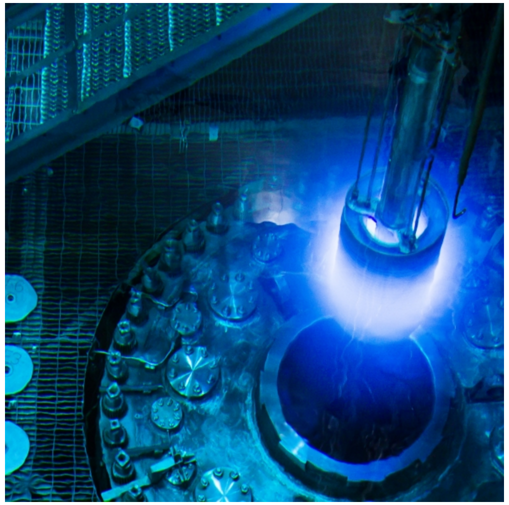


Dark matter, neutrinos & nukes

based on arXiv:2104.13926

Quantum Universe Video Colloquium

09-28-2021, DESY and University of Hamburg

B. Cogswell, A. Goel, P. Huber

Center for Neutrino Physics at Virginia Tech

VIRGINIA TECH

U.S. DEPARTMENT OF ENERGY | Office of Science

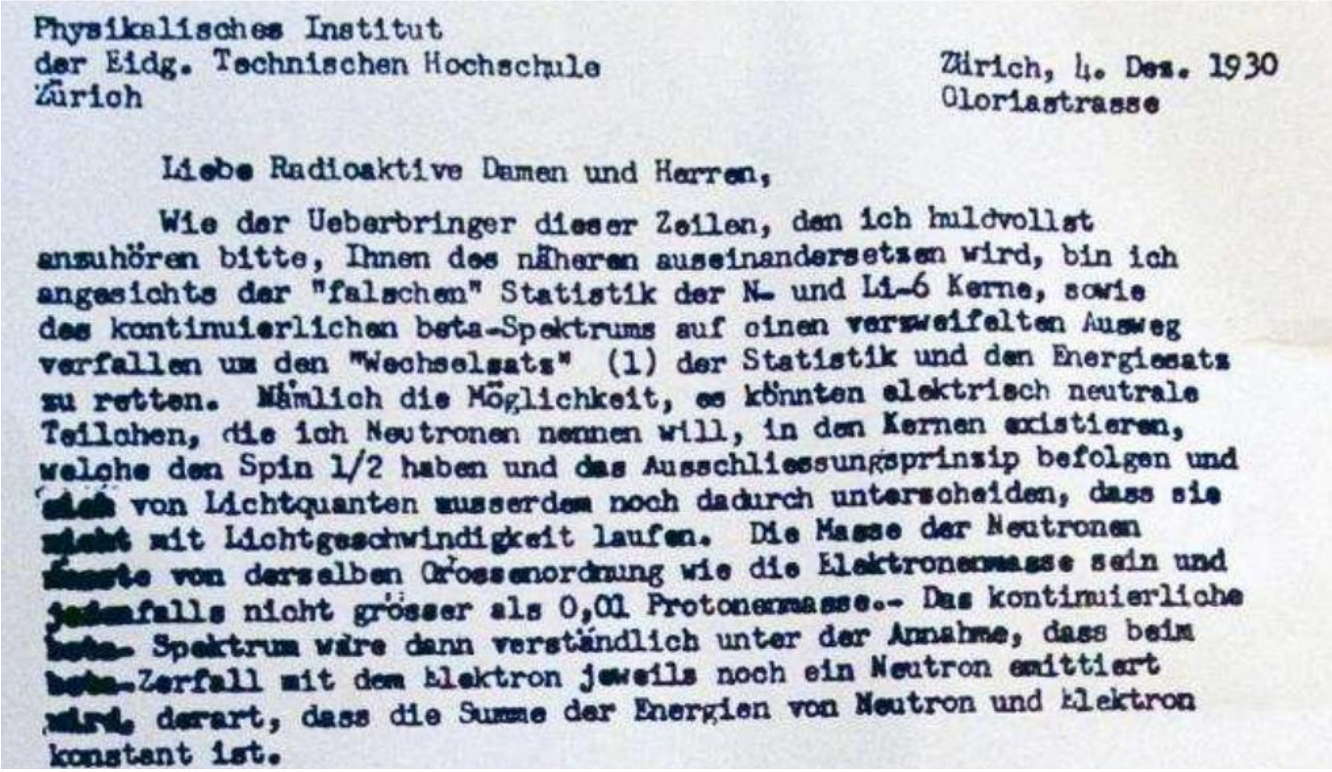
NNSA National Nuclear Security Administration

NSF

Consortium for Monitoring Technology and Verification

Early history of the neutrino

- Neutrino postulated in Pauli's famous letter in 1930
- Fermi theory of beta decay in 1933
- Bethe and Peierls estimate detection cross section in 1934 to be $E_\nu^2\, 10^{-43}\,\mathrm{cm}^2$
- and conclude that the neutrino is practically invisible



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

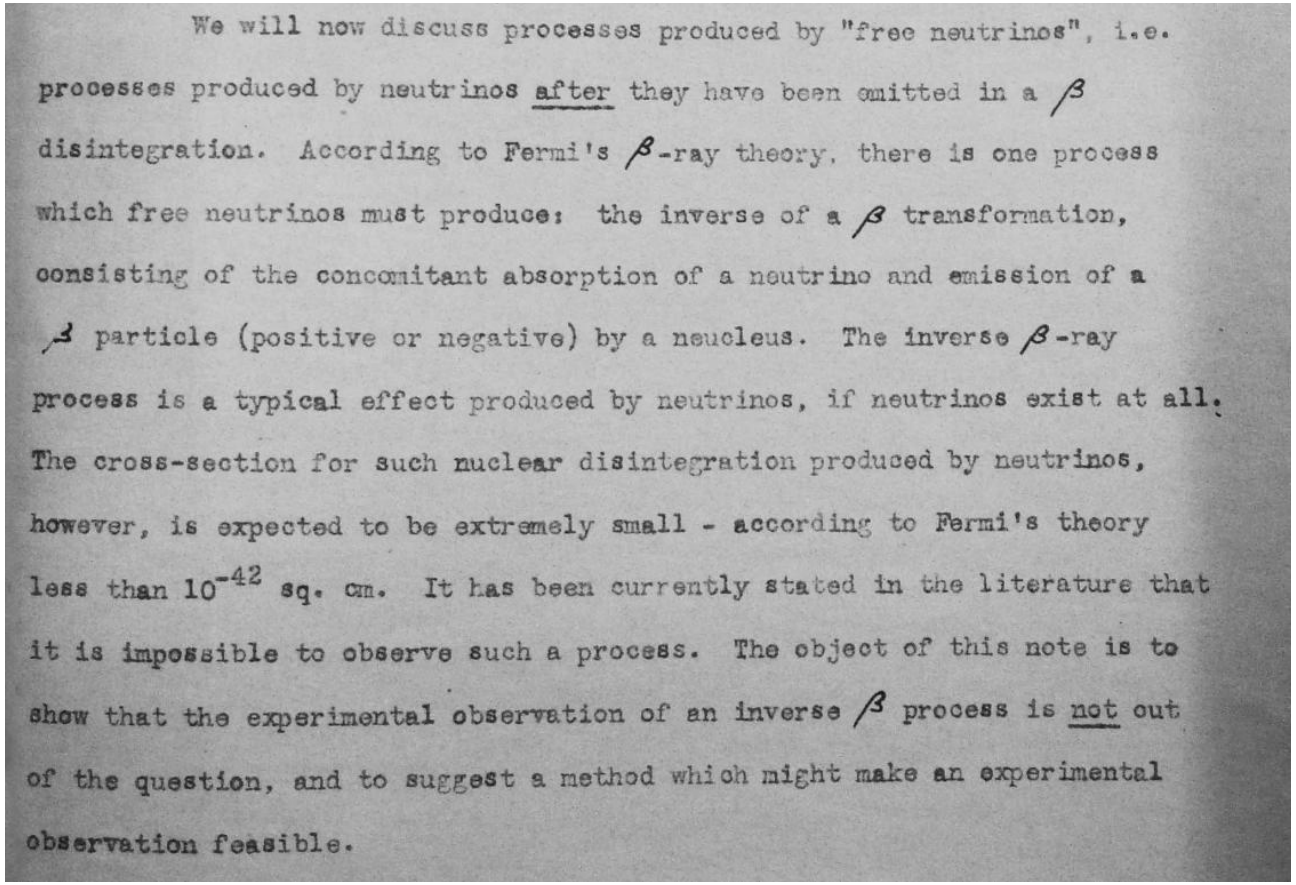
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen dürfte von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

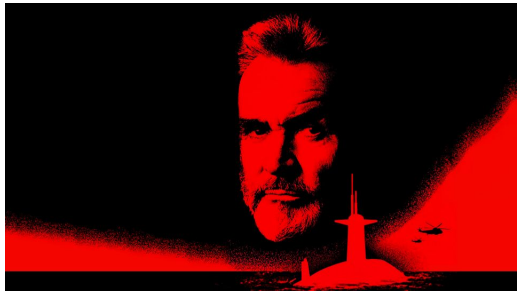
Early history of neutrino detection

Report PD-141, National Research Council of Canada, Division of Atomic Energy, Chalk River



We will now discuss processes produced by "free neutrinos", i.e. processes produced by neutrinos <u>after</u> they have been emitted in a β disintegration. According to Fermi's β-ray theory, there is one process which free neutrinos must produce: the inverse of a β transformation, consisting of the concomitant absorption of a neutrino and emission of a β particle (positive or negative) by a neucleus. The inverse β-ray process is a typical effect produced by neutrinos, if neutrinos exist at all. The cross-section for such nuclear disintegration produced by neutrinos, however, is expected to be extremely small - according to Fermi's theory less than 10^{-42} sq. cm. It has been currently stated in the literature that it is impossible to observe such a process. The object of this note is to show that the experimental observation of an inverse β process is <u>not</u> out of the question, and to suggest a method which might make an experimental observation feasible.

- 1945 Pontecorvo proposes radiochemical detection
- Promptly classified by the Atomic Energy Commission
- Because of the potential for detection of nuclear submarines!



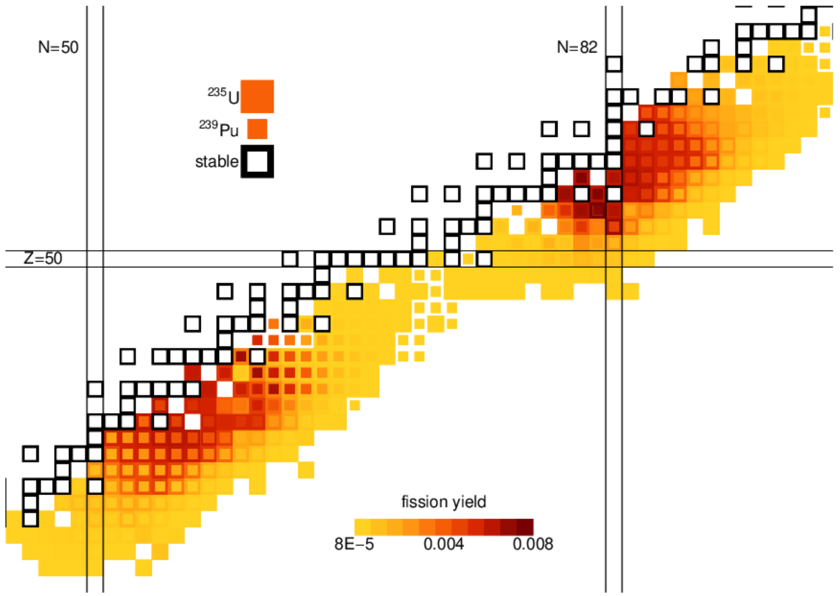
Cl-37+neutrino → Ar-37+electron

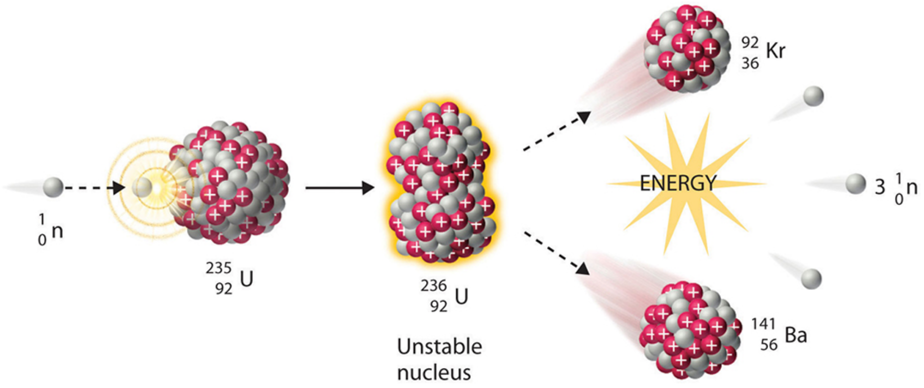
How to beat 10^{-42}cm^2.

Can get 10^{24} from Avogadro's number...

Where to get 10^{18} neutrinos?

Need 10^{18} beta decays...



