TECHNISCHE
UNIVERSITÄT
MÜNCHEN

NEUTRINO
2020

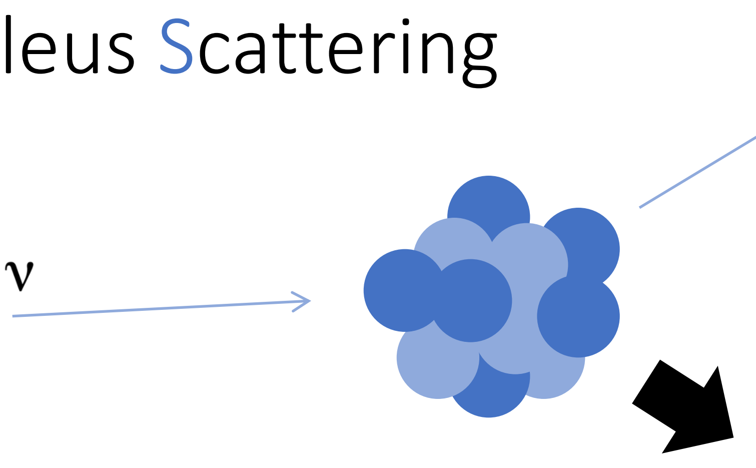
Future Uses of CEvNS

Raimund Strauss

Technical University of Munich

23.06.2020

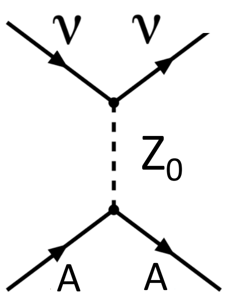
Coherent Elastic ν Nucleus Scattering



recoiling nucleus

Elastic coherent scattering off nuclei

Weak neutral current process



$$\sigma \propto N^2$$

cross-section

neutron number

Leo's* list of CEvNS "beauties":

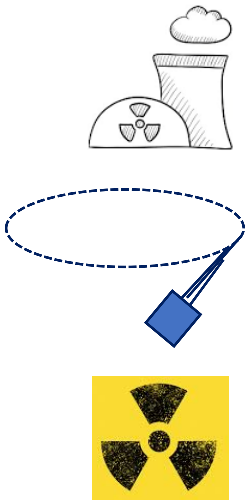
- **High** cross-section
- **Equal response** to all known neutrino flavours
- Response to neutrinos of all energies (**threshold-less**)
- Known (target) **material dependence**

* Drukier&Stodolsky, *Phys.Rev.D* 30 (1984) 2295

Future of CEvNS

What ?

LABORATORY



Enabling detector technology
gram-kg scale
shallow site
sub-keV threshold

NATURE

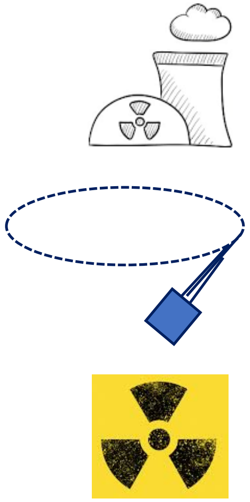
DM detectors
multi-ton scale
deep underground

+
New ideas

Future of CEvNS

What ?

LABORATORY



Enabling
detector
technology
gram-kg scale
shallow site
sub-keV threshold

NATURE

DM
detectors
multi-ton scale
deep underground

+
New ideas

So what ?

PHYSICS

Fundamental neutrino interactions
- Precision test of SM
- BSM physics

Sterile neutrinos
Nuclear physics
Reactor physics
Dark Matter
Solar physics
Supernova physics

TECHNOLOGY

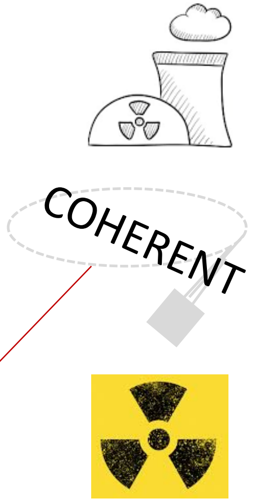
Small-scale neutrino detectors

Application for non-proliferation

Future of CEvNS

What ?

LABORATORY



Enabling
detector
technology
gram-kg scale
shallow site
sub-keV threshold

Jason
Newby's
talk

NATURE

DM
detectors
multi-ton scale
deep underground

+
New ideas

So what ?

PHYSICS

Fundamental neutrino interactions
- Precision test of SM
- BSM physics

Sterile neutrinos
Nuclear physics
Reactor physics
Dark Matter
Solar physics
Supernova physics

TECHNOLOGY

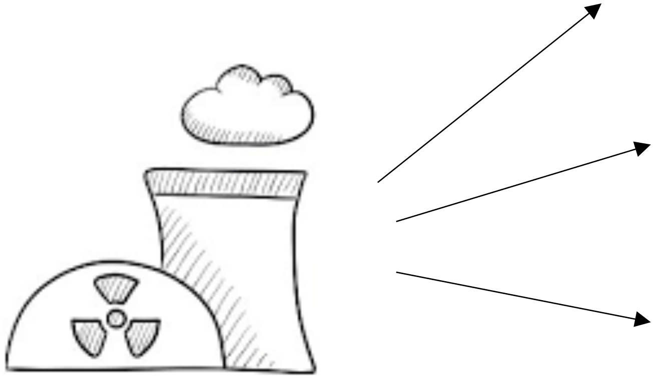
Small-scale neutrino detectors

Application for non-proliferation

Poster #248 J. Johnston

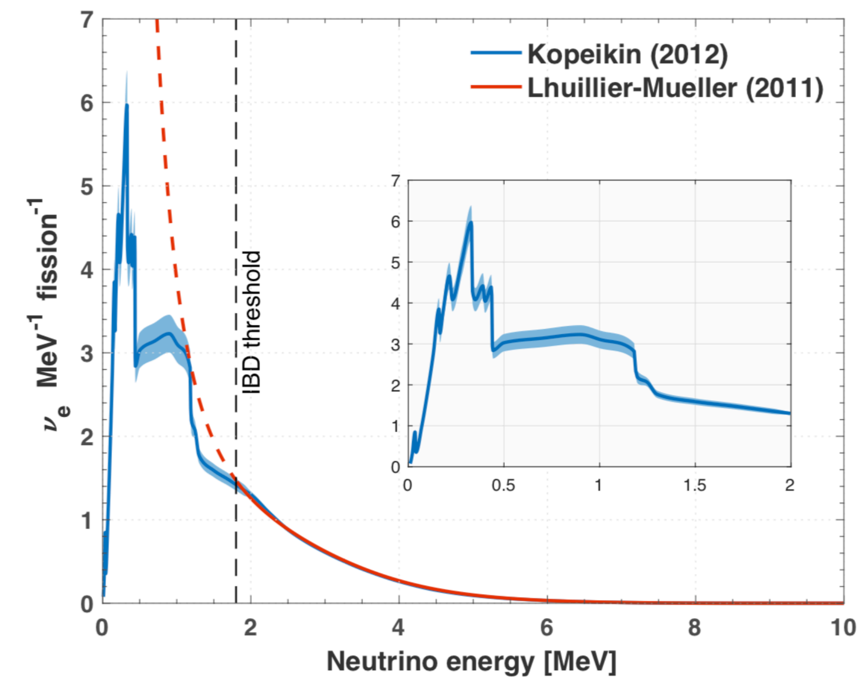
Reactor Experiments

Source



Intense in rate
Clean in background
MeV energies

Antineutrino spectrum

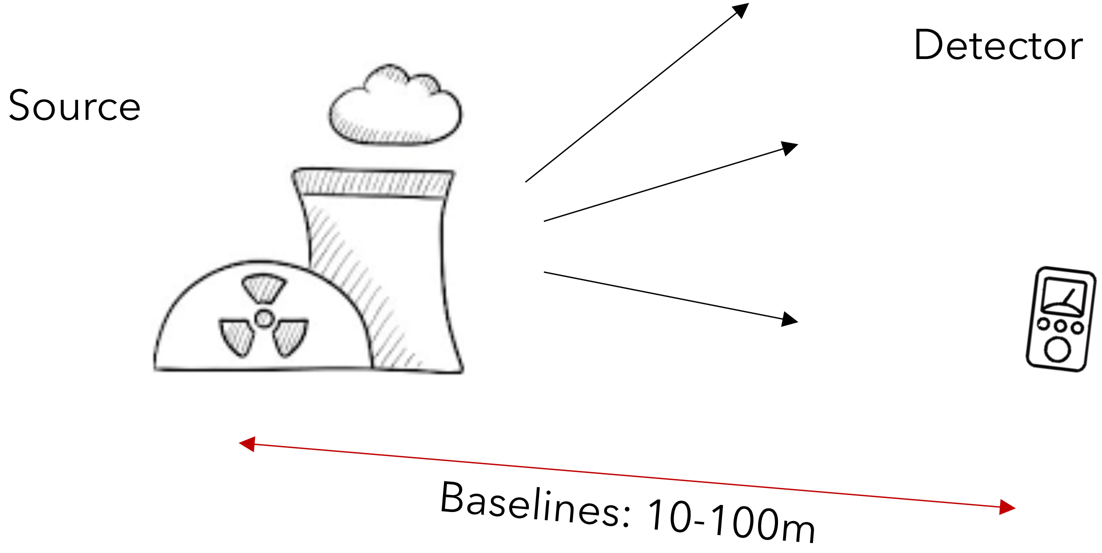


- High flux: 10^{20}nu / s (power reactors)
- Intense at MeV energies to max. 10MeV
- “Low-energy” correlated backgrounds (shieldable)

