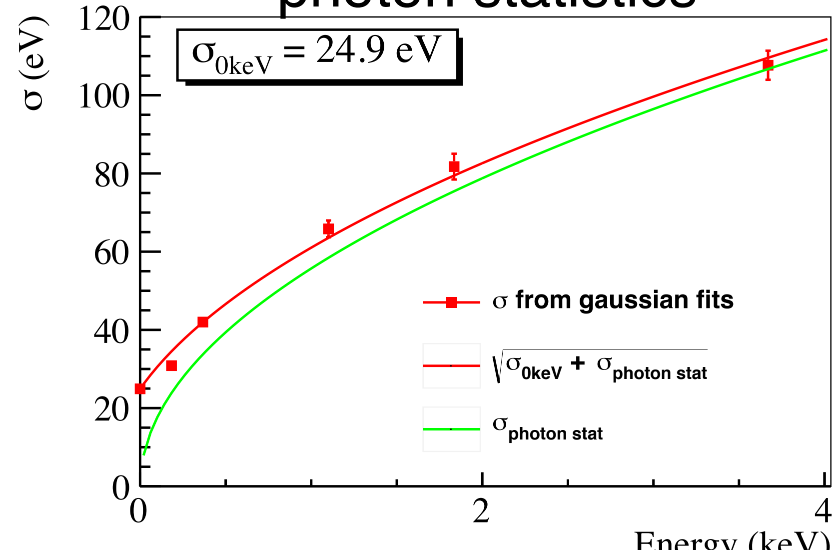


- Al(14)Ti(33)Al(30nm) resonator
- 2x2cm² x 350µm Silicon substrate
- 25 eV RMS @ 0 eV
- Phonon **ε** ~ 10%

Scan with LED driven optical fiber



Self-calibrated with photon statistics

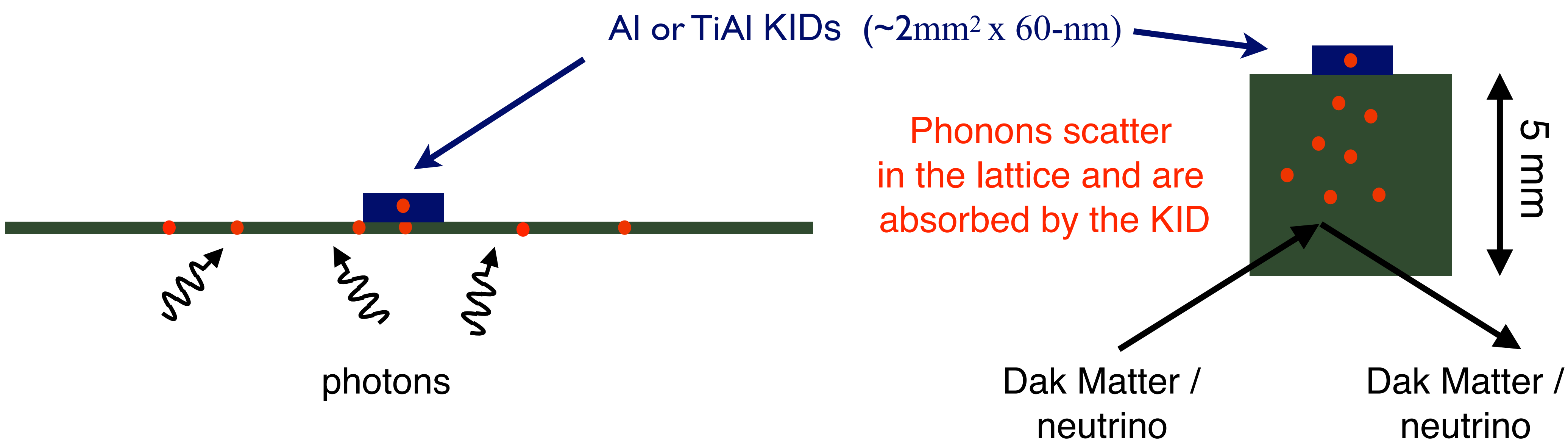


BULLKID single unit

BULLKID aims at a detector of athermal phonons created by nuclear recoils induced by Dark Matter or neutrino scattering.

Mass: increase the detector mass with KIDs on 5 mm instead of 300 μm thick wafers.