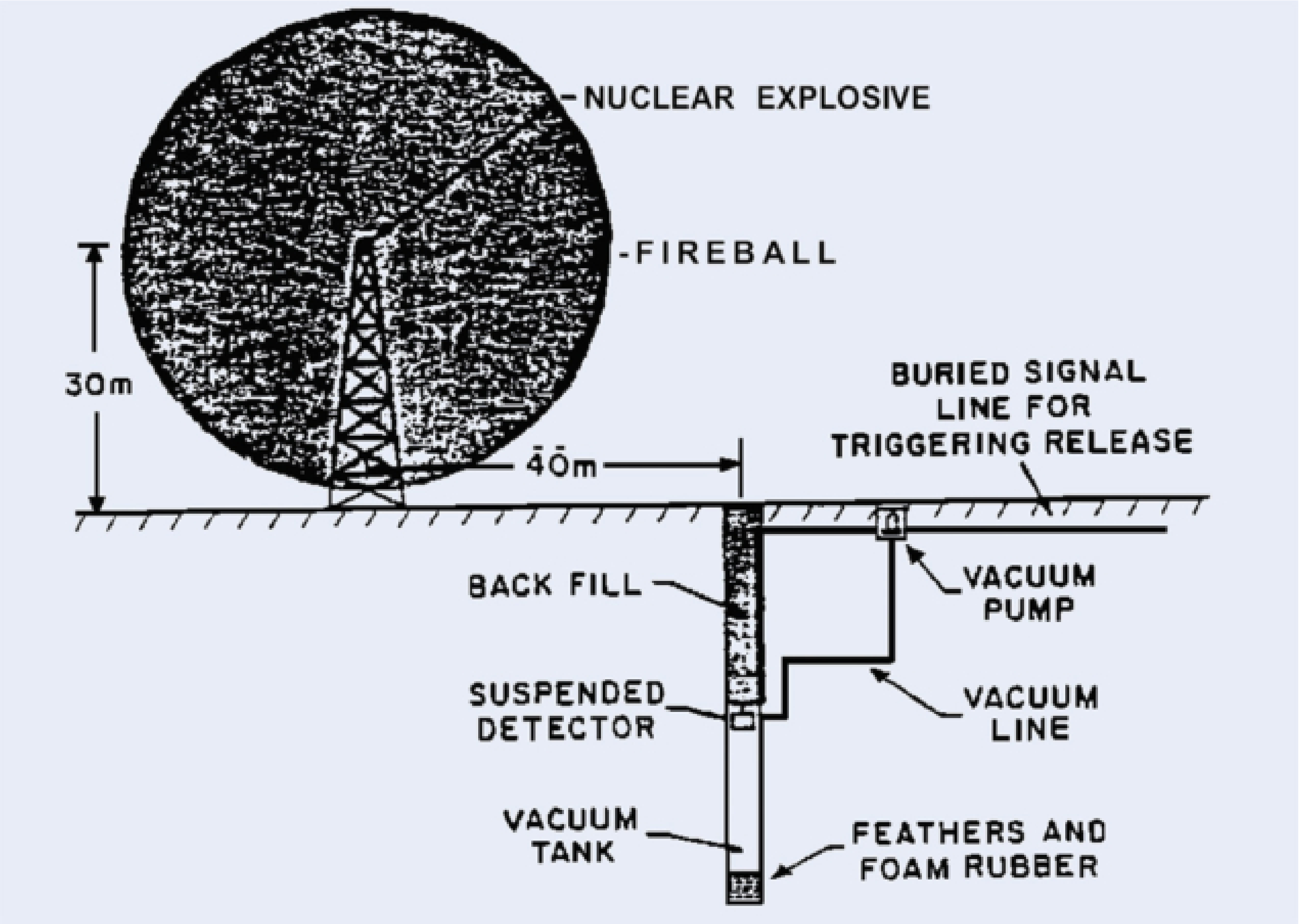


On average 6 neutrinos per fission or 10^{24} neutrinos from fissioning 1 kilogram of U-235

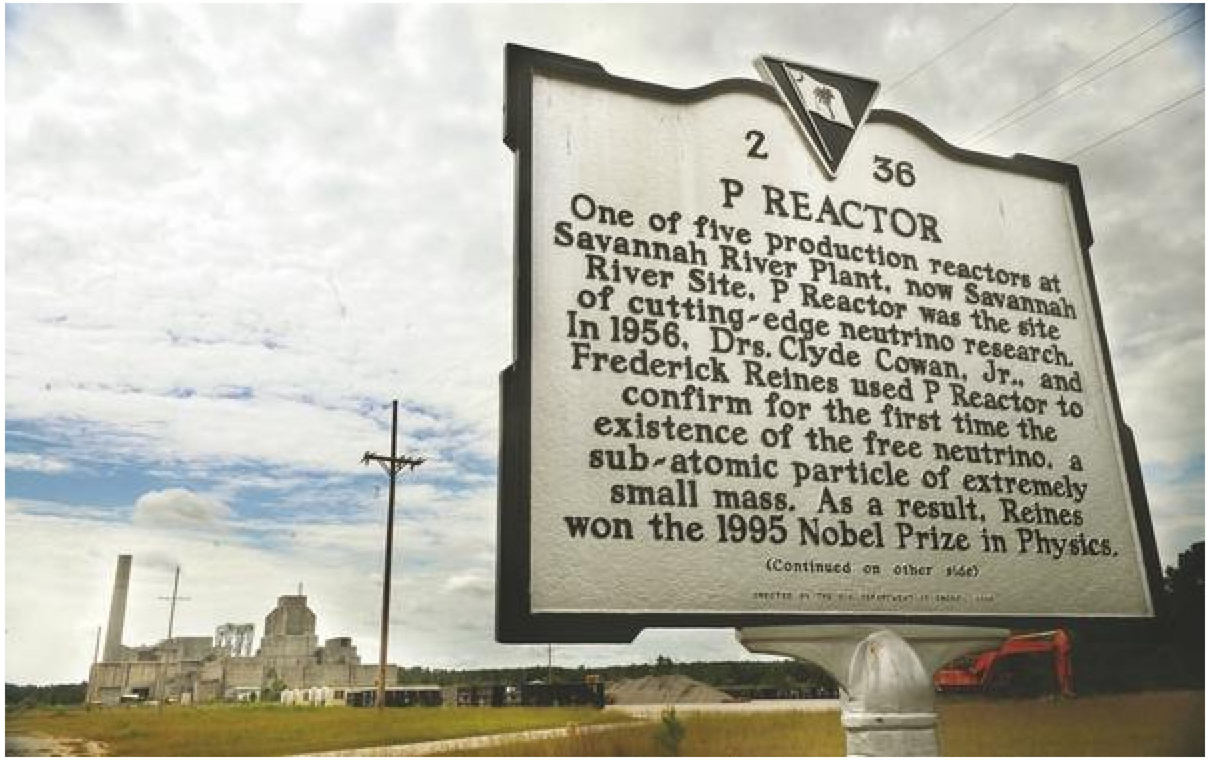
How neutrinos might be discovered

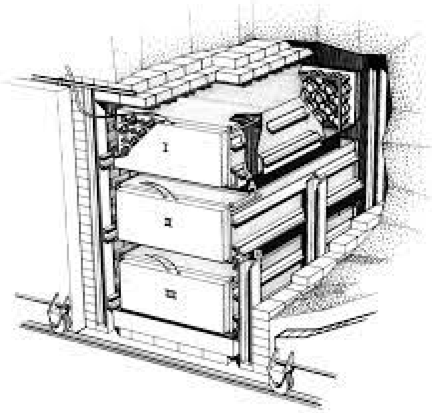
Cowan and Reines proposed this and got approved!

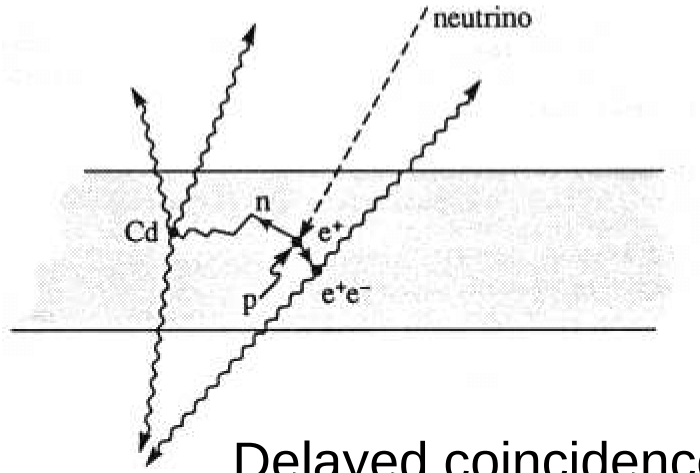
Their day job was to instrument atmospheric nuclear tests.



How neutrinos were really discovered







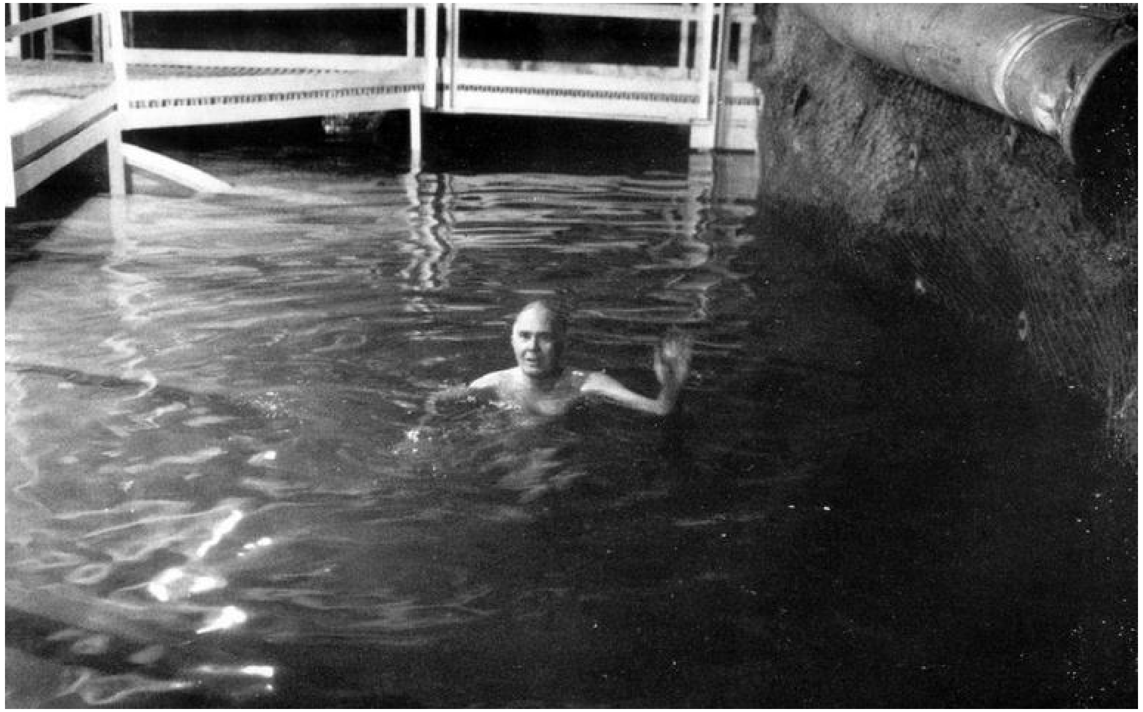
1956

Delayed coincidence allowed them to use a reactor, instead

All reactor neutrinos to date have been detected based on the same principles.

On to solar neutrinos…

- Helicity allows the Cl-37 reaction only for left-handed states, i.e. can not happen at reactors.
- Sun is a neutrino source
- In the 1960s Ray Davis built a solar neutrino experiment at Homestake using Pontecorvo's Cl-37 reaction



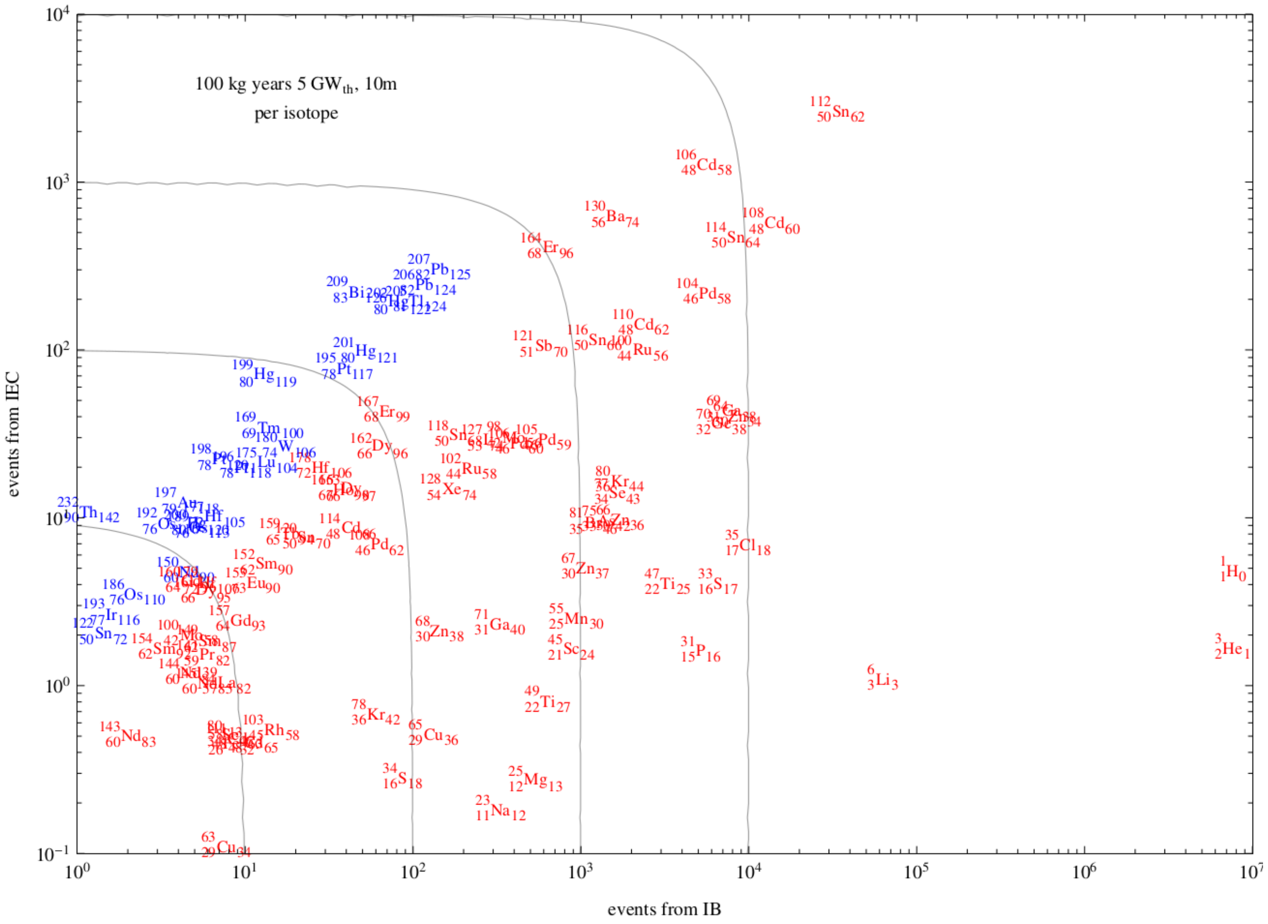
Individual Ar-37 atoms are detected by their decay back into Cl-37.
The half-life is around 30 days, this is a crucial requirement!

Passive detection of reactor neutrinos?