- Realistic goal:
  ν-spectrum uncertainties: 3% (work in progress)

courtesy M. Vivier, CEA, “NeNuFar project”

Reactor Experiments



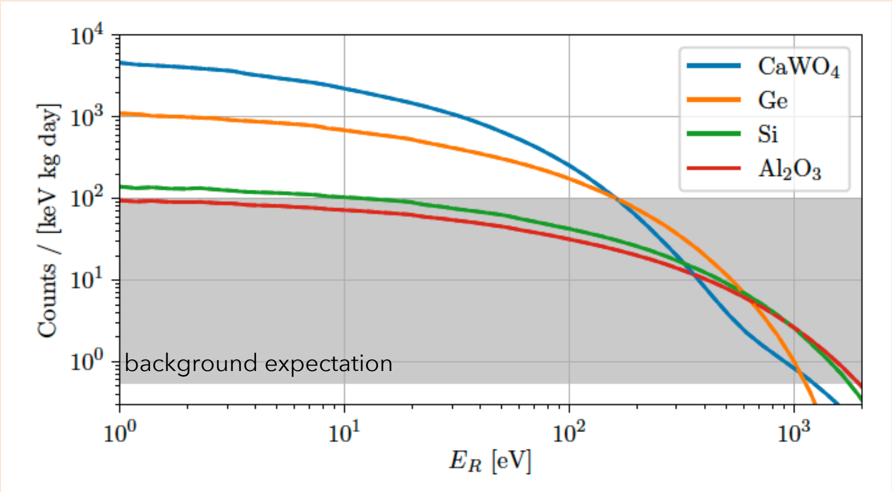
Source

Detector

Baselines: 10-100m

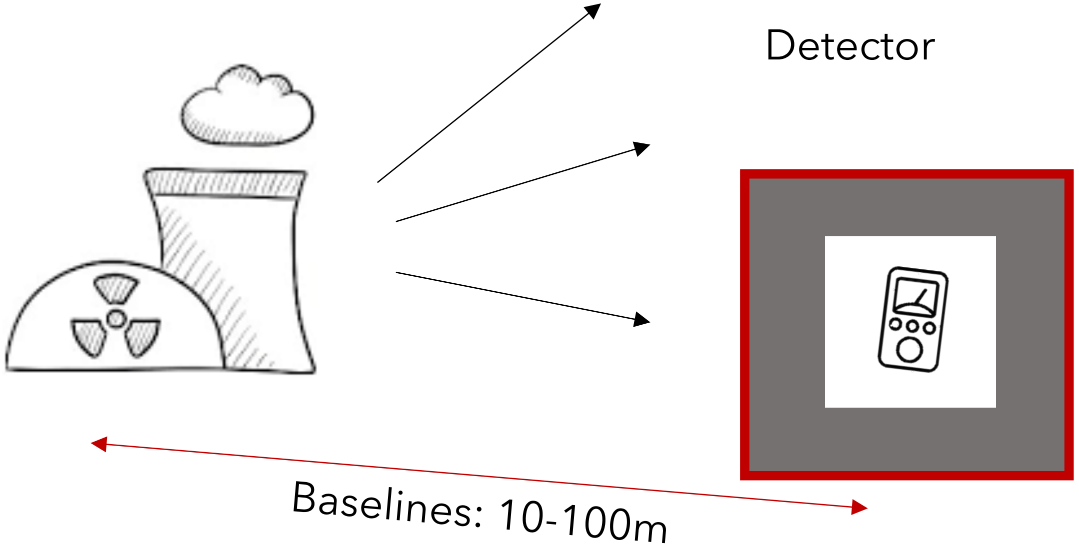
Intense in rate
Clean in background
MeV energies

Nuclear-recoil response



- High rate at low energies O(1) event / 10g / day
- Potentially high signal / background
- Clear material dependence ~N^2
    - ✓ Smoking gun signal
    - ✓ Background discrimination

Reactor Experiments



Source

Detector

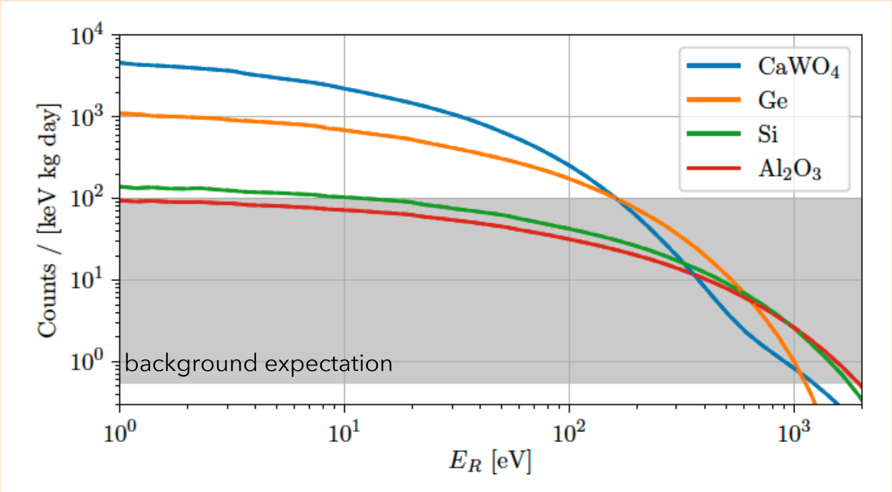
Baselines: 10-100m

Intense in rate
Clean in background
MeV energies

Sub-keV threshold
Compact shielding
Small mass (g-kg)

Shallow site (<100m.w.e)
High muon rate

Nuclear-recoil response



- High rate at low energies O(1) event / 10g / day
- Potentially high signal / background
- Clear material dependence ~N^2
  - ✓ Smoking gun signal
  - ✓ Background discrimination

Reactor Experiments

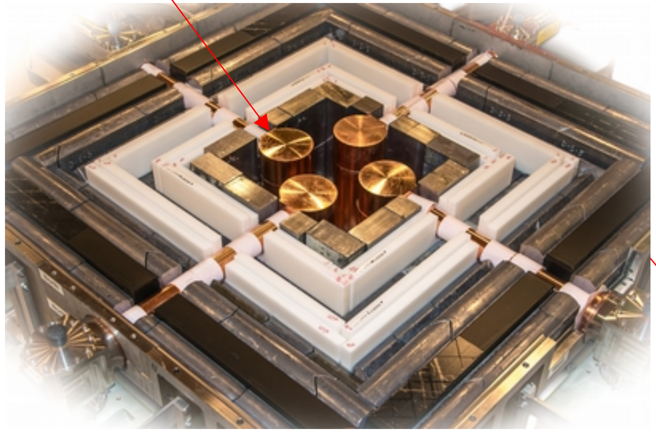
Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

CONUS

Commercial p-type point-contact **HPGe** detectors (m≈4kg)
Threshold: 300eV$_{ee}$

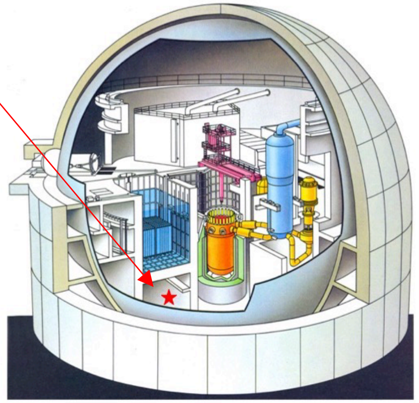


Multi-layer passive shielding + efficient muon veto

Reactor Sites

Brokdorf, Germany

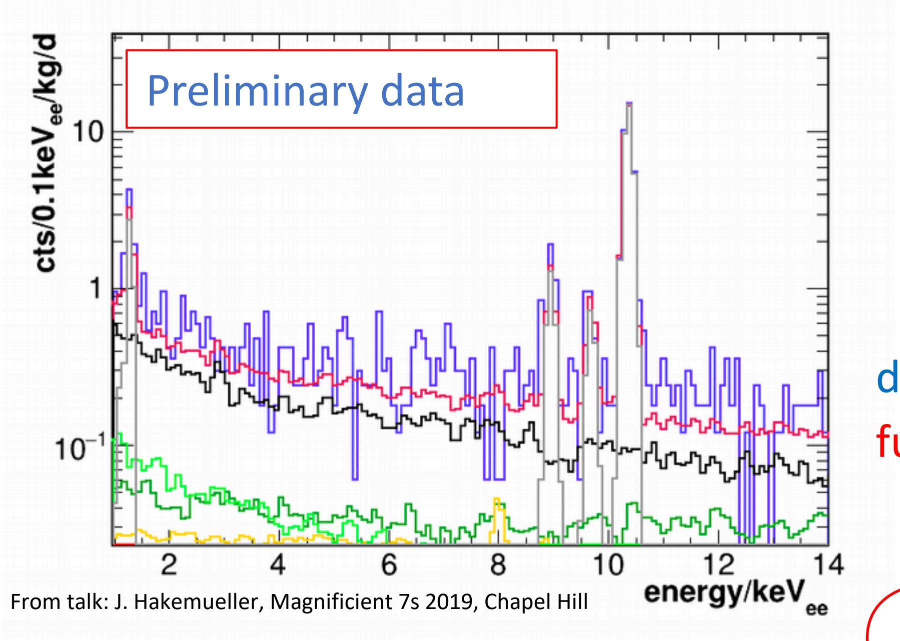
Power	3.9GW$_{th}$
Cores	1
Baseline	17m
ν-flux	2.2×10^{13} cm^{-2}s^{-1}



CONUS Status

Comprehensive background studies performed!