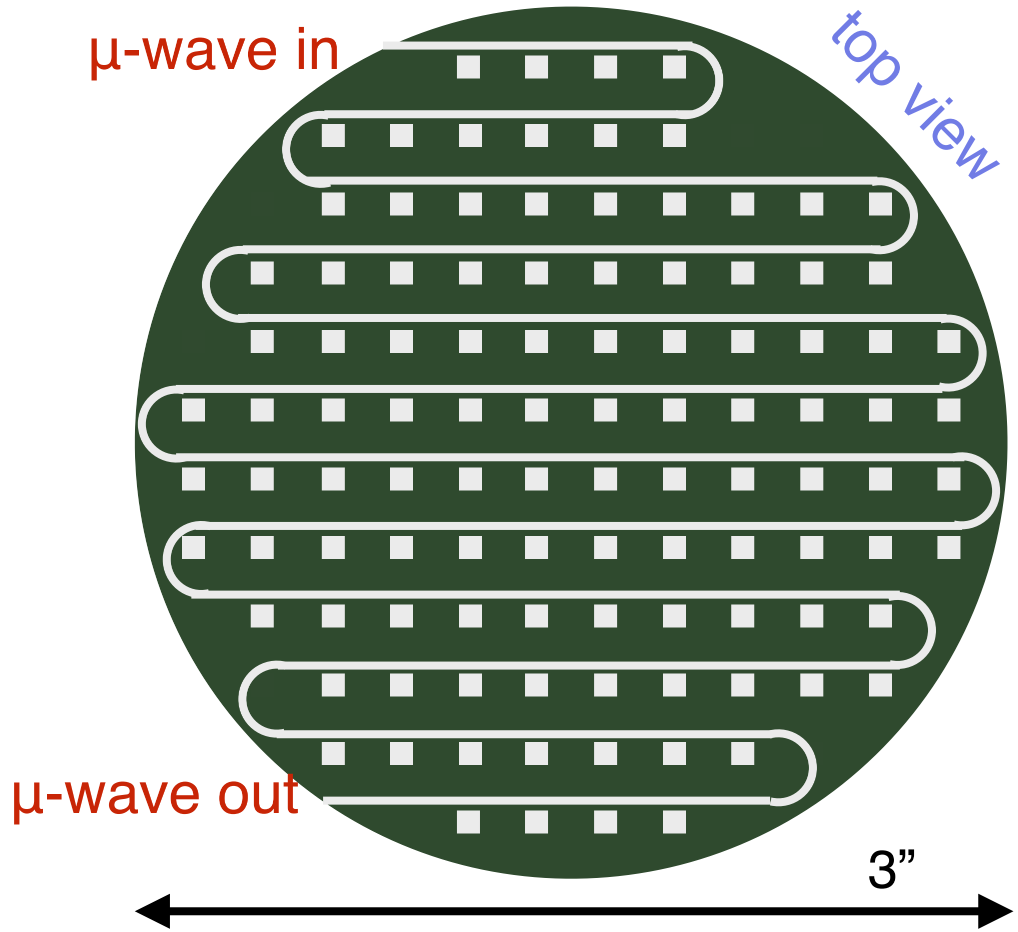
Threshold: reach 20 eVnr threshold acting on the phonon absorption and on the KID sensitivity (25 eV σ demonstrated by CALDER).