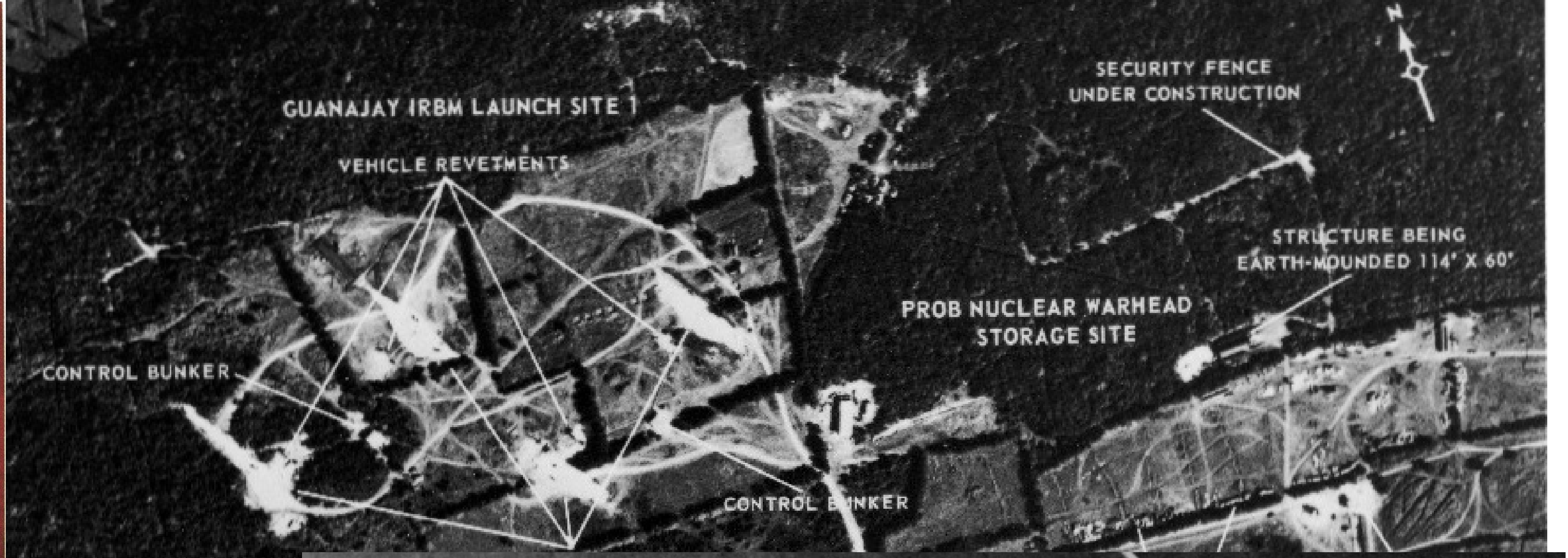
- Need inverse beta decay
- Need small Q-value and large matrix element (small log ft)
- Half-life needs to be more than weeks but less than years
- Looking through the whole chart of isotopes:

$$^3He + \bar{\nu}_e \rightarrow ^3H + e^+$$

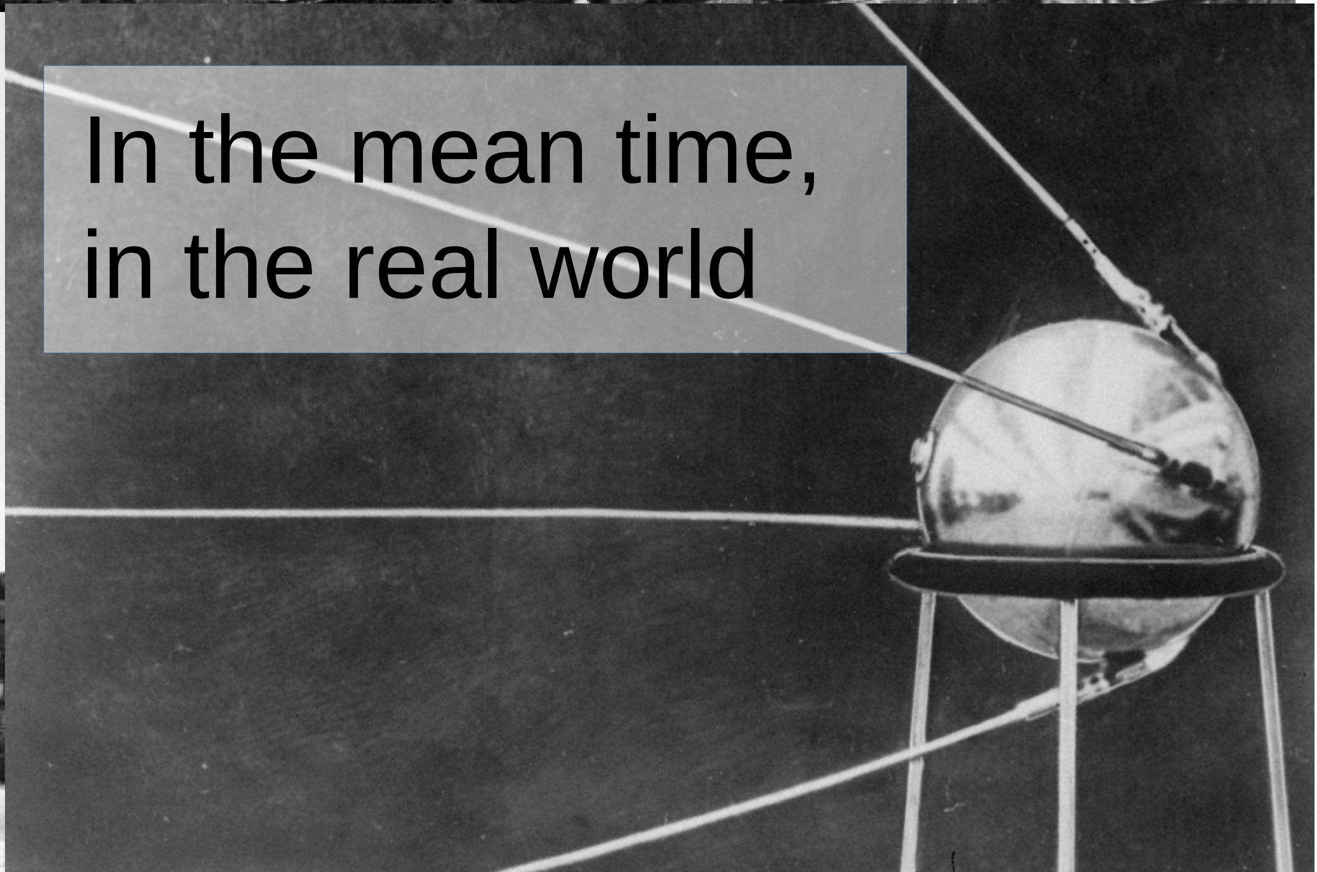
- But: 12.3 years half-life
- He-3 is really rare and expensive

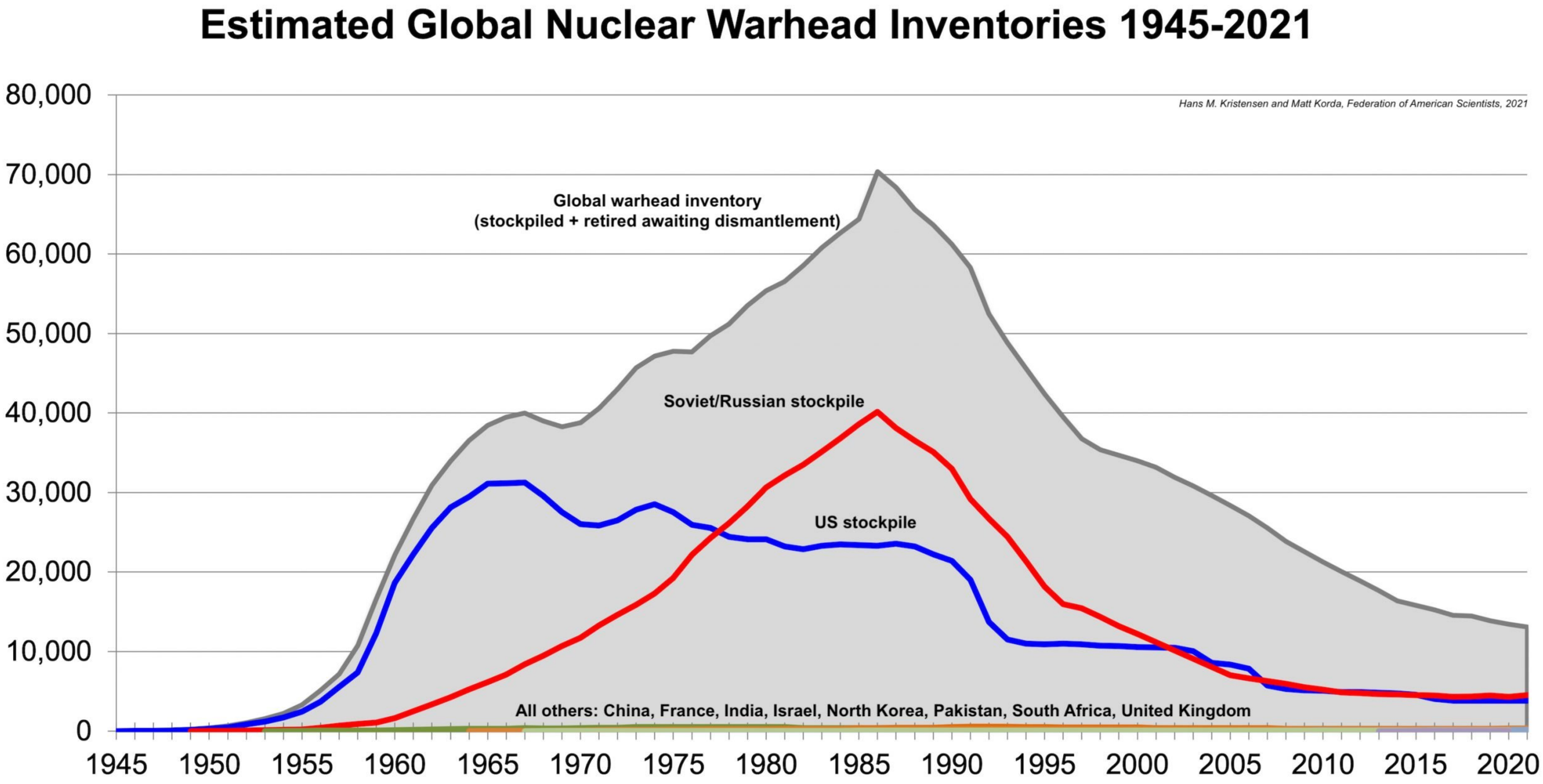


Charged current reaction will not work!



In the mean time, in the real world





Estimated Global Nuclear Warhead Inventories 1945-2021
Hans M. Kristensen and Matt Korda, Federation of American Scientists, 2021
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Global warhead inventory
(stockpiled + retired awaiting dismantlement)
Soviet/Russian stockpile
US stockpile
All others: China, France, India, Israel, North Korea, Pakistan, South Africa, United Kingdom
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020

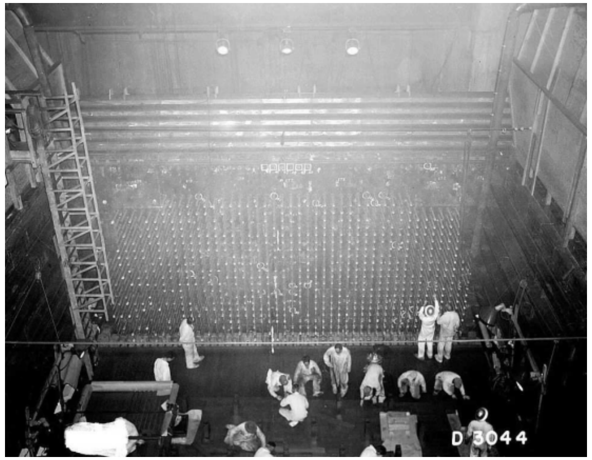
How to control nuclear weapons

- Only very few isotopes can maintain a fast neutron chain reaction

Isotope	235U	233U	239Pu
Half-life	700 Million years	160,000 years	24,000 years
Natural abundance	0.72%	0%	0%
Bare critical mass	52kg	15kg	10kg

Only U-235 occurs naturally and needs to be enriched

U-233 and Pu-239 need to made in a nuclear reactor



NUCLEAR NONPROLIFERATION TREATY (NPT)

Bans the acquisition of nuclear weapons by non-weapon states, including the transfer of knowledge; commits weapon states to disarm; verified by IAEA safeguards

1970s

COMPREHENSIVE TEST BAN TREATY (CTBT)

Bans all nuclear explosions in all environments; verified by IMS and CTBTO; not yet entered into force, some states like the U.S. have not yet ratified it

1990s

PLUTONIUM MANAGEMENT AND DISPOSITION AGREEMENT (PMDA)

Both Russia and the U.S. commit to dispose of 34 MT each of weapons-usable Pu-239 declared excess to their military needs; currently suspended