Eur. Phys. J. C (2019) 79:699



From talk: J. Hakemueller, Magnificient 7s 2019, Chapel Hill

data

full MC

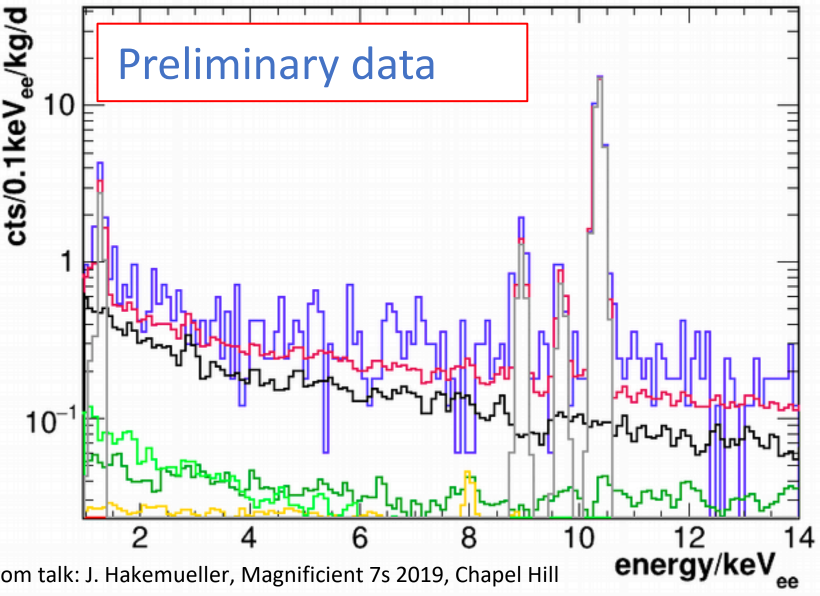
Community Milestone

- ➢ Background level of O(1)/[kg keV day]
  - at shallow site
  - in reactor containment
- ➢ Reactor-correlated backgrounds negligible

CONUS Status

Comprehensive background studies performed!

Eur. Phys. J. C (2019) 79:699



From talk: J. Hakemueller, Magnificient 7s 2019, Chapel Hill

Community Milestone

- Background level of O(1)/[kg keV day]
  - at shallow site
  - in reactor containment
- Reactor-correlated backgrounds negligible

Back of the envelope…

Lindhard model, measurements = **0.15 – 0.4** @300eV$_{ee}$

$$\mathbf{E_{nr} = E_{ee} / Quenching\text{-}Factor}$$

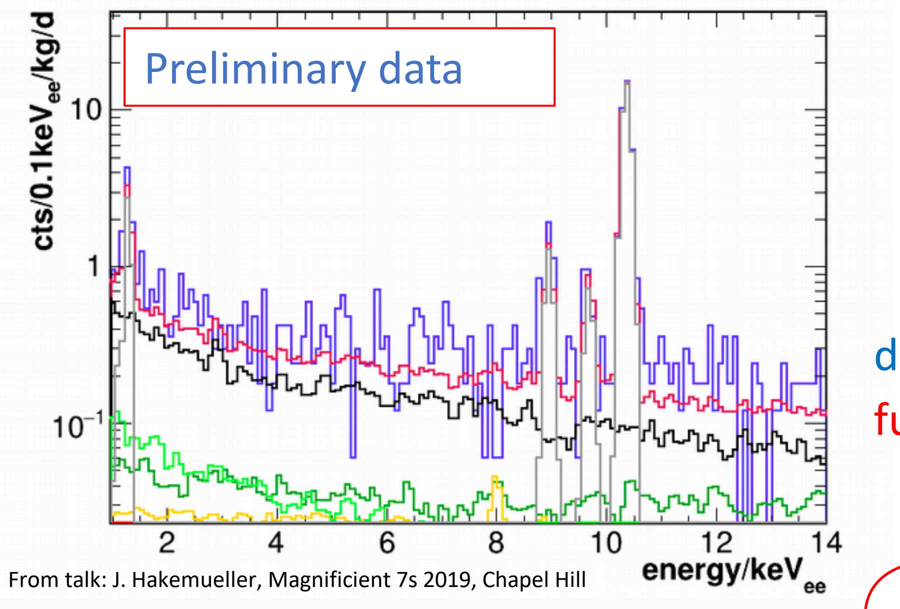
CONUS-1: **0.8 - 2 keV$_{nr}$**

CONUS-1: **300eV$_{ee}$**

CONUS Status

Comprehensive background studies performed!

Eur. Phys. J. C (2019) 79:699



From talk: J. Hakemueller, Magnificient 7s 2019, Chapel Hill

data

full MC

Community Milestone

- ➢ Background level of O(1)/[kg keV day]
  - at shallow site
  - in reactor containment
- ➢ Reactor-correlated backgrounds negligible

Back of the envelope…

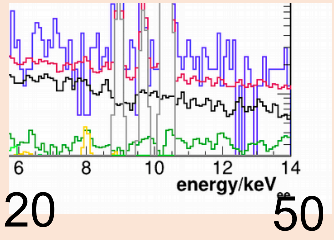
Lindhard model, measurements = **0.15 – 0.4** @300eV$_{ee}$

$$\mathbf{E_{nr} = E_{ee} / \text{Quenching-Factor}}$$

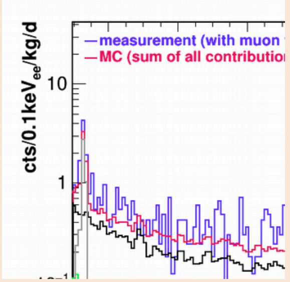
CONUS-1: **0.8 - 2 keV$_{nr}$**

CONUS-1: **300eV$_{ee}$**

2 effects:



higher energies

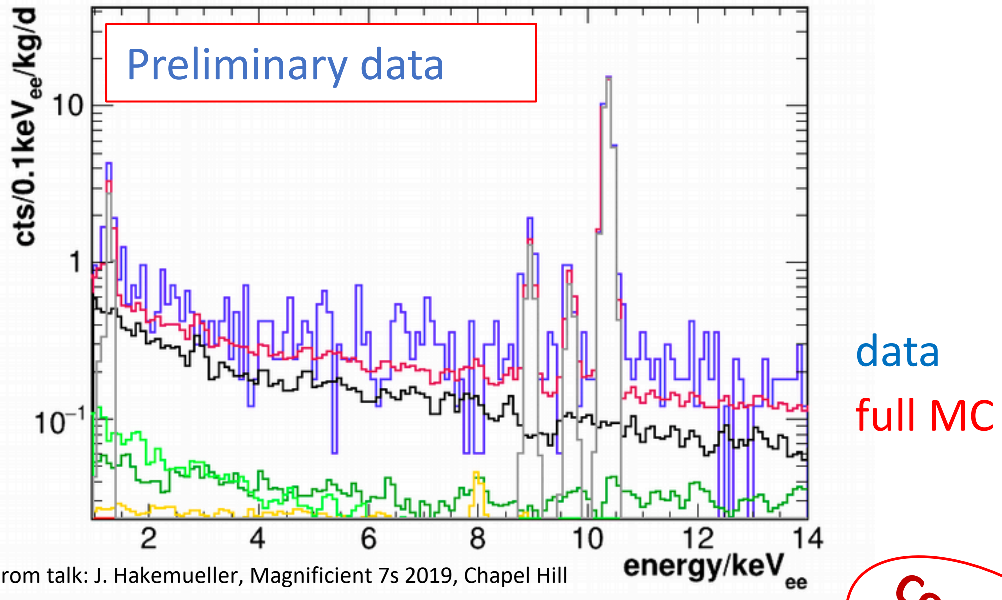


“stretch spectrum”

CONUS Status

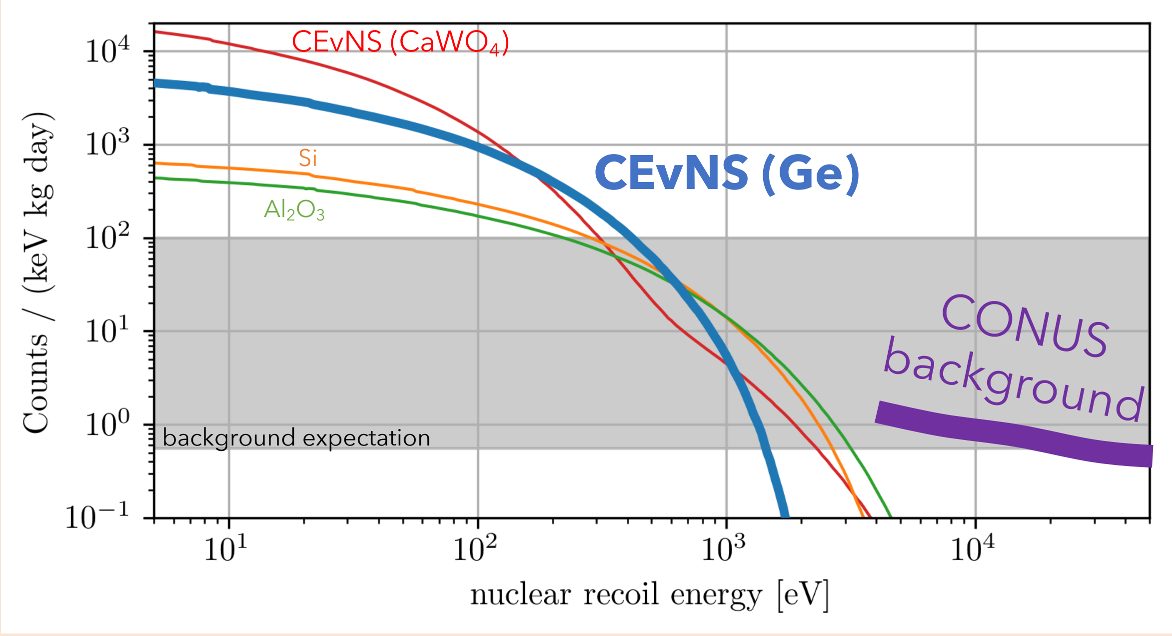
Comprehensive background studies performed!