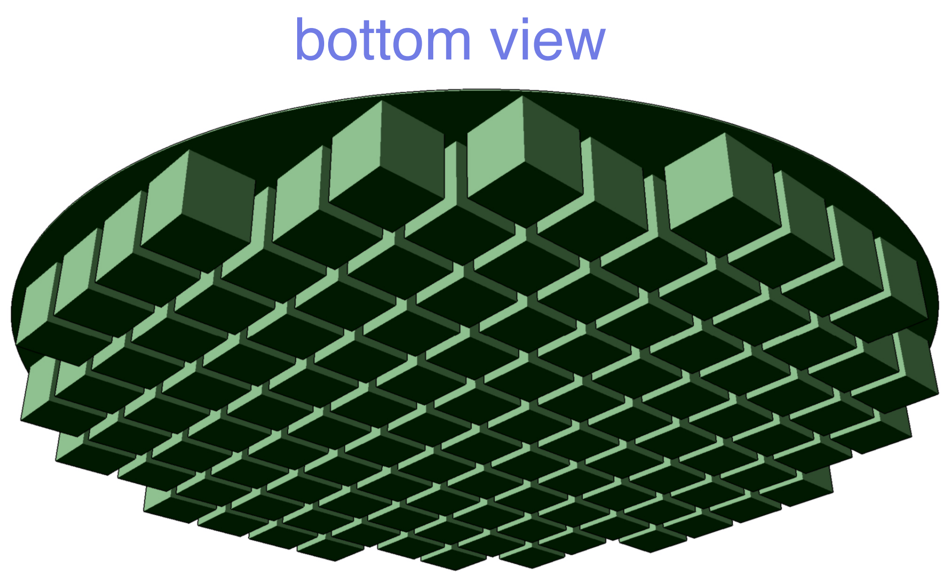


CALDER
Silicon (2x2 cm² x300 μm)

BULLKID
Silicon (5x5x5 mm³)

BULLKID array



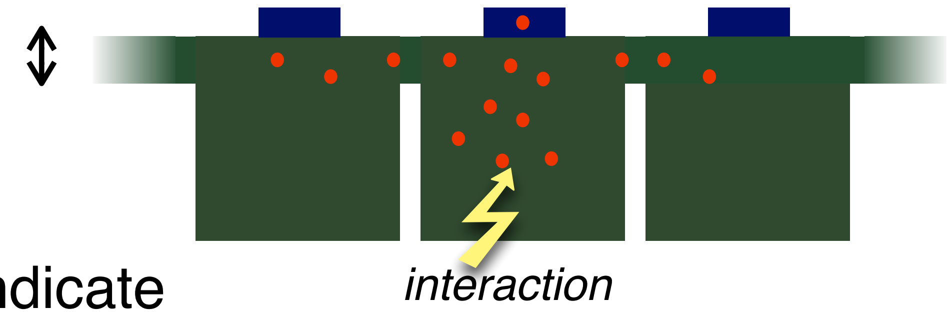


- The wafer is diced from the bottom to create cubic voxels of 5x5x5 mm^3 .
- ~ 110 cubic voxels of 5x5x5 mm^3 can be exploited.
- 0.29 g / voxel
- 32 g total target mass.

- We will deposit ~ 110 KIDs at once on top of a 3” wafer.
- The KIDs will be coupled to the same feedline for multiplexing.

Phonon x-talk and silicon dicing

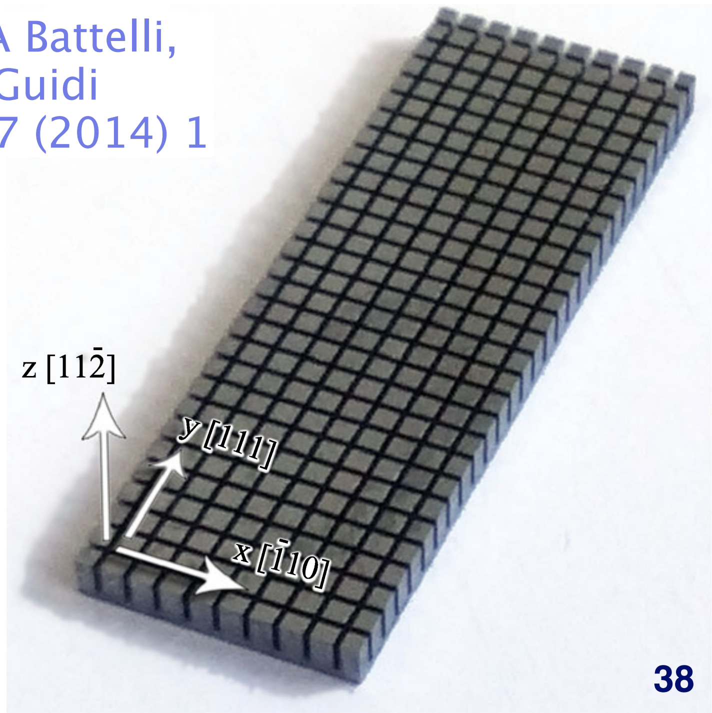
- The smaller the surface thickness the smaller the leak in nearby voxels



- MC Phonon simulations ongoing to quantify the leak. Preliminary results indicate it is 15% (vs 10% in CALDER)
- Risk: poor surface quality reduce phonon propagation. The dicing technology is being tuned to the BULLKID needs.