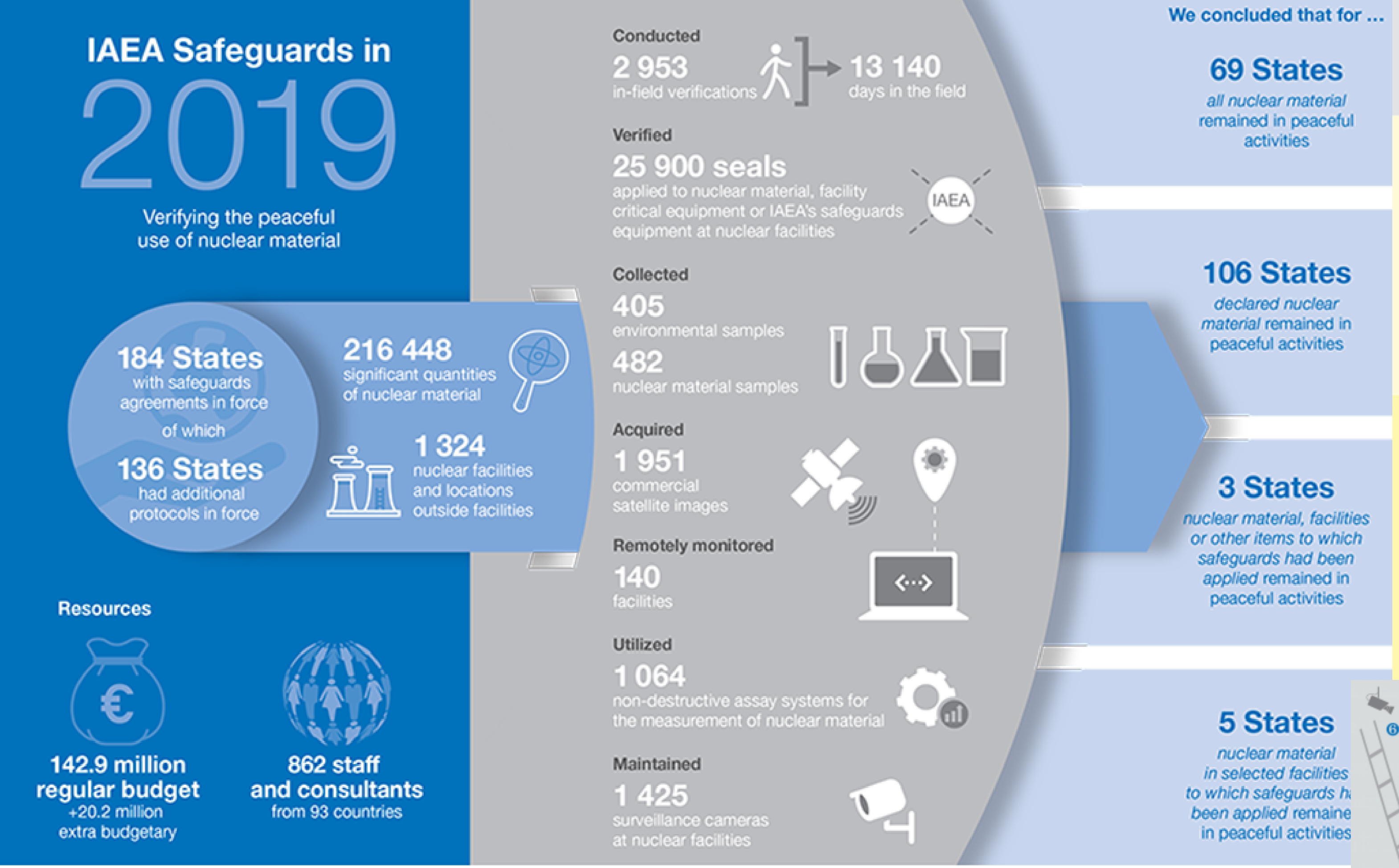
2010s

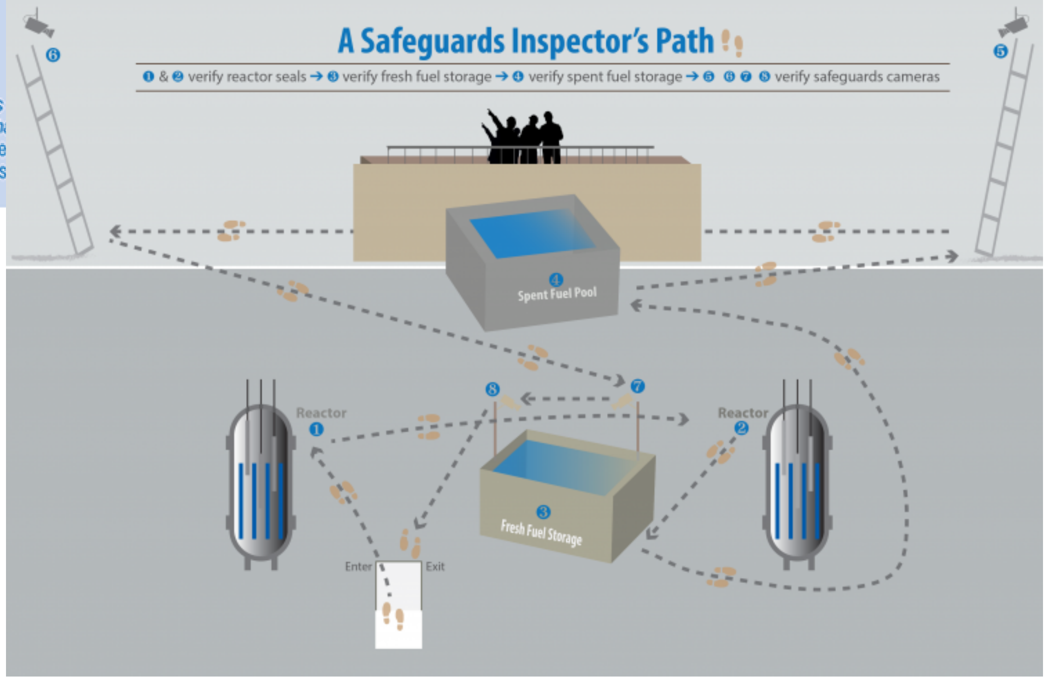
TREATY ON THE PROHIBITION OF NUCLEAR WEAPONS (TPNW)

Prohibits development, testing, production, stockpiling, transfer, use, and threat of use of nuclear weapons

2021

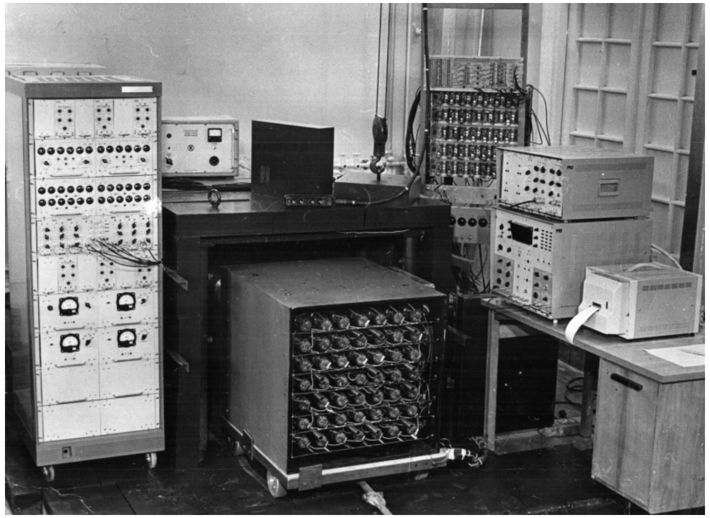
Slide courtesy B. K. Cogswell

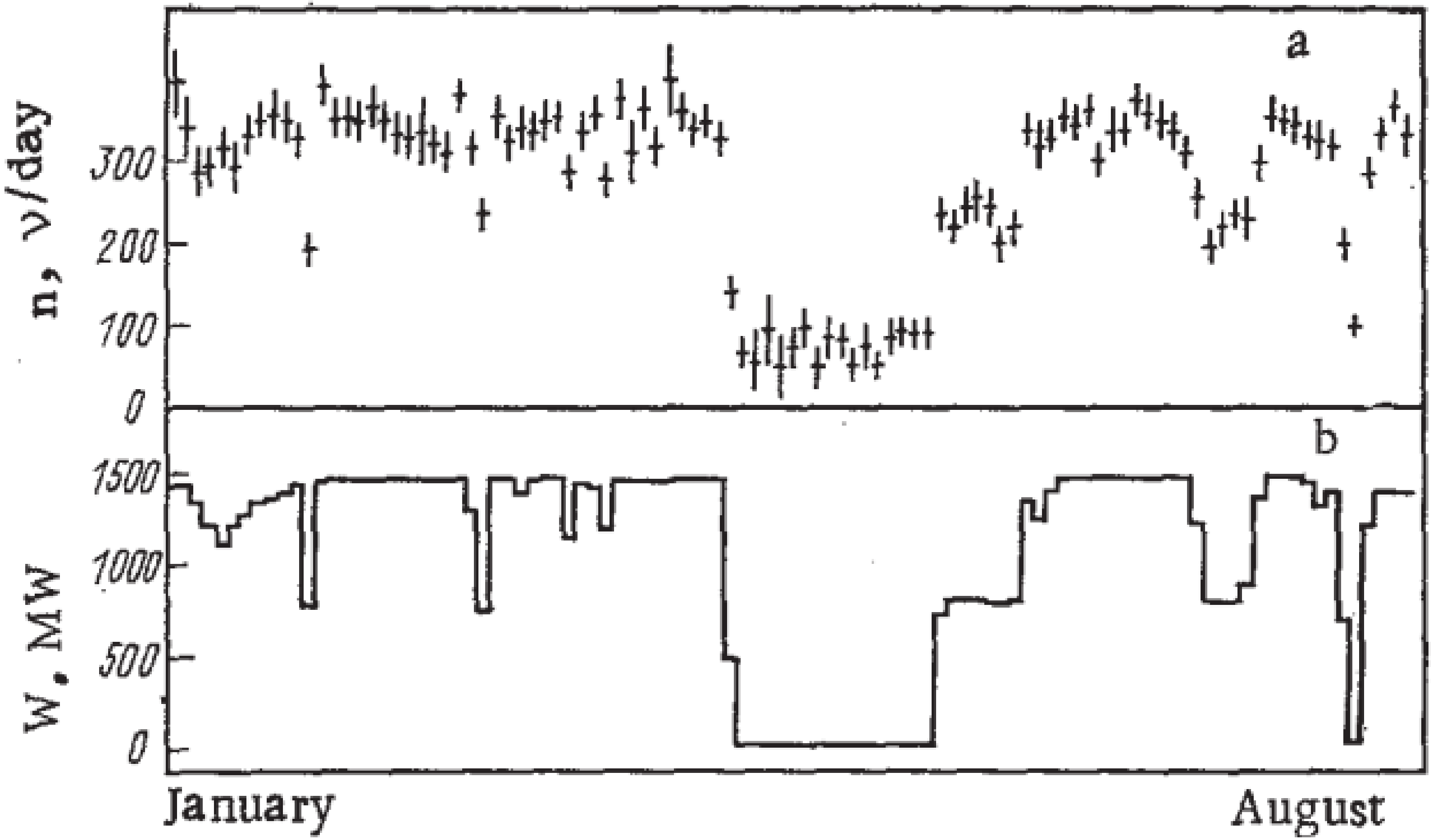




Limited time
Limited budget

Neutrino reactor monitoring





Korovkin *et al.* Atomic Energy 76 (1994) 123–127.

First proposed by Borovoi & Mikaelyan in 1978
Soviet Atomic Energy 44 (6), 589–592.

Proof of concept at the Rovno power plant in the 1980s
Based on inverse beta decay, long line of detectors: SONGS, Nucifer, PANDA, VIDARR, CHANDLER, iDREAM, IMRAN, ...

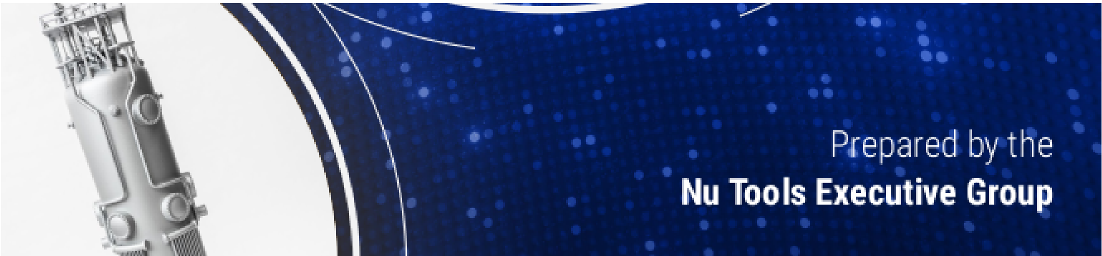
Uses of Neutrinos

Chartered in 2019 by the Office for Defense Nuclear Non-proliferation within the US DOE NNSA

The charge was to engage end-users and to explore via this engagement what area are plausible use cases for neutrinos. Two areas were identified as particular strong cases:

Advanced Reactors: Advanced reactors present novel safeguards challenges which represent possible use cases for neutrino monitoring.

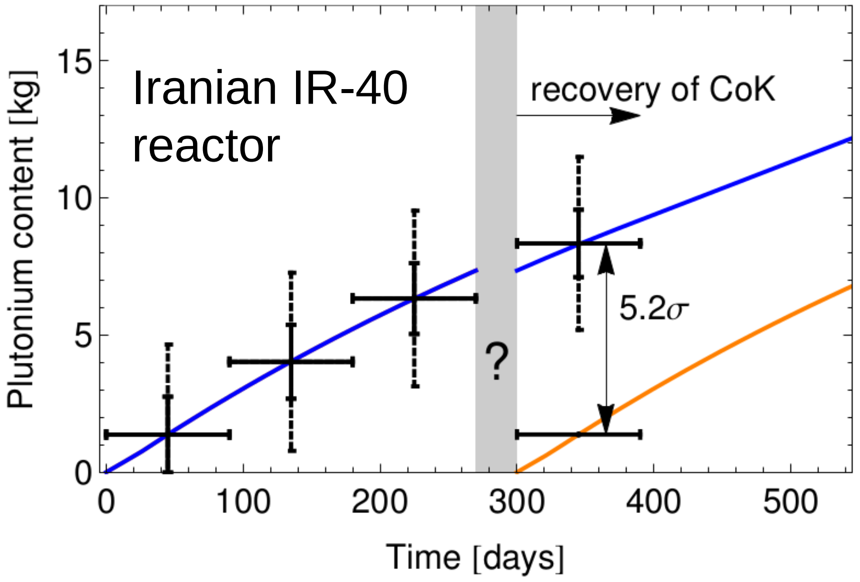
Future Nuclear Deals: There is interest in the policy community in neutrino detection as a possible element of future nuclear deals involving cooperative reactor monitoring or verifying the absence of reactor operations.



Full report at https://nutools.ornl.gov

Neutrino detectors as of today

Christensen, PH, Jaffke, Shea,
Phys. Rev. Lett. 113 (2014) 042503.



In 2018 finally neutrino detectors could function **at the surface** and actually would be able to do the above

PROSPECT
liquid scintillator
can and does leak

CHANDLER, solid scintillator,

Million dollar, ton-scale devices – not a great fit for the IAEA

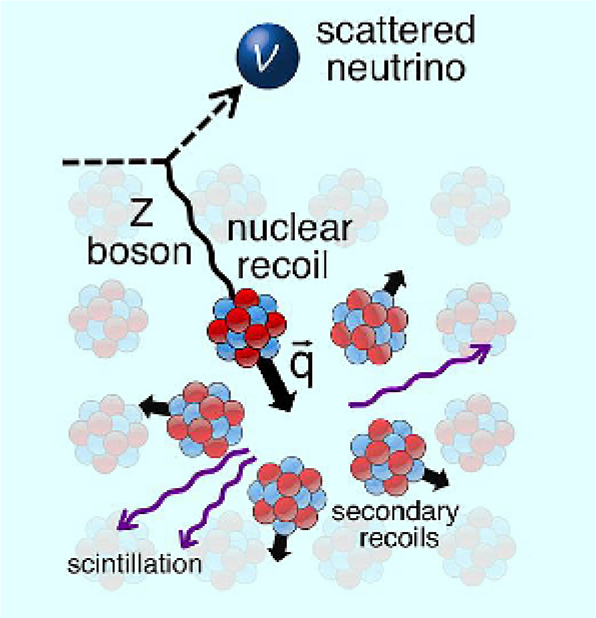
CEvNS

Coherent Elastic Neutrino Nucleon Scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} N^2 M_N \left(1 - \frac{M_N T}{2E_\nu^2}\right)$$

T recoil energy, N neutron number

Large cross section but only at very low recoil energy



First observed by the COHERENT collaboration in 2017 at the SNS at ORNL

Detection at reactors still outstanding

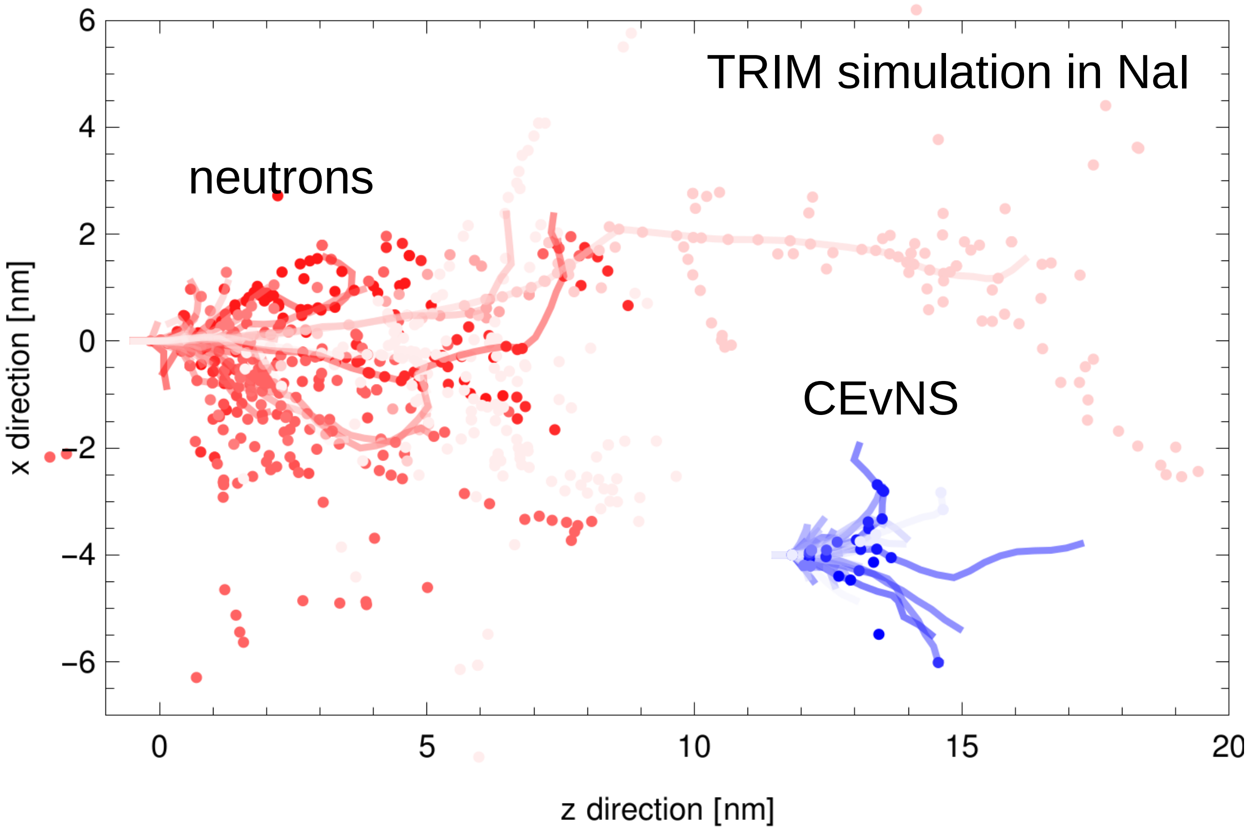
Threshold in eV for parity in event rate per unit mass with IBD

^{12}C	^{20}Ne	^{28}Si	^{40}Ar	^{74}Ge	^{127}I	^{132}Xe	^{133}Cs
790	770	702	672	491	353	347	343

Bowen, PH, Phys. Rev. D 102 (2020) 053008.