Eur. Phys. J. C (2019) 79:699



From talk: J. Hakemueller, Magnificient 7s 2019, Chapel Hill

Back of the envelope…



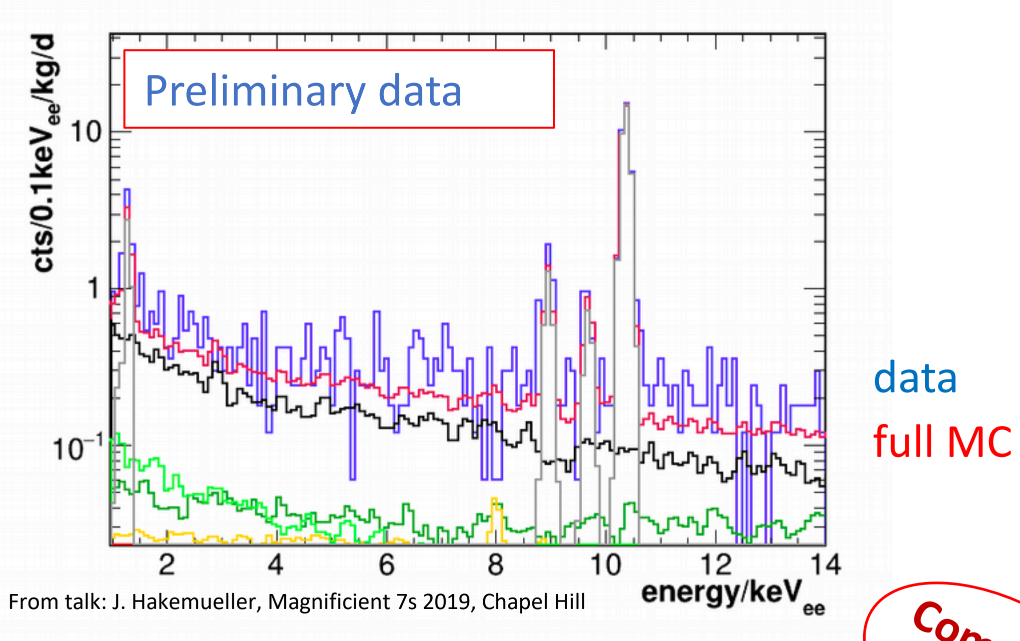
Community Milestone

- ➢ Background level of O(1)/[kg keV day]
  - at shallow site
  - in reactor containment
- ➢ Reactor-correlated backgrounds negligible

CONUS Status

Comprehensive background studies performed!

Eur. Phys. J. C (2019) 79:699

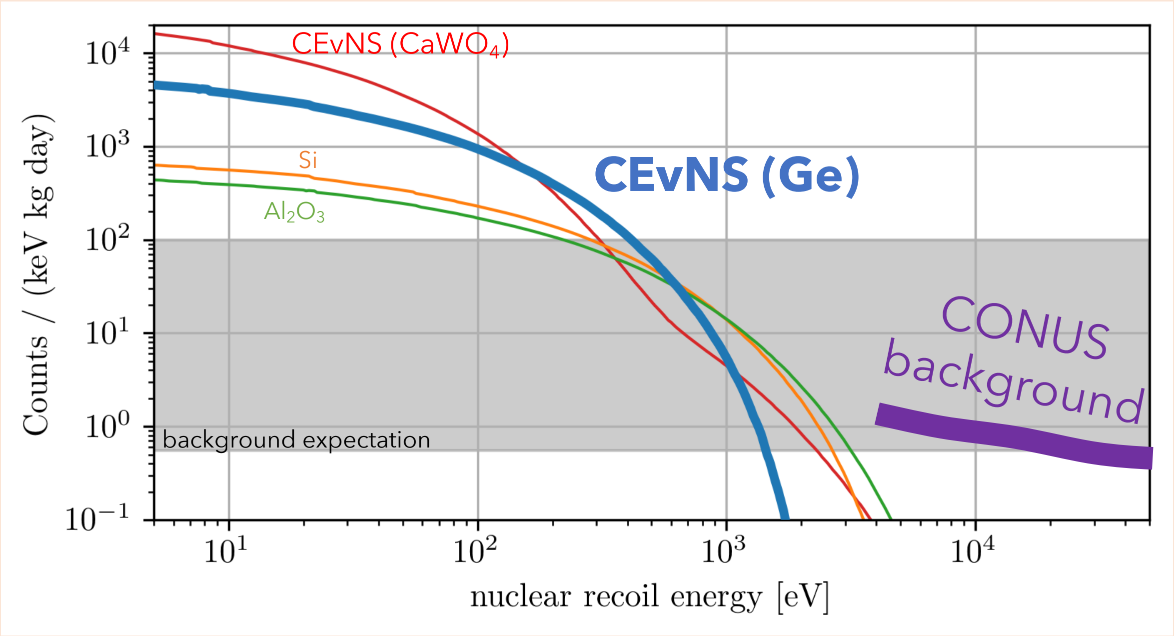


From talk: J. Hakemueller, Magnificient 7s 2019, Chapel Hill

Community Milestone

- ➢ Background level of O(1)/[kg keV day]
  - at shallow site
  - in reactor containment
- ➢ Reactor-correlated backgrounds negligible

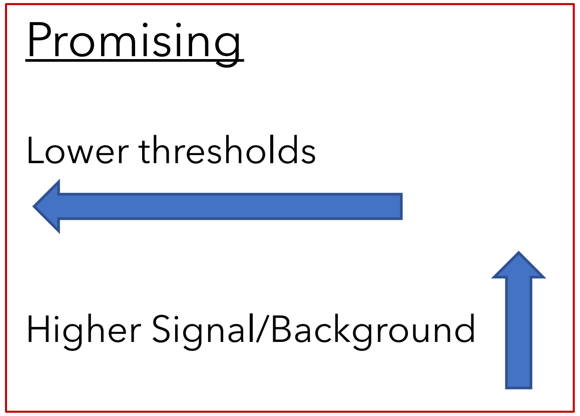
Back of the envelope…



- ➢ **2.4σ excess** at Neutrino2018
- ➢ More run1 data (up to Nov 2018) -> lower signif.
- ➢ CONUS run2 (2019) – stable data taking
- ➢ 100kg upgrade planned (CONUS100)

“At the edge of the first observation at reactors!”

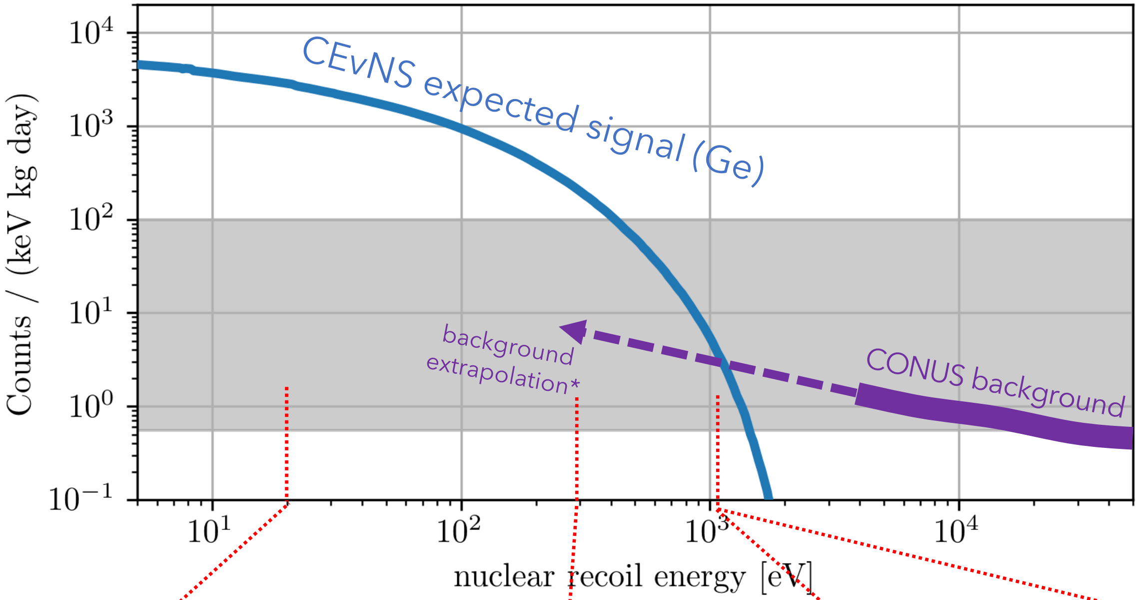
Impact of Energy Threshold



Promising

Lower thresholds

Higher Signal/Background

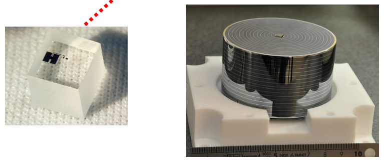


* let's speculate a bit!