Material	Germanium
Tile size (mm^3)	30×10×2
Blade type	G1A 320
Blade width (μm)	250
Blade rotation (rpm)	3000
Blade speed (mm/s)	0.1
Groove depth (μm)	1550
Number of grooves	9×28
Groove step (mm)	1
Primary radius of curvature along y (m)	40
QM radius of curvature (m)	95.6
Angular bandpass (arcsec)	4.3

R. Camattari, A Battelli, V. Bellucci, V. Guidi
Exp. Astron. 37 (2014) 1



Detector array

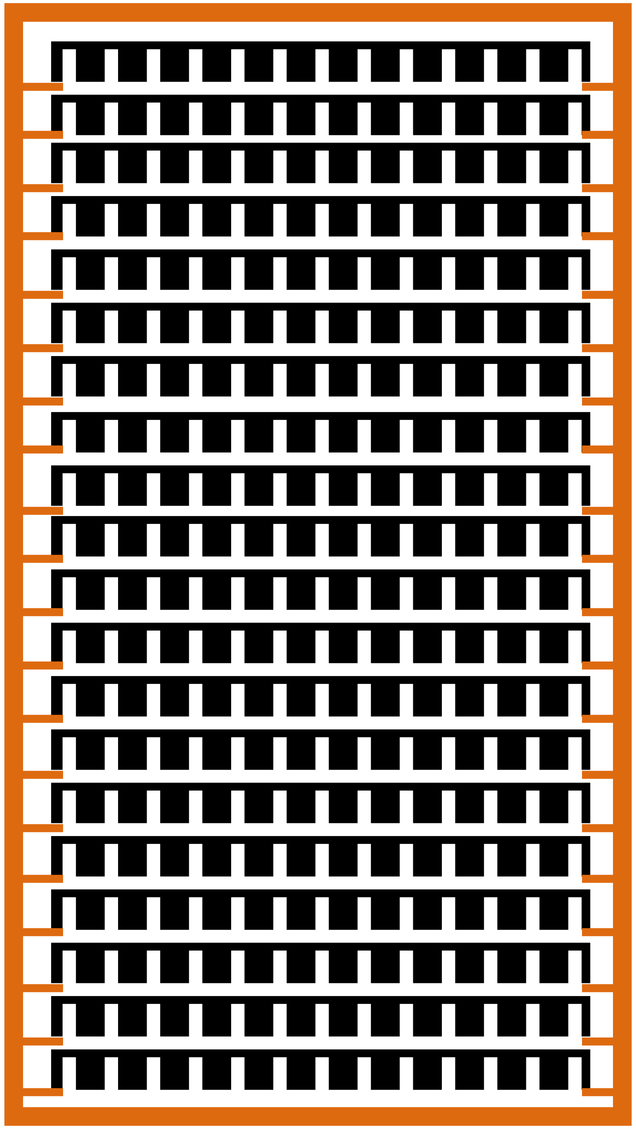
BULLKID: one 3” 5mm thick wafer

- 0.29 g / voxel
- 110 voxels / 3” wafer
- 32 g / 3” wafer.

Possible experiment with kg mass:

  - Maybe 4” or 6” wafer 1 cm thick.
  - Stack a number of wafers to reach the total target mass.

- No inert material between inner voxels:
  - Background identification (mulitple hits).
  - Fiducialization.



BULLKID collaboration

Istituto Nazionale di Fisica Nucleare:
C. Bellenghi, L. Cardani, N. Casali, A. Cruciani, V. Pettinacci and M. Vignati.

Zaragoza University:
M. Martinez

Consiglio Nazionale delle Ricerche
I. Colantoni, G. Pettinari.

Ferrara University:
V. Guidi, A. Mazzolari

Genova University
S. Di Domizio.

CSNSM - CNRS/IN2P3
H. Le Sueur

Institut Néel - CNRS
M. Calvo, J. Goupy, A. Monfardini

Conclusions

- Large and growing interest in CEνNS since its observation in 2017
- Room for:
  - Precision measurements
  - Search for non-standard interactions
  - Non-proliferation application
- Cryogenic detectors can lead the field thanks to the low threshold:
  - ν-cleus experiment (TES)
  - Ricochet (NTD-Ge)
  - BULLKID R&D (KID)