The concept

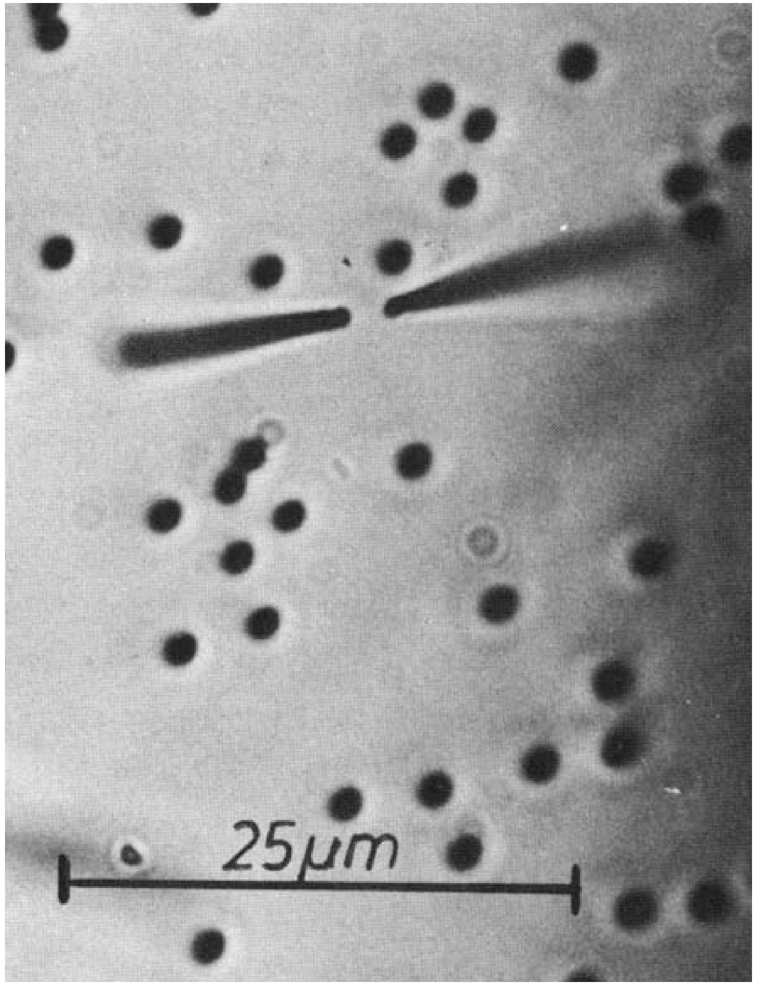
- Nuclear recoils damage crystal lattice permanently, either by forming tracks or vacancies
- This allows off-site readout, hence detector is passive
- Intrinsic rejection of ionizing backgrounds, leaves only neutrons
- This has been explored for dark matter detection but not for reactor neutrinos



Essig, Marden, Slone, Volansky Phys.Rev.D 95 (2017) 5, 056011.
Rajendran *et al*., Phys.Rev.D 96 (2017) 3, 035009.
Budnik, Chesnovsky, Slone, Volansky, Phys.Lett.B 782 (2018) 242-250.
Baum, Drukier *et al.,* Phys.Lett.B 803 (2020) 135325, Phys.Rev.D 99 (2019) 4, 043014, Phys.Rev.D 99 (2019) 4, 043541

Solid state nuclear track detectors

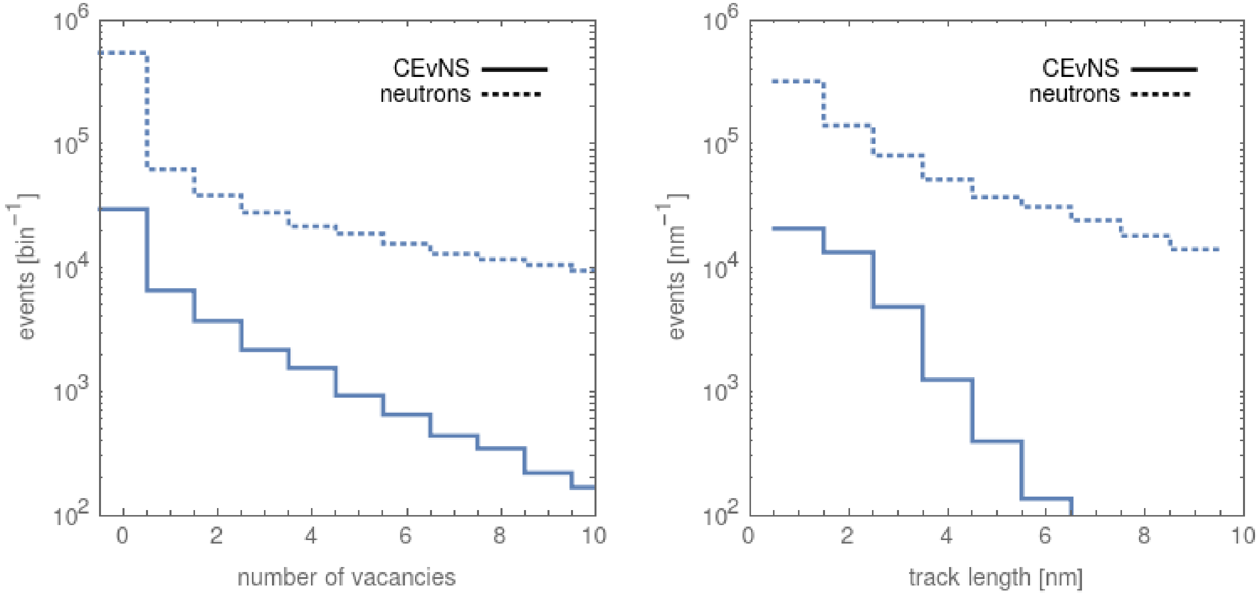
- Crystal damage tracks from multi-MeV events
- Made visible by etching
- Mica and special plastics
- Has been used to put limits on magnetic monopoles using ancient mica Price, Phys. Rev. Lett. 56 (1986) 1226-1229.



Vater, *et al.*, NIM 174 (1977) 271-278

Tracks vs vacancies

- Damage tracks result from distortion of crystal lattice in response to ionization
- Vacancies are point defects in the lattice
- Both are persistent at room temperature in many materials

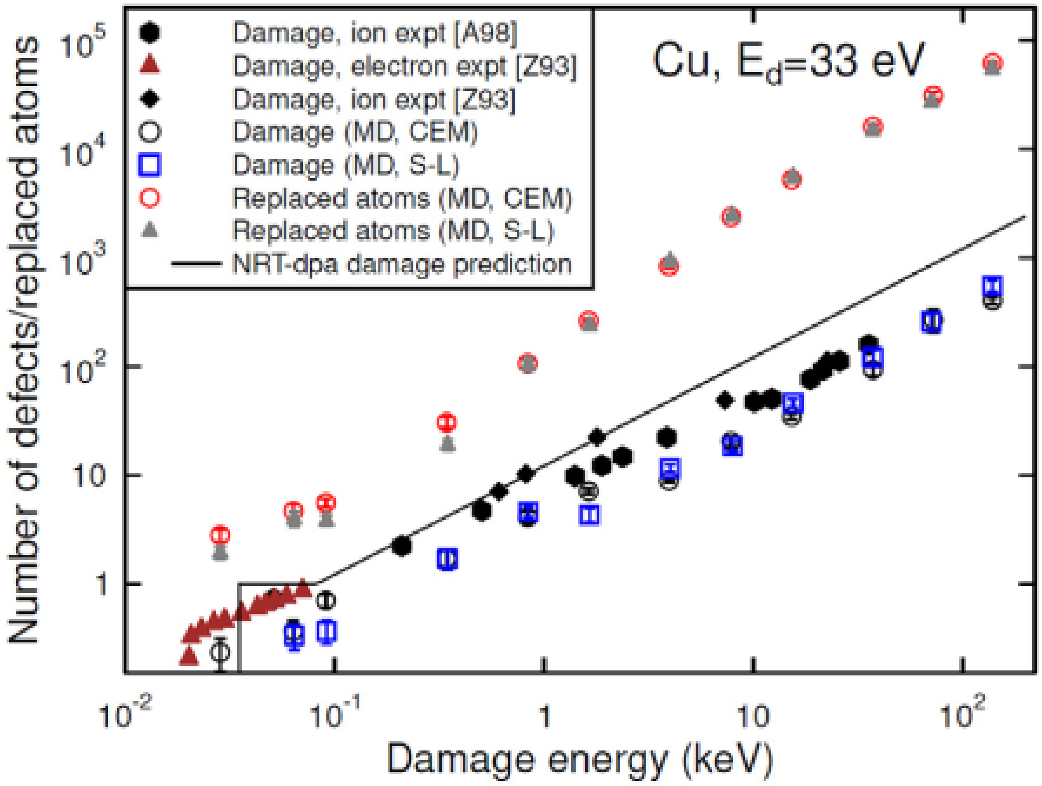


Example:
100g NaI 20m from a 3GWth reactor, 90 days
Sea level cosmogenic neutron flux
Simulation with TRIM

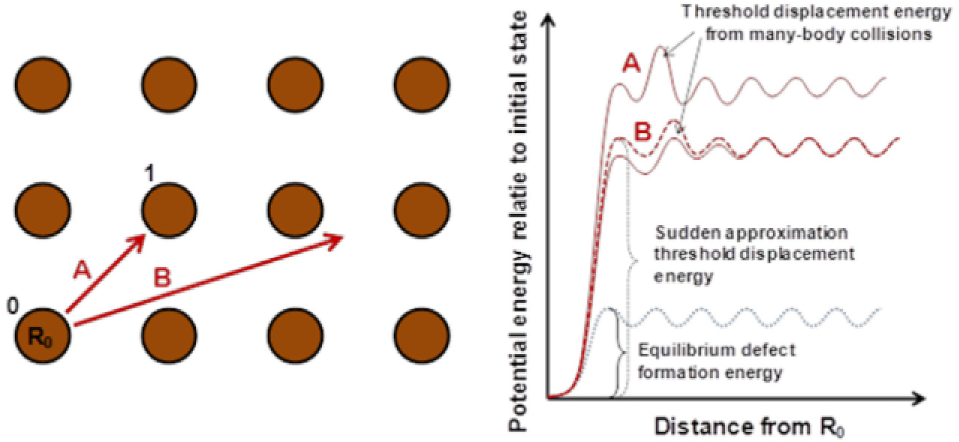
Vacancy formation

- Need big enough separation to prevent recombination
- Main mechanism for radiation damage in e.g. reactor vessels
- We use the TRIM package in full cascade mode

Ziegler, Ziegler, Biersack, NIM B 268 (2010) 1818-23.