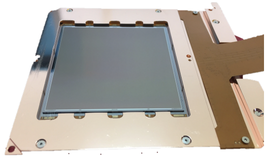
$E_{th} = O(10eV_{nr})$

$E_{th} = O(100eV_{nr})$

$E_{th} \approx 1keV_{nr}$



Cryogenic detectors



Si CCD

Ge ionization

liquid Xe TPC

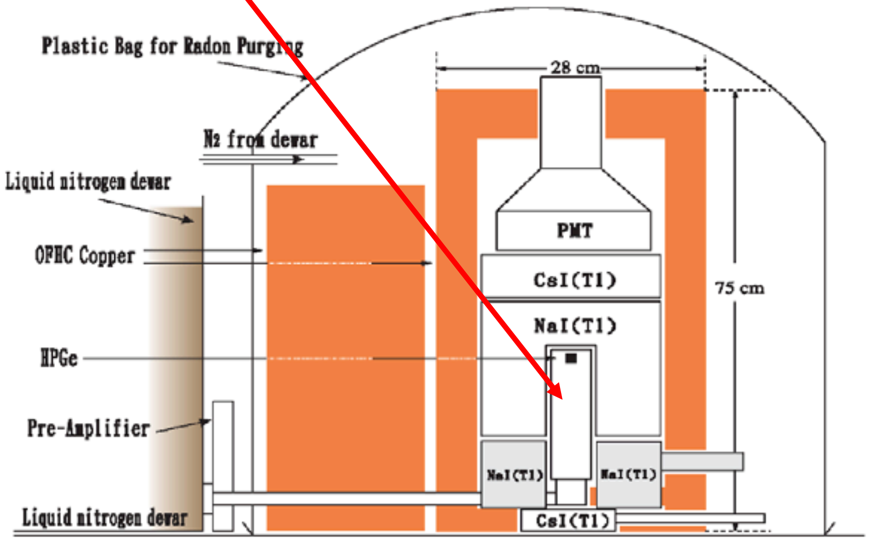
Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	$O(1\text{keV}_{nr})$	Running
TEXONO	Ge ionization	$O(1\text{keV}_{nr})$	Running
Nu-GEN	Ge ionization	$O(1\text{keV}_{nr})$	commissioning
RED-100	Liquid Xe TPC	$O(1\text{keV}_{nr})$	Construction
CONNIE	CCD (Si)	$\sim 300\text{eV}_{nr}$	running
MINER	Cryogenic (mK)	$O(100\text{eV}_{nr})$	commissioning
RICOCHET	Cryogenic (mK)	55eV_{nr}	construction
NUCLEUS	Cryogenic (mK)	20eV_{nr}	construction

arXiv:1603.08786

R&D towards lower threshold:

$E_{th,ee}$ = 200eV$_{ee}$ (achieved)
$E_{th,ee}$ < 150eV$_{ee}$ (next benchmark)



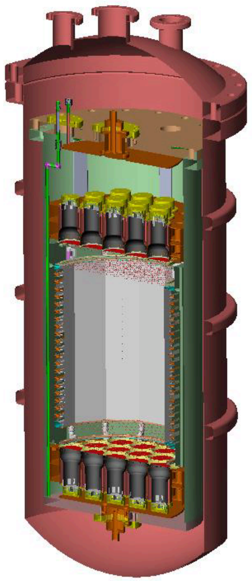
Reactor Sites CEvNS

Kuosheng, Taiwan

Power	2.7GW$_{th}$
Cores	2
Baseline	28m
ν-flux	5×10^{12} cm^{-2}s^{-1}

Reactor Experiments

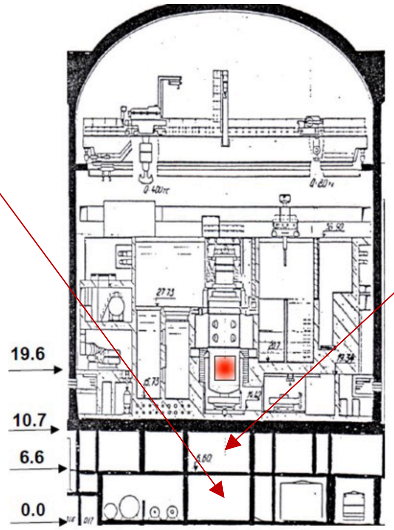
Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction



arXiv:1910.06190

Liquid Xe TPC

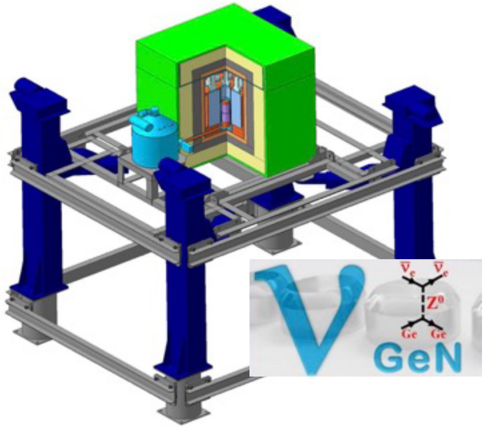
- 160kg fiducial volume
- Commissioned on ground level!



Reactor Sites

Kalinin, Russia

Power	3.2GW$_{th}$
Cores	4
Baseline	10m
ν-flux	5×10^{13} cm^{-2}s^{-1}



HP Ge array

Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

CONνNie

Poster NEUTRINO 2020

#289 B. Vergara

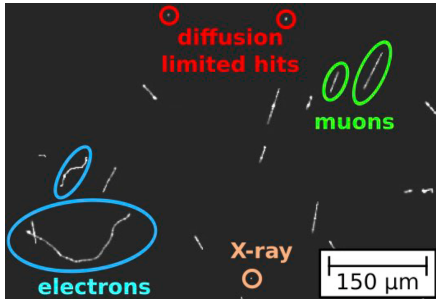
arXiv:1906.02200
arXiv:1910.04951

Reactor Sites

Angra, Brazil

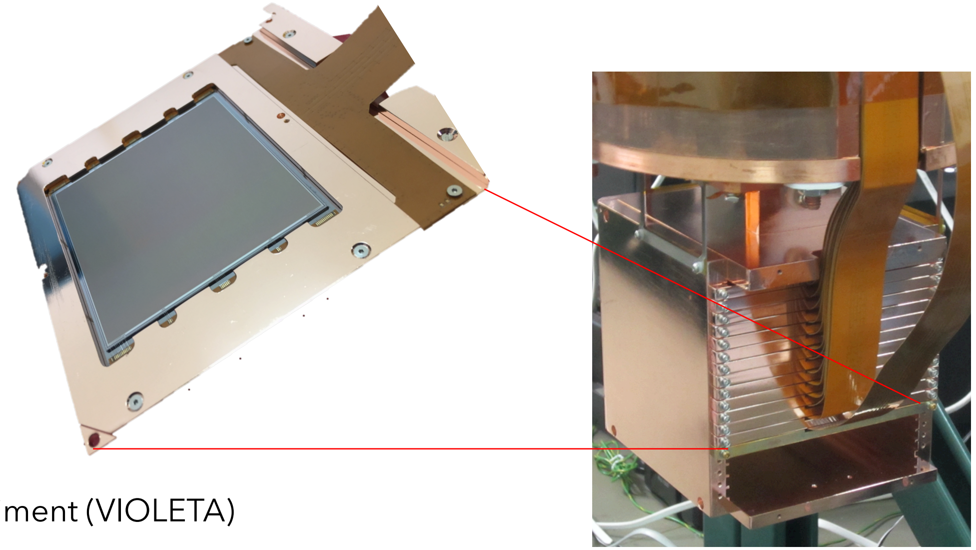
Power	3.8GW$_{th}$
Cores	1
Baseline	30m
ν-flux	7×10^{12} cm^{-2}s^{-1}

Particle discrimination in CCDs



Mass: 6g each

Total payload: 50g Si (fiducial)



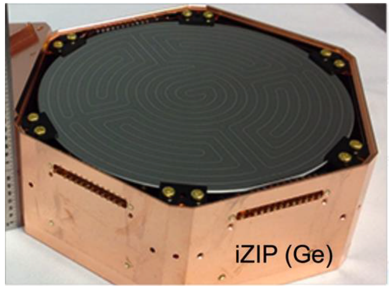
Future: 10kg skipper CCD experiment (VIOLETA)

Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

MINER

arXiv:1609.02066
arXiv:1511.02834

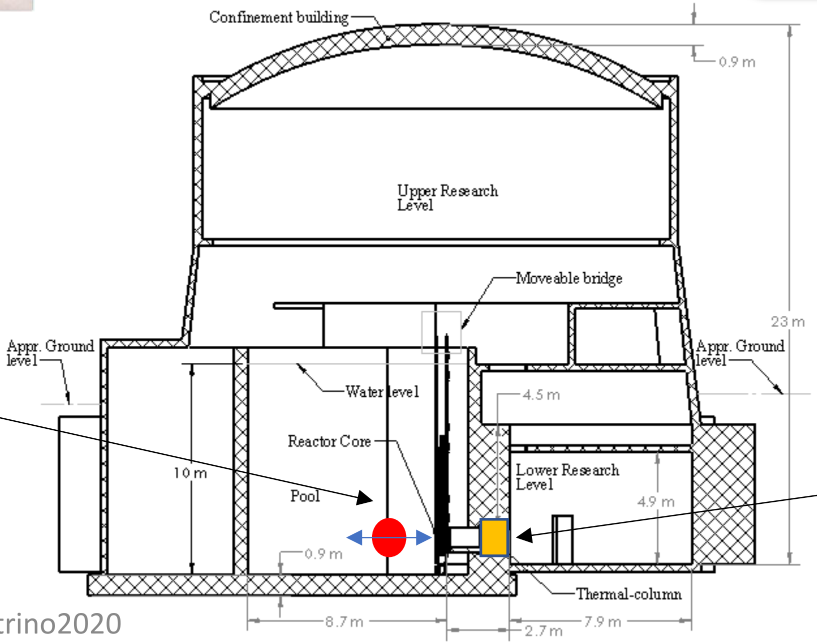


CDMS-II detectors
Current Payload
5x0.6kg (Ge/Si)

Reactor Sites

TAMU, Texas

Power	1MW$_{th}$
Cores	1
Baseline	2-10m
ν-flux	4×10^{11} cm^{-2}s^{-1}



Movable core (!)

Interesting for sterile neutrinos

detector

Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

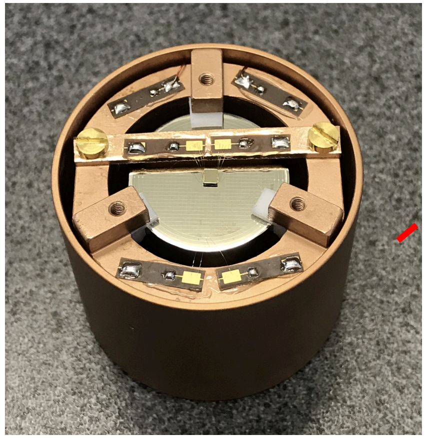
Poster NEUTRINO 2020

#587 R. Chen

RICOCHET

arXiv:1612.09035

Cryocube - array

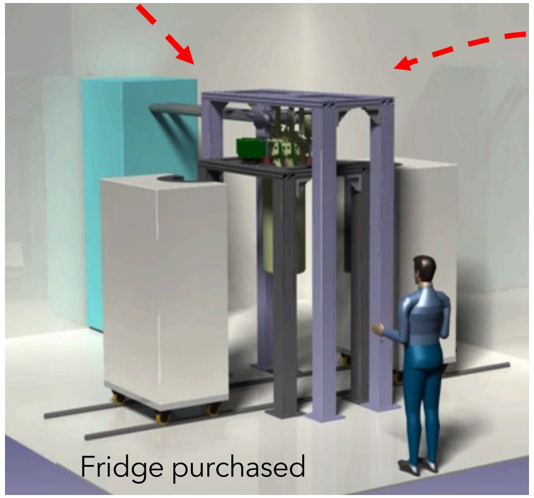


RED20 Ge detector

Low threshold demonstrated:

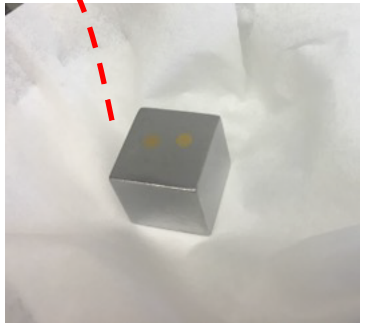
E_{th} = 55eV$_{nr}$

m = 32g



Dry refrigerator

Q-array



R&D on Zn detectors

Reactor Sites

ILL, France

Power	58MW$_{th}$
Cores	1
Baseline	10m
ν-flux	9×10^{11} cm^{-2}s^{-1}

Reactor Experiments

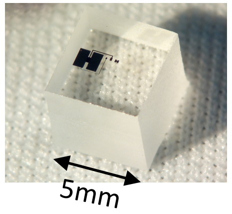
Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

nucleus EXPERIMENT

Poster NEUTRINO 2020
#397 A. Erhart

arXiv:1704.04320
arXiv:1704.04317

$CaWO_4$ + Al_2O_3



Lowest energy threshold for nuclear recoils **E_{th} = (19.7±0.8) eV**

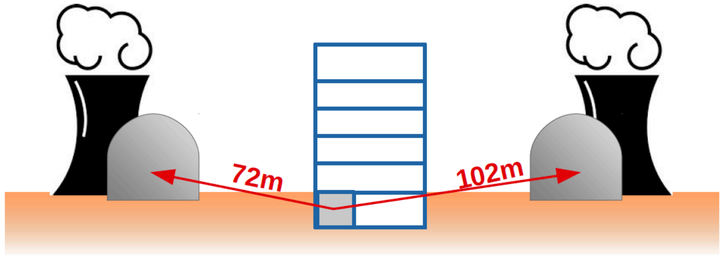
NUCLEUS fridge commissioned in May 2020

Reactor Sites

CHOOZ, France

Power	4.25GW$_{th}$
Cores	2
Baseline	70-100m
ν-flux	2×10^{12} cm^{-2}s^{-1}

New experimental site @CHOOZ



arXiv:1905.10258

Reactor Experiments

Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

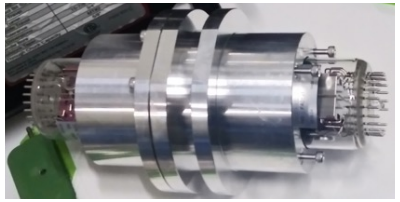
New experiments, R&D project, interested experiments:

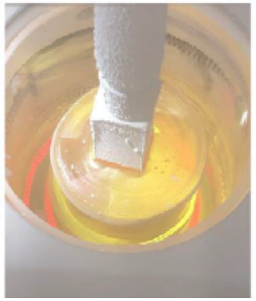
NEON @ Hanbit reactor, South Korea

NeON

- R&D ongoing, goal: E_{th} = 2keV$_{nr}$
- Phase 1 with 50kg payload ~2023

NaI scintillation detectors





Poster NEUTRINO 2020
#103 J. Choi

BASKET, BULLKID…

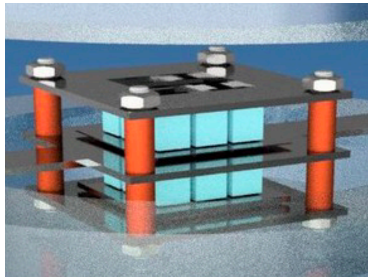
NEWS-G, CYGNUS…

Lab Experiments - Perspectives

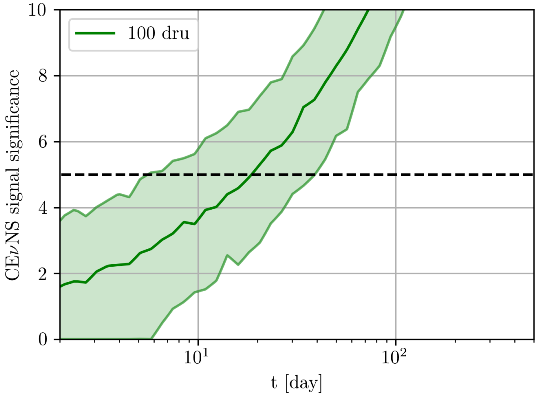
PHASE 1 Experiments

Example

NUCLEUS 10g



2020-2022



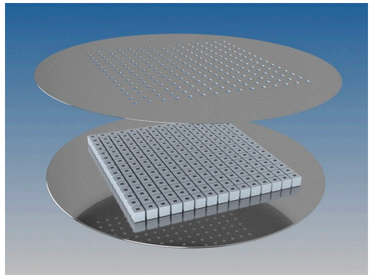
Precision 10%
Limited by statistics

PHASE 2 Experiments

Scale-up target mass

Improve background/threshold

NUCLEUS 1kg



>2024

Precision 2-3%
Limited by reactor systematics

PHASE 3 Ideas

Use radioactive neutrino sources at well-shielded sites
e.g. ^{51}Cr source arXiv:1905.10611

So What?

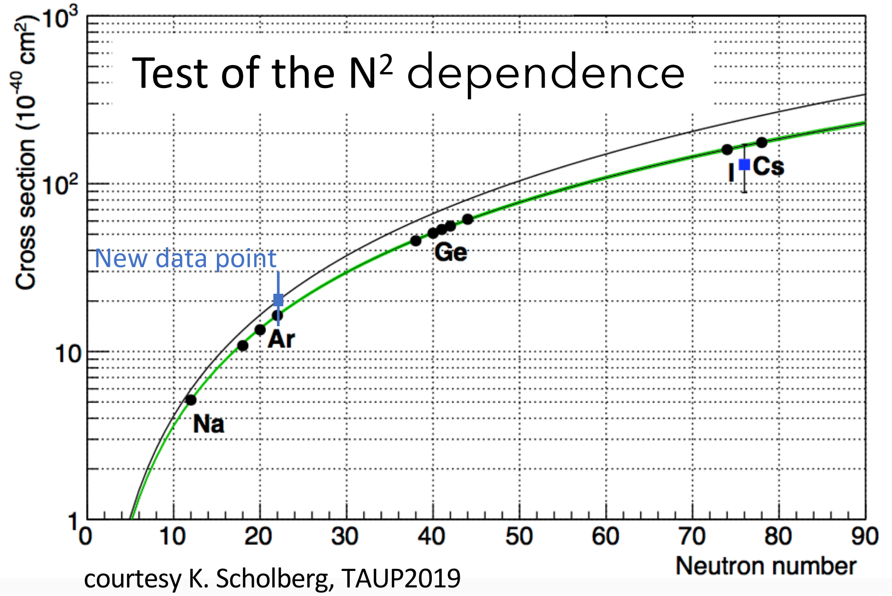
$$+\frac{1}{2} - 2\sin^2\theta_W$$

Weak vector nuclear Form factor (**=1** at reactors)