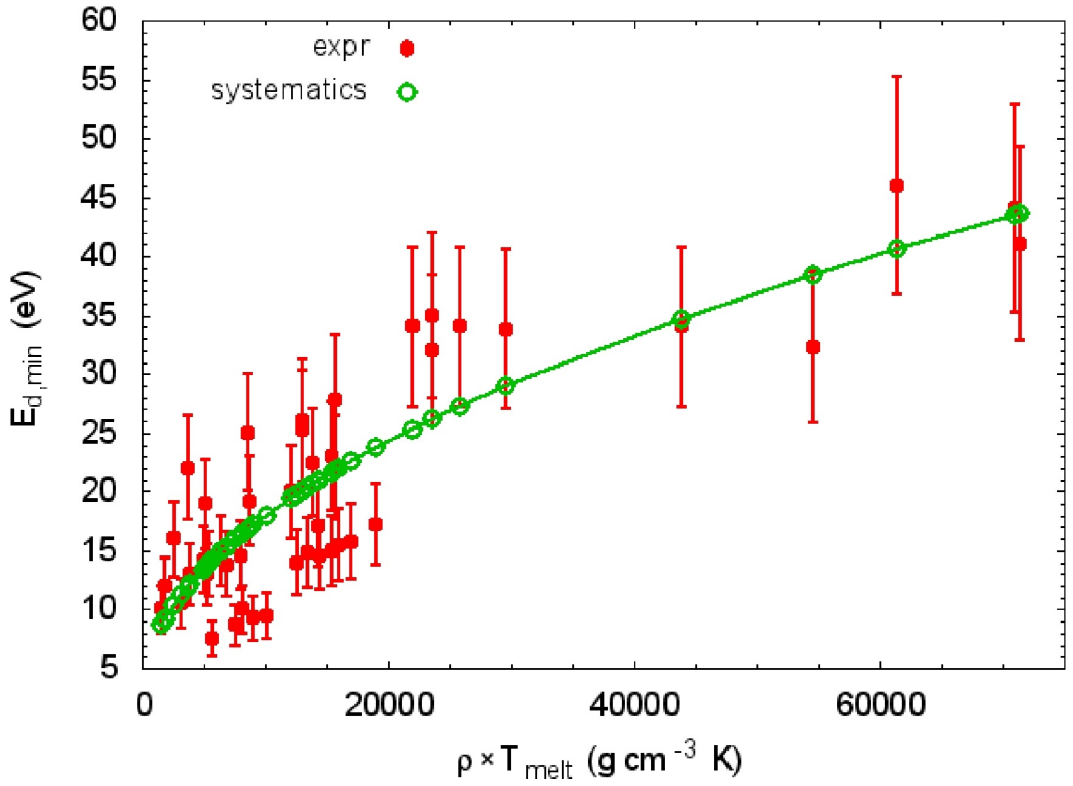


Nordlund, *et al.*, J. Nucl. Mat. 512 (2018) 450-470



Threshold displacement energy

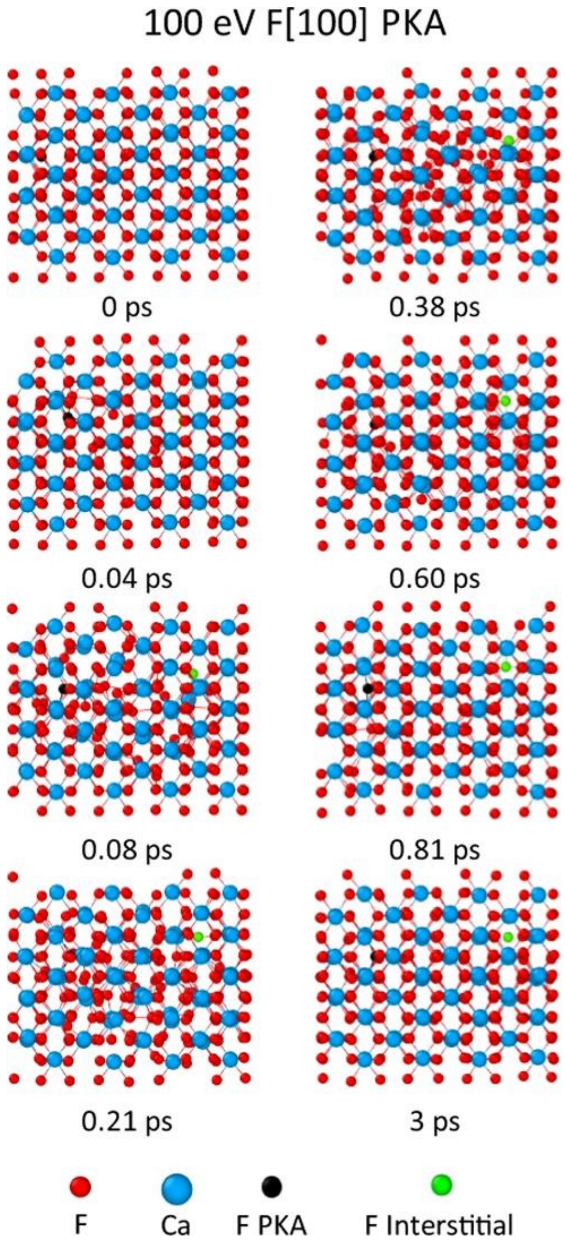
- Crucial input parameter to TRIM
- Difficult to measure
- Data mostly for metals
- Empirically found to scale with the melting point
- Use this heuristic to obtain values for materials of interest



Konobeyev, *et al.*, Nucl. Energy & Technology, 3 (2017) 169-175

Test case CaF2

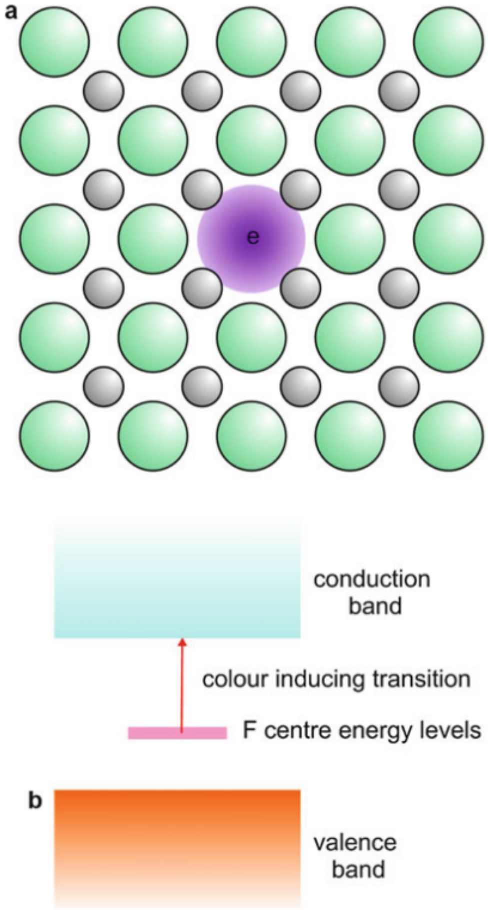
- CaF2 has been studied in detail
- Goal: neutron dosimetry at very high fluences (like inside a reactor)
- Molecular dynamics simulation with LAMPPS
- Strong anisotropy in TDE
- Value for average TDE and resulting recoil threshold within 20-30% of TRIM and melting point heuristics



Morris, Cowen, Teysseyre, Hecht, Comp. Mat. Science, 172 (2020) 109293,

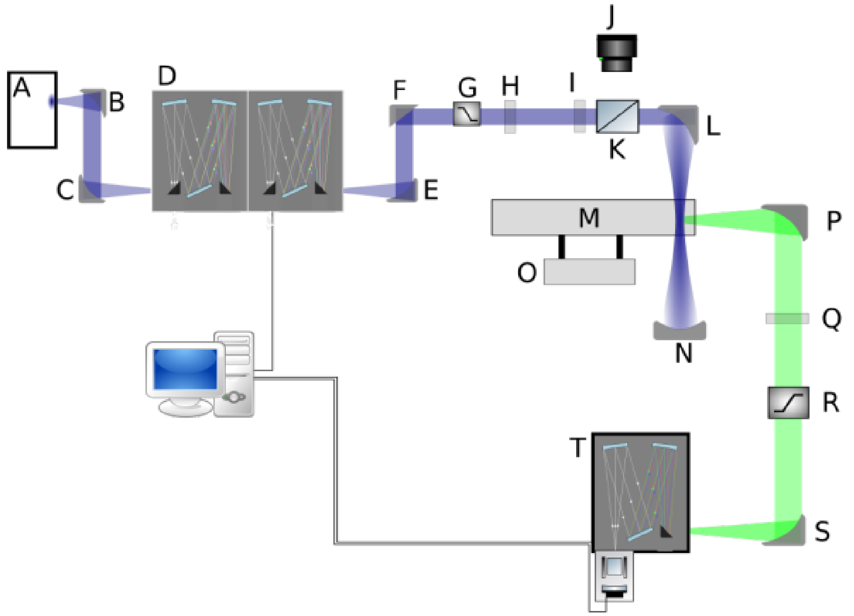
Color centers

- In ionic crystals (e.g. NaCl), anion vacancies trap electrons
- Quantum mechanics in a square well → distinct energy levels
- Used to artificially change colors of gem stones
- Individual color centers can be seen in visible light by fluorescence spectroscopy (NV in diamond, SiC)
- Observed in a wide class of materials



From: R. Tilley, Encyclopedia of Color Science and Technology, Springer 2013

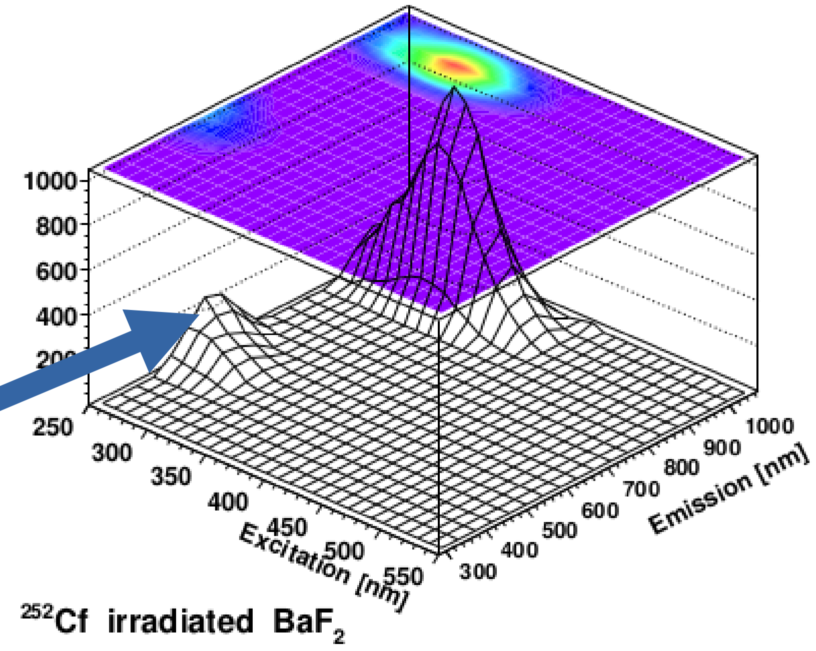
Does it work?



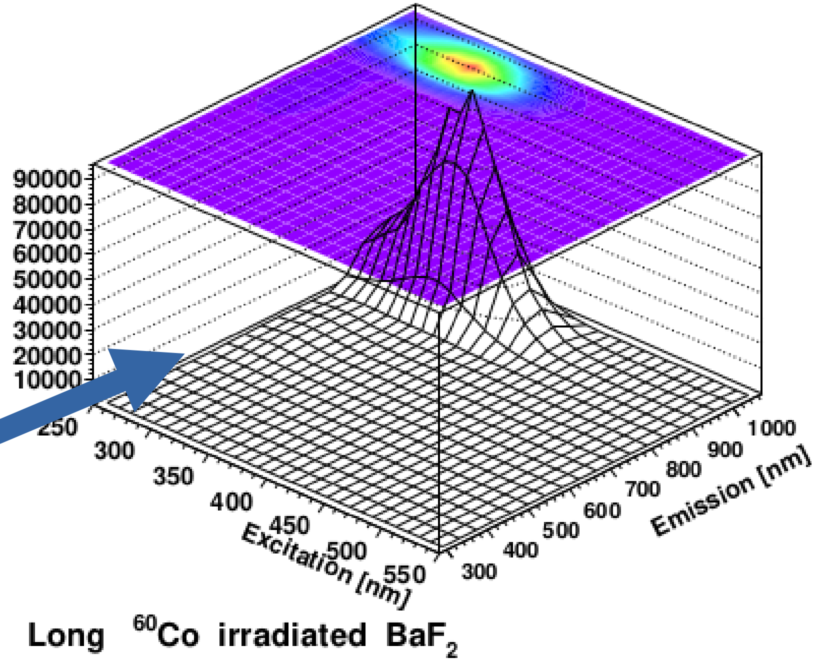
Mosbacher *et al*, arXiv:1902.10668 irradiated a number of materials with neutrons and gammas to study bulk color center formation.

Similar results for Al2O3 and LiF2

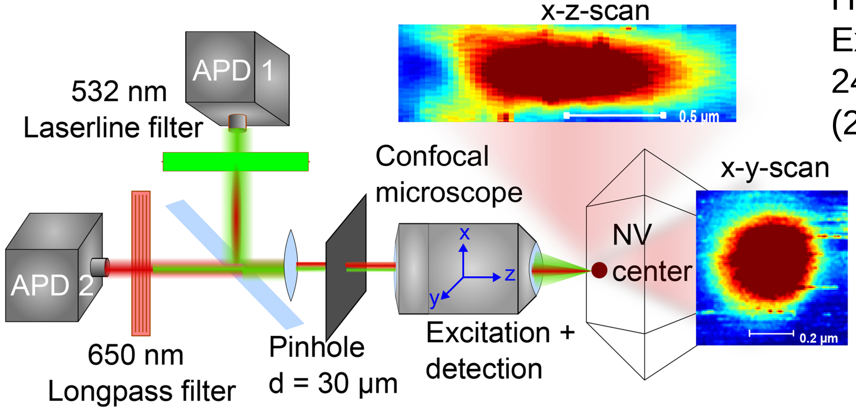
Color centers formed **selectively** by neutrons



Nothing here with 500x higher dose of gammas



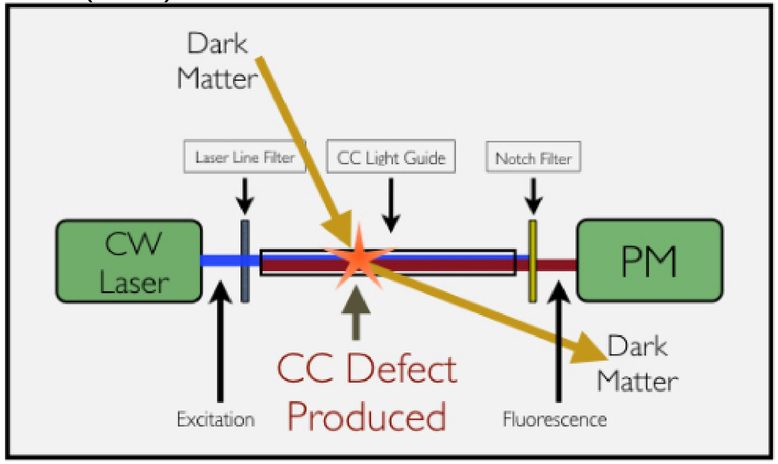
Readout schemes



Häußler, *et al.*, Optics Express Vol. 22, Issue 24, pp. 29986-29995 (2014)

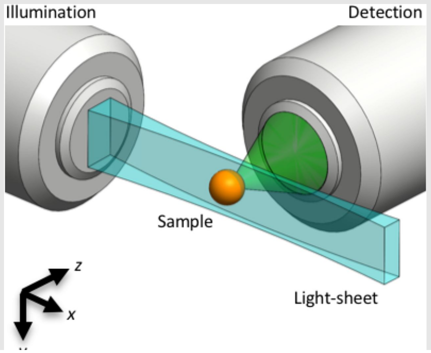
Location of defect, but tiny volume

Budnik, Chesnovsky, Slone, Volansky, Phys.Lett.B 782 (2018) 242-250.

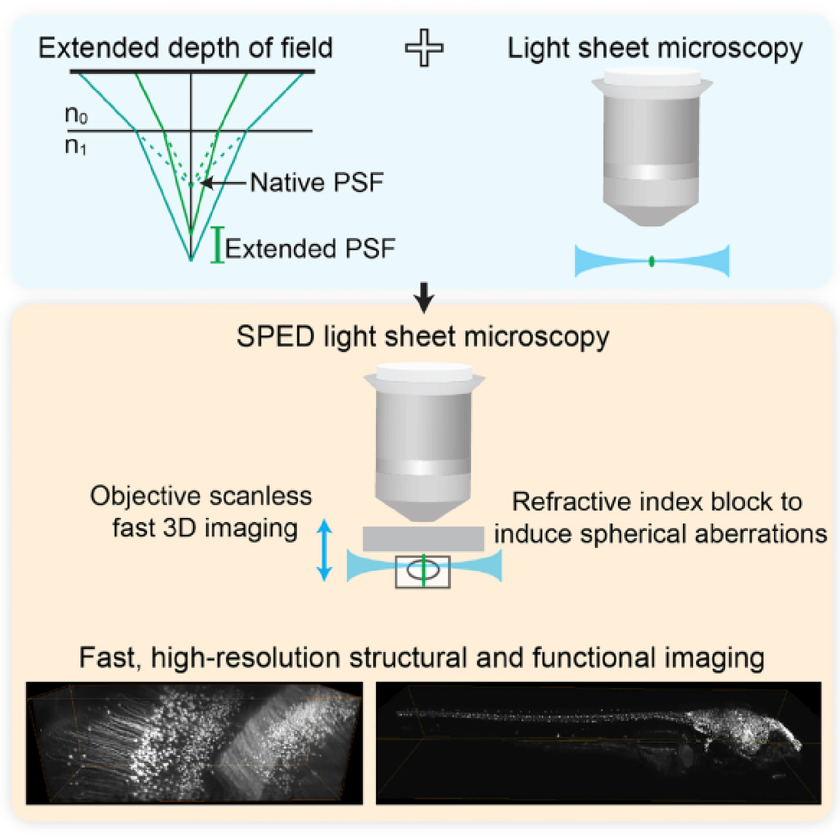


Volume imaging, but no location of defect.