Standard model cross-section

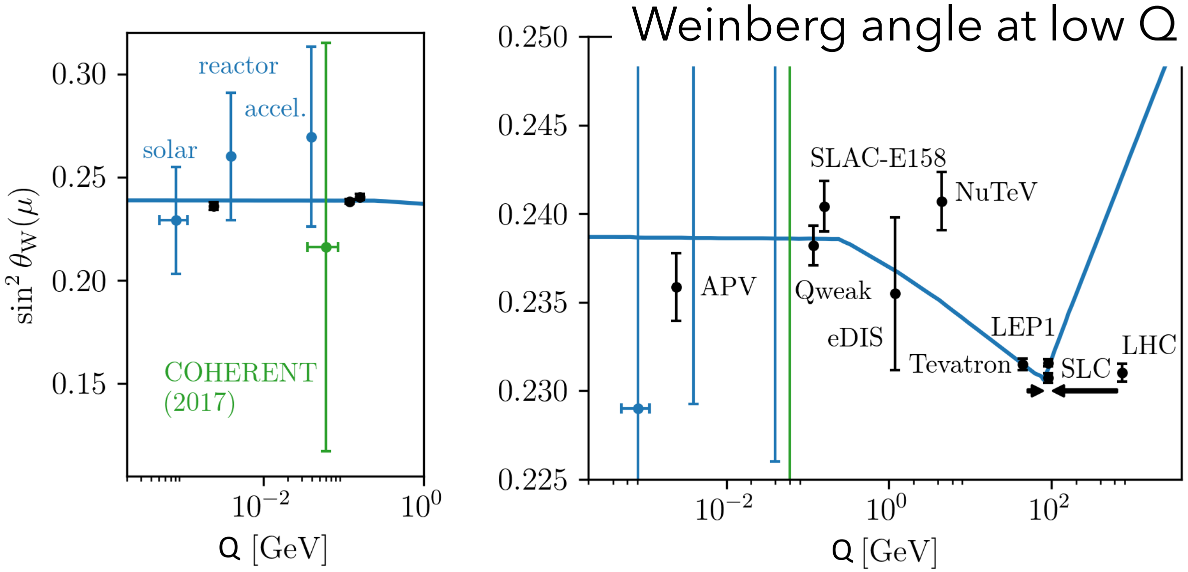
$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{G_F^2 M}{\pi} G_V^2 \left\{1 - \frac{MT}{2E_\nu^2}\right\} \quad \text{with} \quad G_V = \left[g_V^p \cdot Z + g_V^n \cdot N\right] \cdot F_V(Q^2)$$

Precision tests of the Standard Model



Test of the N² dependence

courtesy K. Scholberg, TAUP2019



Weinberg angle at low Q

courtesy J. Rothe, PhD 2020

So What?

BSM physics – **Light mediators**

Modifies SM cross-section:

$$\left(\frac{G_F}{(\hbar c)^2}\cdot\left[\bar{g}_V^p\cdot Z+\bar{g}_V^n\cdot N\right]\right)^2 \rightarrow \left(\frac{G_F}{(\hbar c)^2}\cdot\left[\bar{g}_V^p\cdot Z+\bar{g}_V^n\cdot N\right]-\frac{\hbar c}{\sqrt{2}}\cdot\frac{3A\cdot g_q g_\nu}{2Mc^2\cdot T+m_{Z'}^2 c^4}\right)^2$$

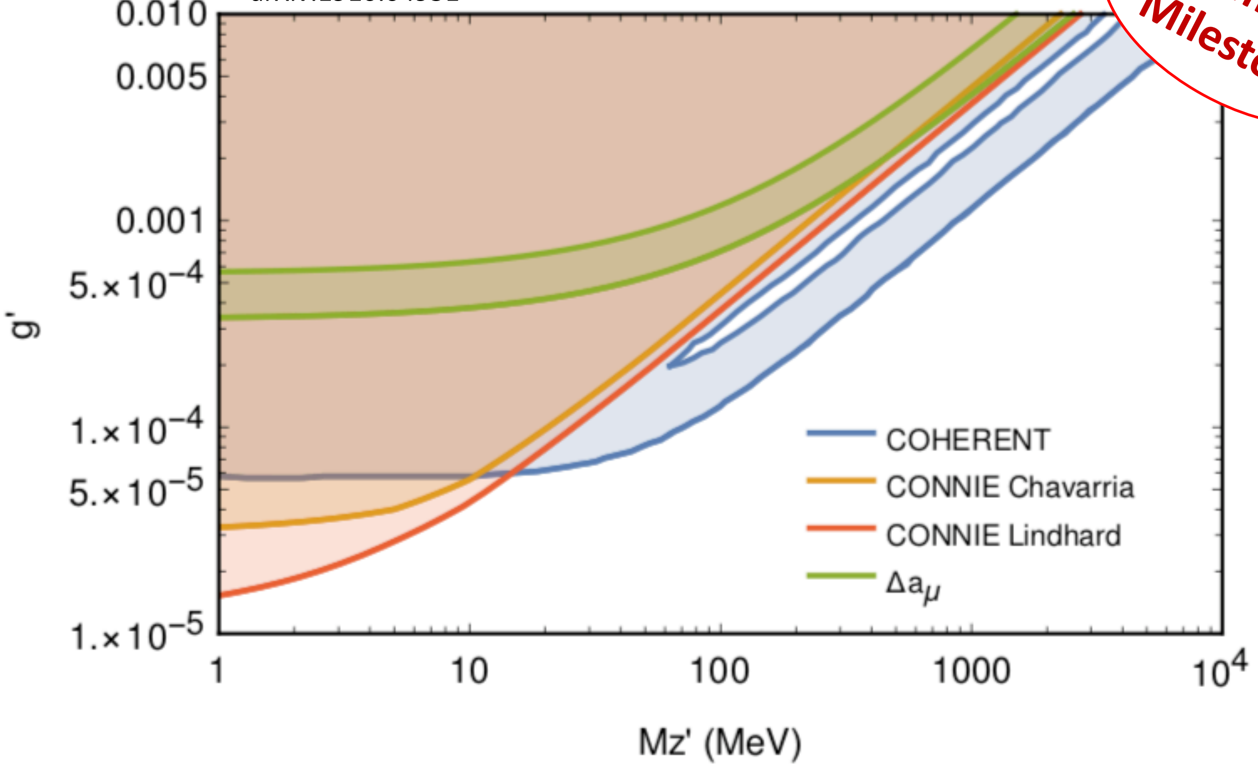
coupling

Mass of mediator

<u>Assumption:</u>
universal coupling of Z` to all neutrinos and quarks

Poster
NEUTRINO 2020
#289
B. Vergara

arXiv:1910.04951



Community Milestone

First competitive BSM constraint from CEvNS at reactors!

Despite background ~40 times above CEvNS signal.

So What?

BSM physics – **New heavy mediators**

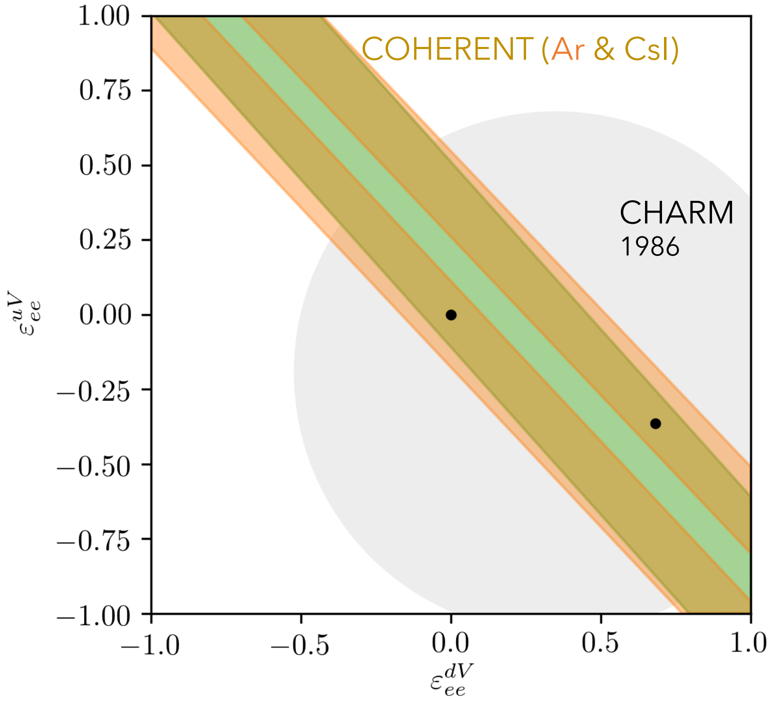
Standard parametrization of modified CNNS cross-section:

K.Scholberg, *Phys. Rev. D* **73**, 033005 (2006)

Additional neutrino-quark couplings

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1-\frac{ME}{2k^2}\right]\times$$

$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$



So What?