Problem for pre-existing defects!



Sub-micron real-time 3D fluorescence imaging of biological samples, corresponding to 50-100 cm³ per day

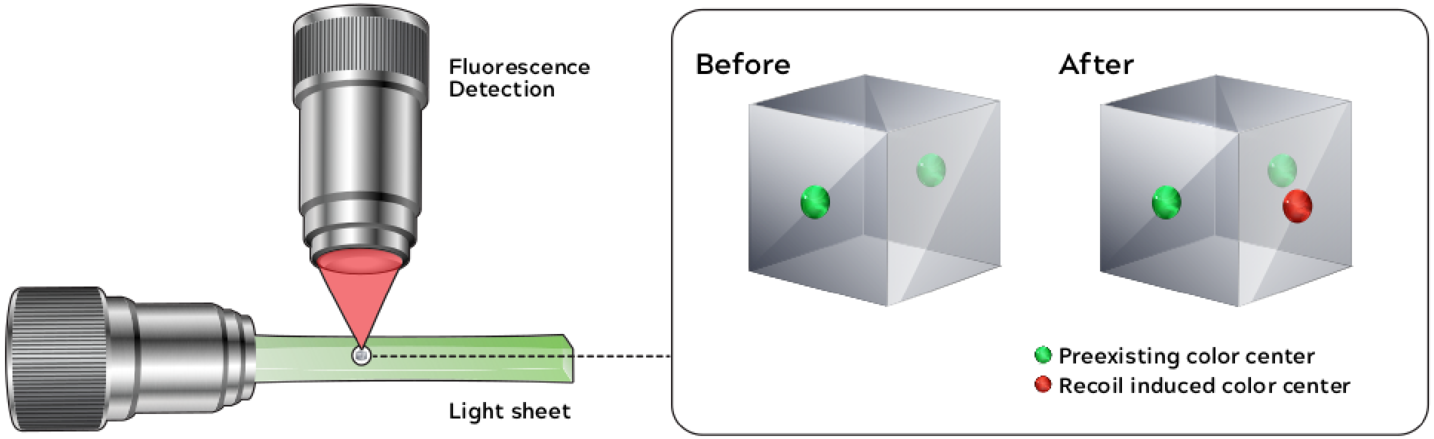


3D position
+
Large volume

Commercially available

Tomer *et al.*, 2015, Cell 163, 1796–1806

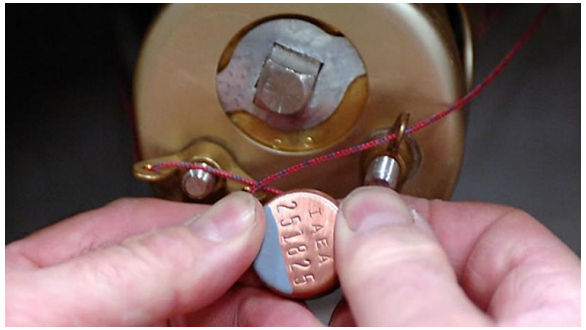
How does this work?



Crystal is scanned prior to deployment to record the location of pre-existing defects (green dots).

Crystal is scanned after deployment and any new defects are candidates for neutrino events (red dots).

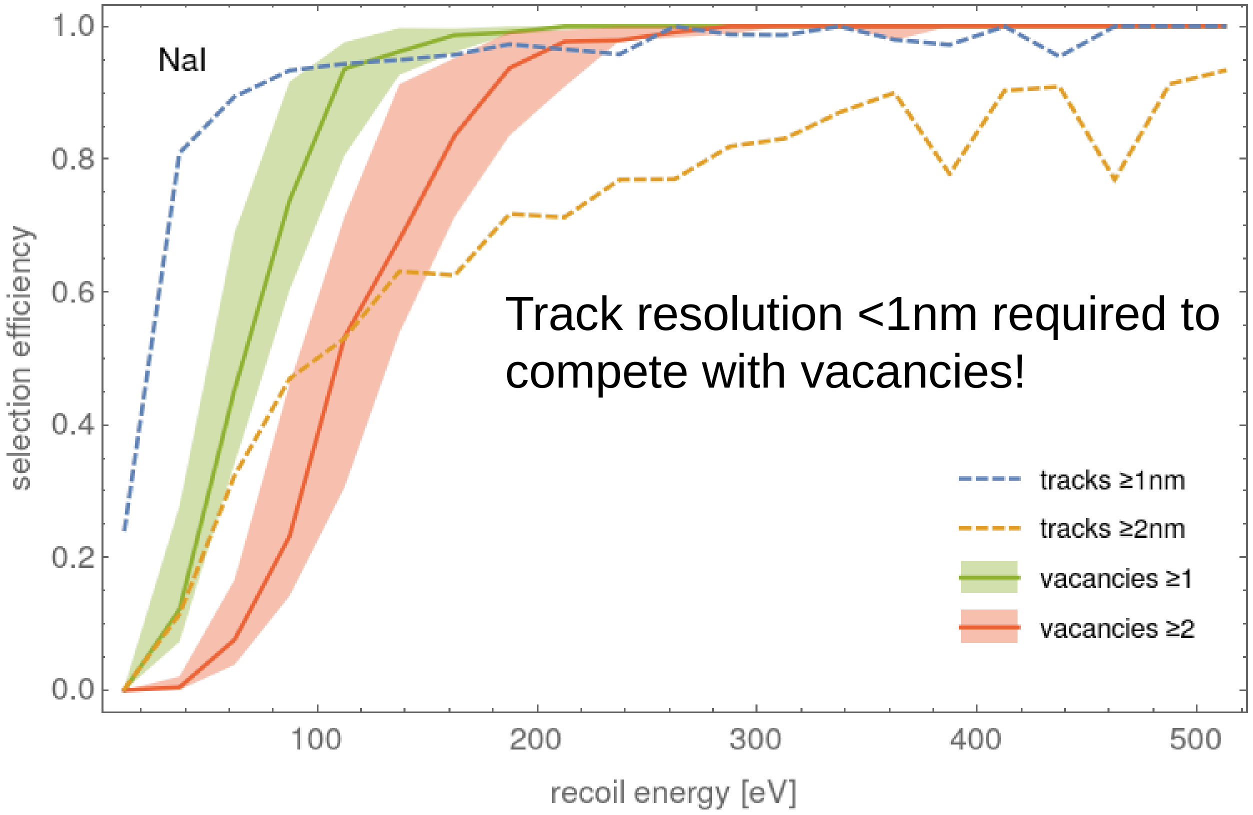
Finding the green dots in their correct location verifies that the crystal is indeed the **same** crystal and that no attempt at **erasing** any defects by heating was made.



Tamper proof!

Nuclear recoil threshold

- CEvNS/DM detection rates are a steep function of the nuclear recoil threshold (NRT)
- NRT is generally higher than ionization or scintillation threshold due to quenching
- NRT is a key performance parameter: sub 100eV for both tracks and vacancies.
- NRT<100eV only achieved by mK cryogenic bolometers.



Material selection

material	A [u]	m_A [%]	density [g cm^{-3}]	melting point [K]	TDE [eV]	$E_{1/2}$ [eV]	CEvNS events	selection efficiency [%]	usable events
LiF	19.0	73.2	2.64	1120	27	80	5600	75	4200
BaF_2	137.3	78.3	4.88	1625	35	105	48800	20	9600
NaI	126.9	85.0	3.67	935	24	65	46900	32	15100
CsI	132.9	~100	4.51	900	23	55	55700	37	20600
$CaWO_4$	183.8	63.9	6.06	1895	41	110	55400	8	4600
$Bi_{12}GeO_{20}$	209.0	86.4	9.22	1175	28	85	83500	17	14000

- Melting point well above 300K
- Electrical insulator
- Permit color centers
- Color centers selectively formed by nuclear recoil

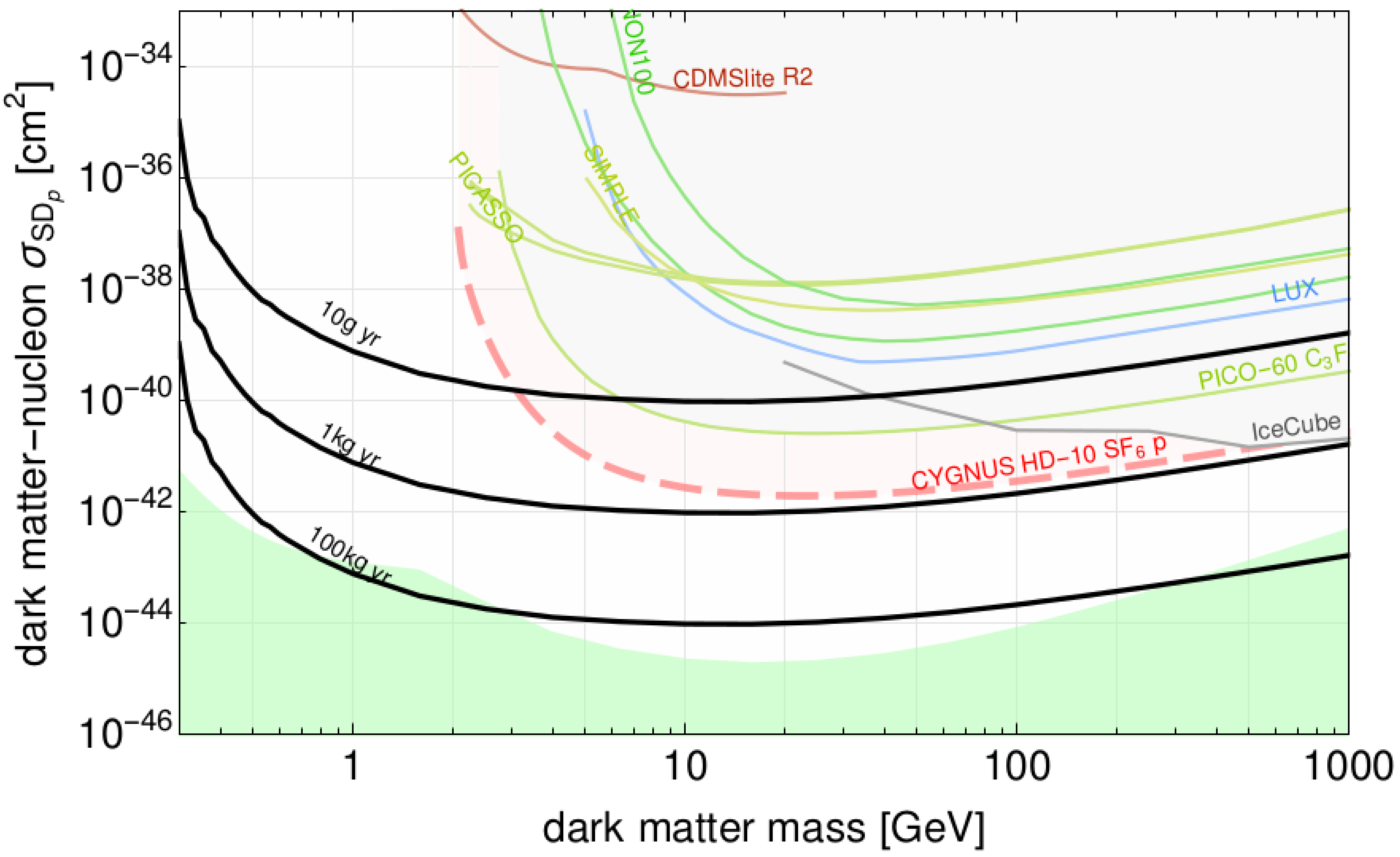
- Optical quality crystals
- High atomic mass (for CEvNS)
- Low threshold damage energy
-

Dark matter detection

LiF2 great target for spin-dependent interactions

Spin-dependent interactions: hard to compete with Ge detectors

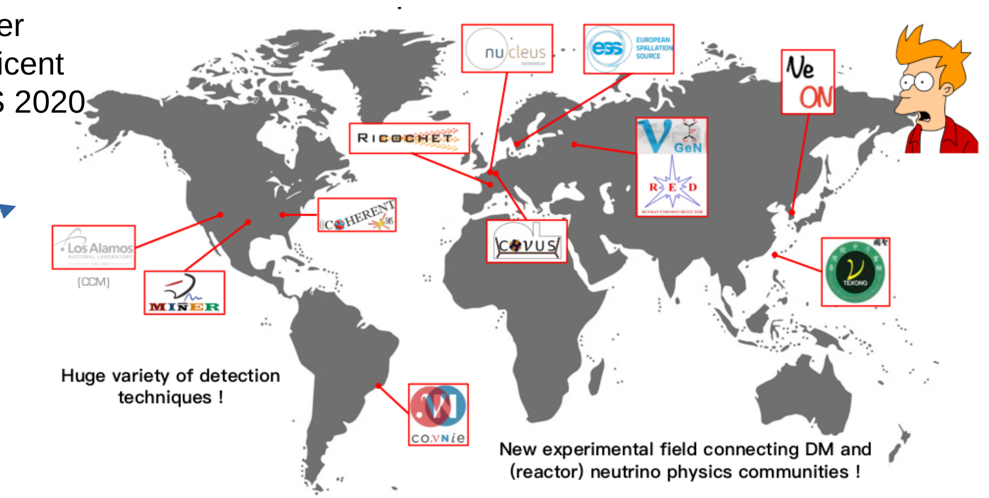
Neutron backgrounds negligible well into the 10 kg year exposure range