BSM physics – **New heavy mediators**

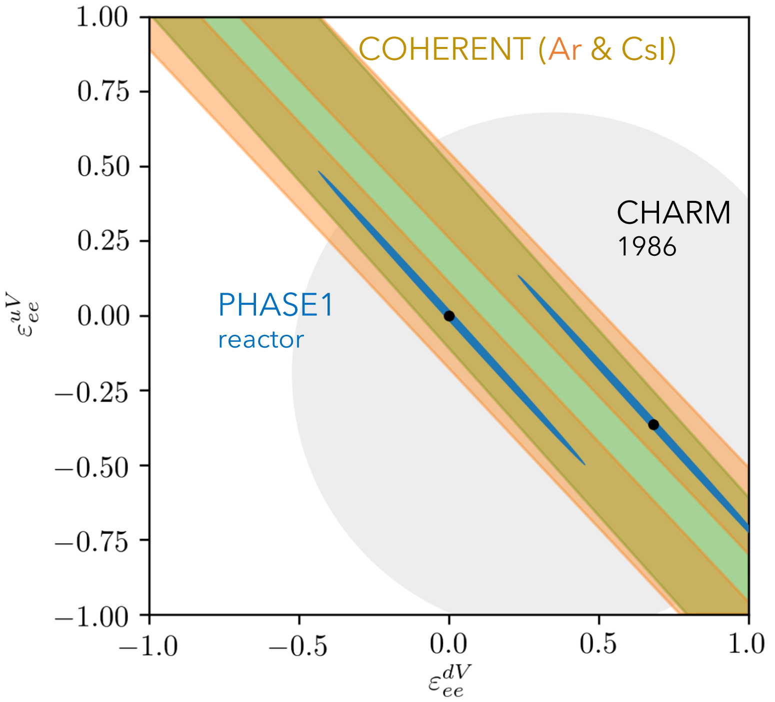
Standard parametrization of modified CNNS cross-section:

K.Scholberg, *Phys. Rev. D* **73**, 033005 (2006)

Additional neutrino-quark couplings

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$
$$\{[Z(g_V^p + \boxed{2\varepsilon_{\alpha\alpha}^{uV}} + \boxed{\varepsilon_{\alpha\alpha}^{dV}}) + N(g_V^n + \boxed{\varepsilon_{\alpha\alpha}^{uV}} + \boxed{2\varepsilon_{\alpha\alpha}^{dV}})]^2$$

Assumptions:
Target mass: 10g
Material: $CaWO_4$ + Al_2O_3
Measurement time: 1 year
Precision on σ_{7s}: 10%



Break degeneracy + constrain parameter space with multi-target, precision experiments at reactors!

So, what more?

More fundamental neutrino physics

- Neutrino magnetic dipole moment
- Neutrino charge radii
- Sterile neutrinos

Reactor physics

Reactor monitoring for Society

- Reactor-power monitoring
- Non-proliferation of weapon-grade material

New generation IBD experiments

- Breeding of plutonium

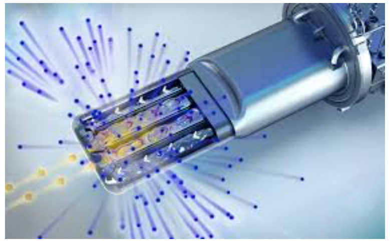
M. Bowen, P. Huber, arXiv:2005.10907

→ Next-generation CEvNS experiments

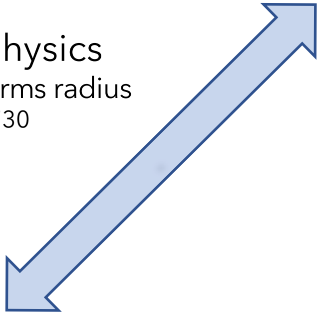
Poster NEUTRINO 2020
#477 C. Awe

TALK NEUTRINO 2020
Th25 10:30 A. Tomi

Complementarity



CEvNS at Stopped-pion-source
- Slightly in-coherent
- Medium neutrino energies



Nuclear physics

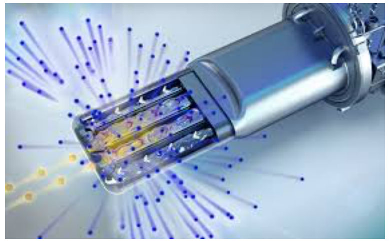
e.g. neutron rms radius

arXiv:1710.02730

CEvNS at reactors
- Fully coherent
- Low neutrino energies

Complementarity

Poster NEUTRINO 2020
#75 V. Pandey



CEvNS at Stopped-pion-source

- Slightly in-coherent
- Medium neutrino energies

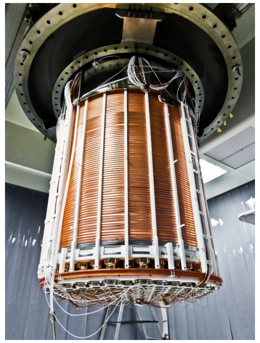
Nuclear physics
e.g. neutron rms radius
arXiv:1710.02730

CEvNS cross section
Form factors

CEvNS at reactors

- Fully coherent
- Low neutrino energies

CEvNS cross section



Supernova neutrinos

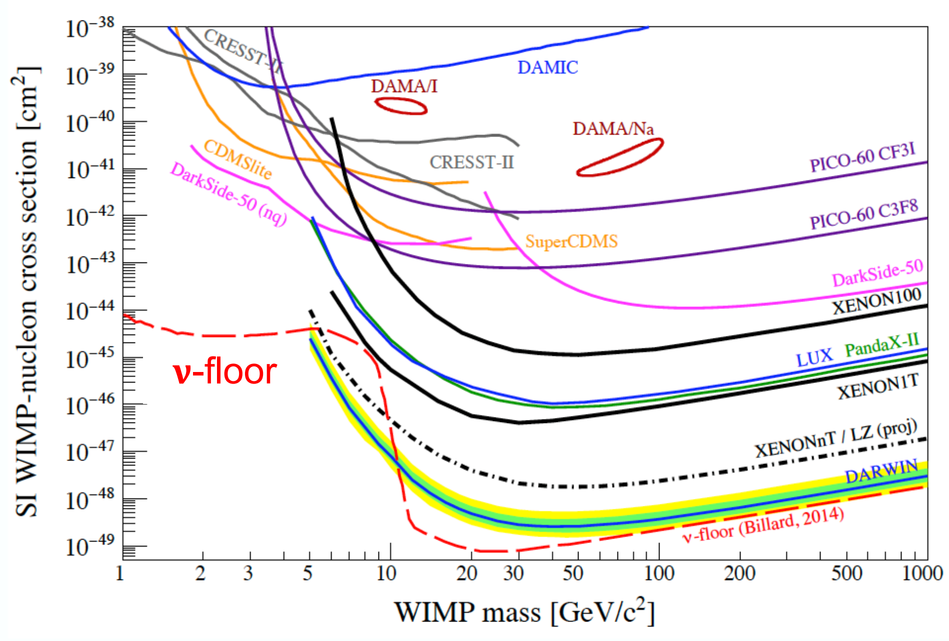
Solar neutrinos

CEvNS in Direct Dark Matter Searches

- Deep underground
- Multi-ton scale

Natural Sources

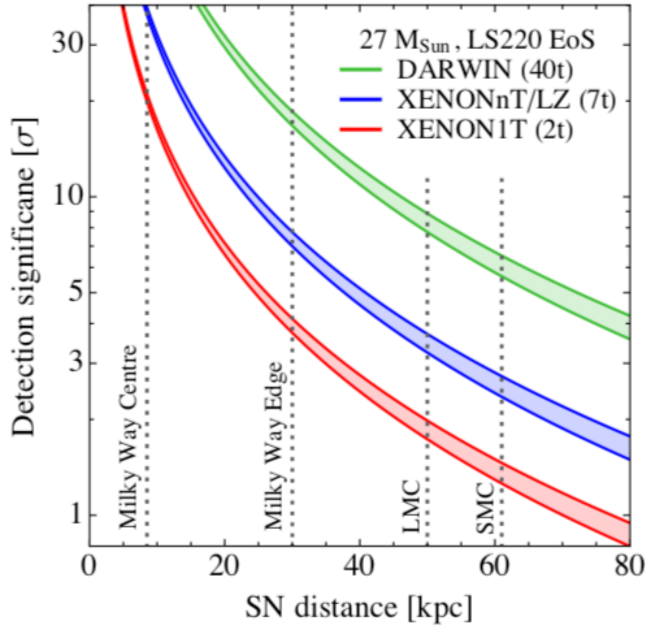
Solar neutrinos



- XENON, LZ close to observation of ^{8}B neutrinos from the Sun
- Sensitivity to Solar physics, metallicity problem etc.
- Continue searches for Dark Matter beyond the neutrino floor?
- Low-mass DM searches (CRESST, NEWS-G, CDMS…): measure pp flux ?

Supernova neutrinos

arXiv:1606.09243



- Flavour-insensitive probe of neutrinos from core-collapse supernovae
- **XENONnT, LZ** on path arXiv:1606.09243
- Interesting new experimental ideas **RES-NOVA** arXiv:2004.06936

Future Uses of CEvNS

- **CEvNS**: Blooming and very active field!
- Huge **complementarity** between COHERENT and reactor-based experiments
- **Phase 1** Experiments – NOW!
    - ✓ Demonstrate detector technology
    - ✓ Observe CEvNS at reactors
    - ✓ Competitive SM and BSM physics results
- **Phase 2** Experiments ~ 2024 -
    - ✓ Precision physics
    - ✓ Exploit full CEvNS physics potential
- **Large-Scale** Dark Matter Searches
    - ✓ Reach “neutrino floor” soon
    - ✓ Solar and supernova physics

Workshop announcement:

THE MAGNIFICENT CEvNS

VIRTUAL
NOV 16-20, 2020

MUNICH
OCT 5-7, 2021