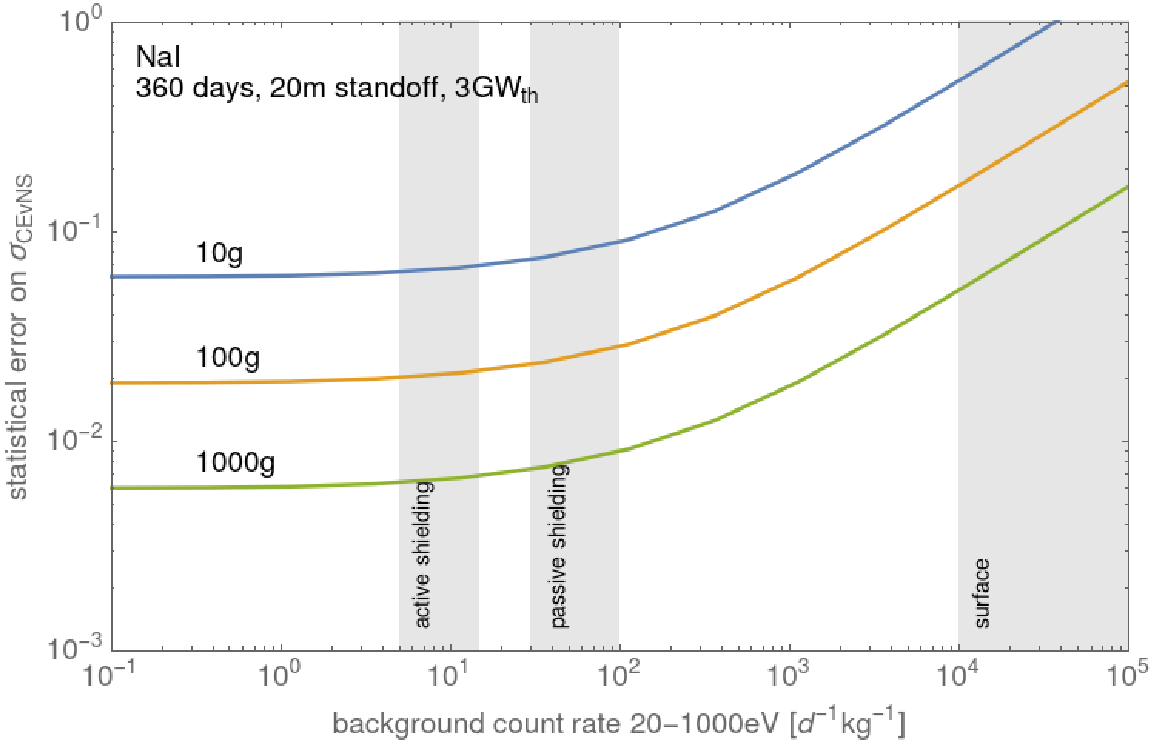


CEvNS detection

- CEvNS not yet observed at reactors, very active field
- 10g crystals could deliver 5 sigma detection
- Neutron background:
- 1mwe passive shield would be really helpful
- Active shielding not required
- Passive detector, no cryogenics small footprint

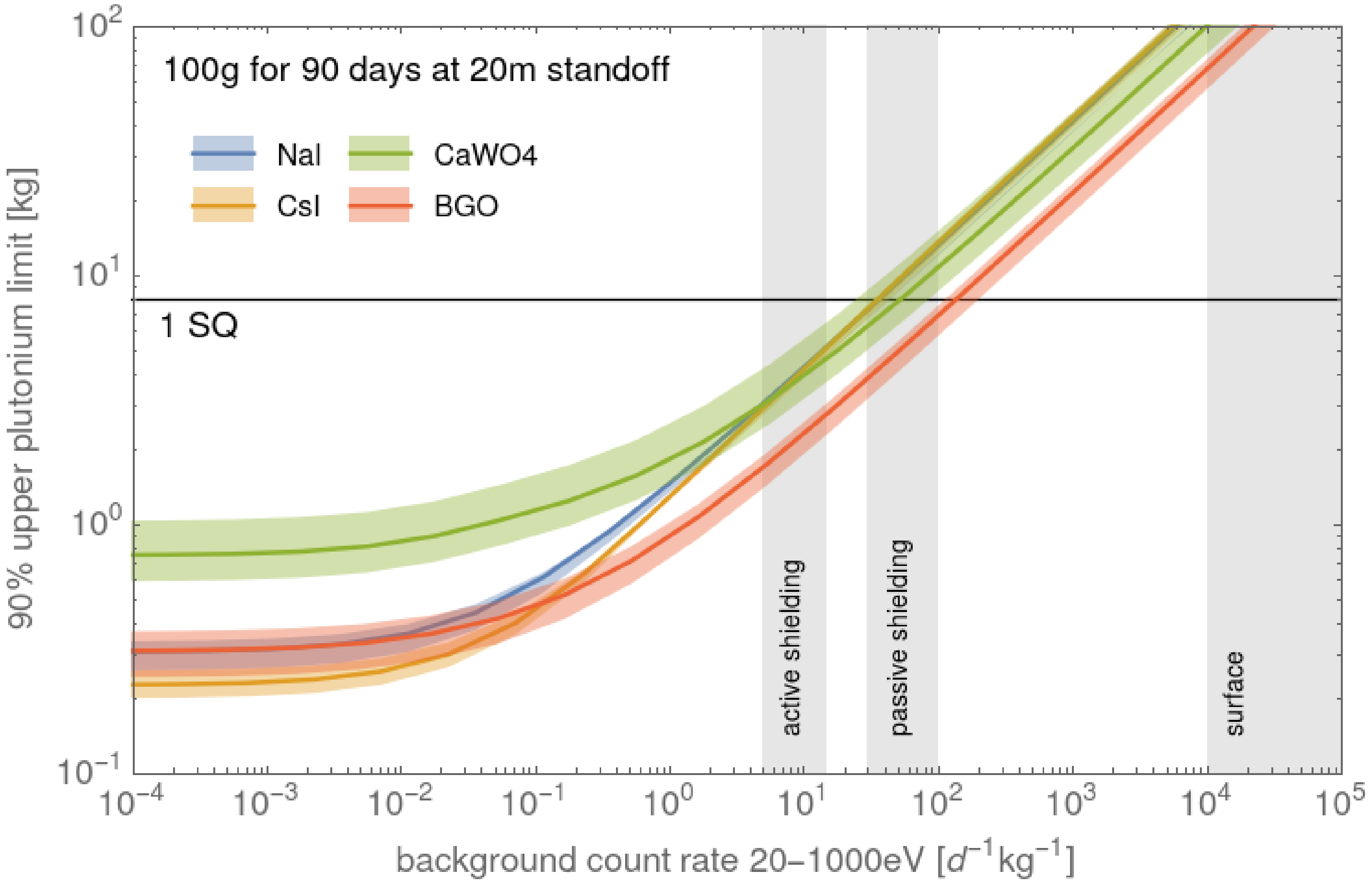
M. Vivier
Magnificent
CEvNS 2020





CEvNS for safeguards

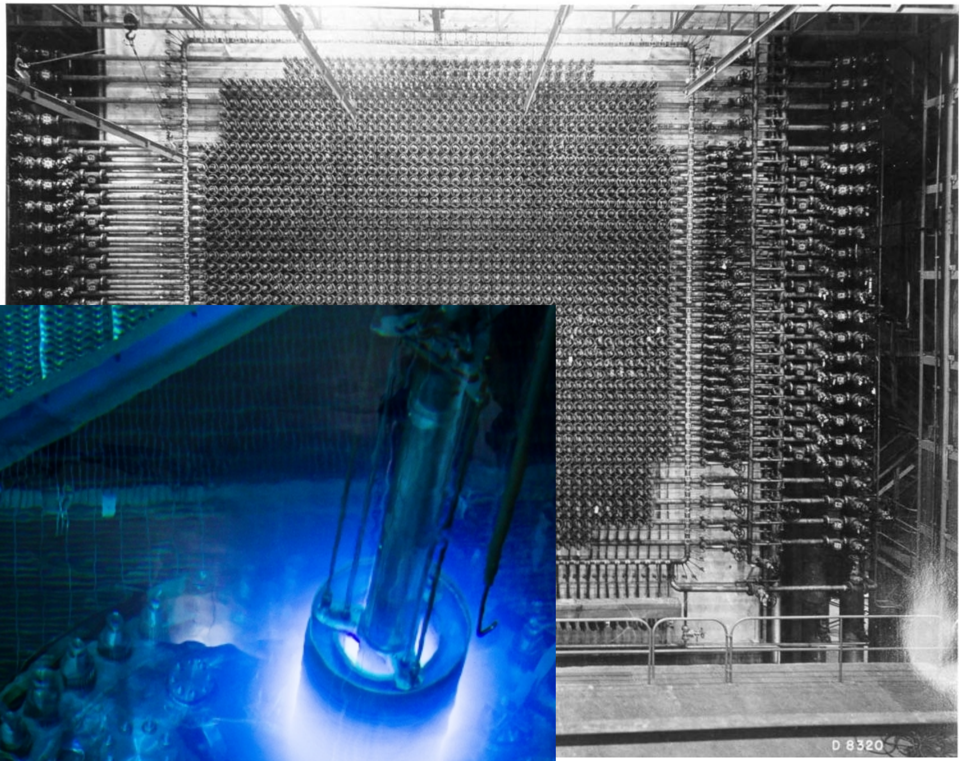
- Verification of reactor shutdown
- 90 day, 1SQ criterion
- Several candidate materials
- All commercially available as radio-clean optical quality crystals
- 1 meter water equivalent passive shield needed

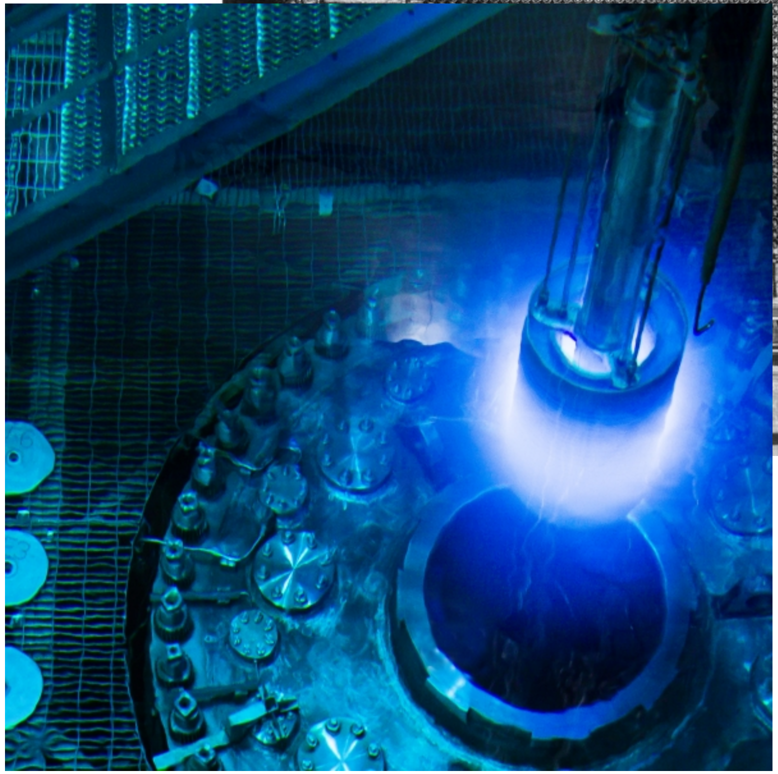


Mission Relevance

- Verification of reactor shutdown
- Verification of end of plutonium production
- For smaller reactors: limit on reactor power & duration of operation

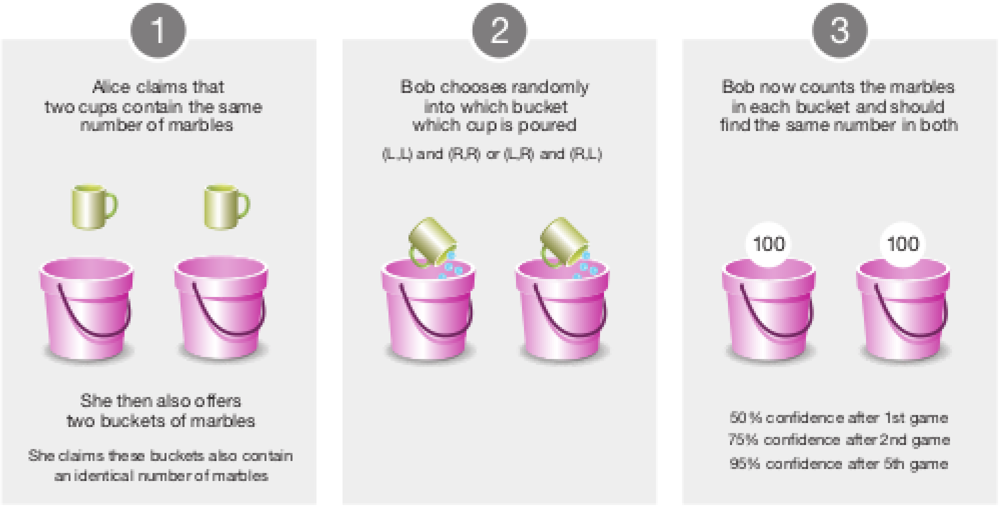
- → directly supports non-proliferation





Nuclear disarmament verification

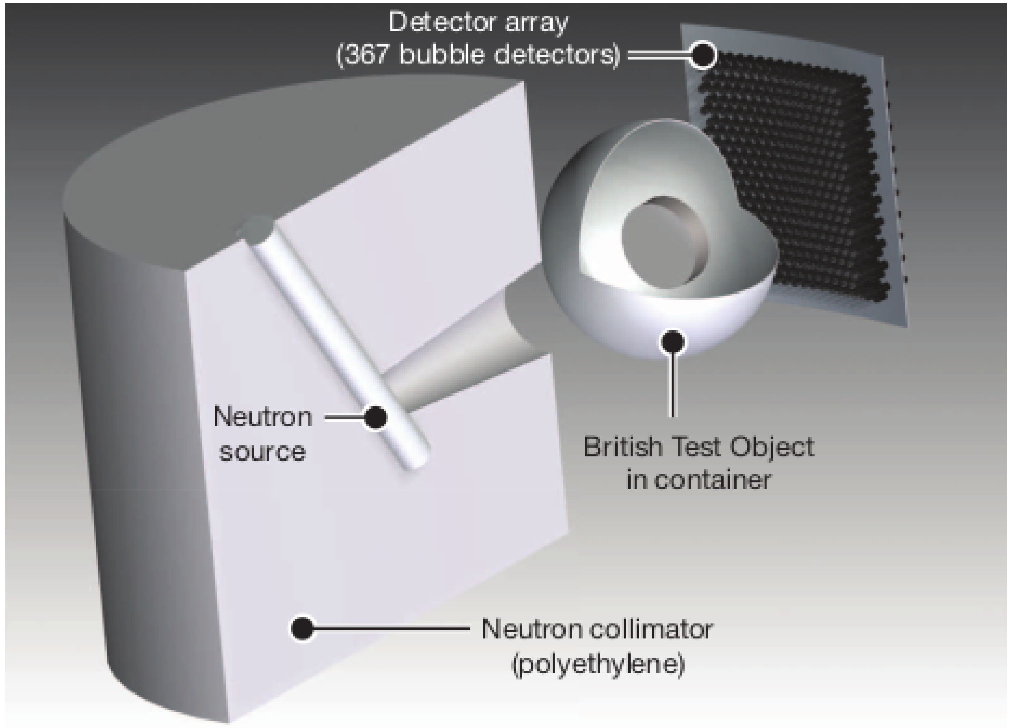
How to prove two objects are the same without revealing any other information?



Glaser, Borak, Goldstone, Nature 510 (2014) 497-502.

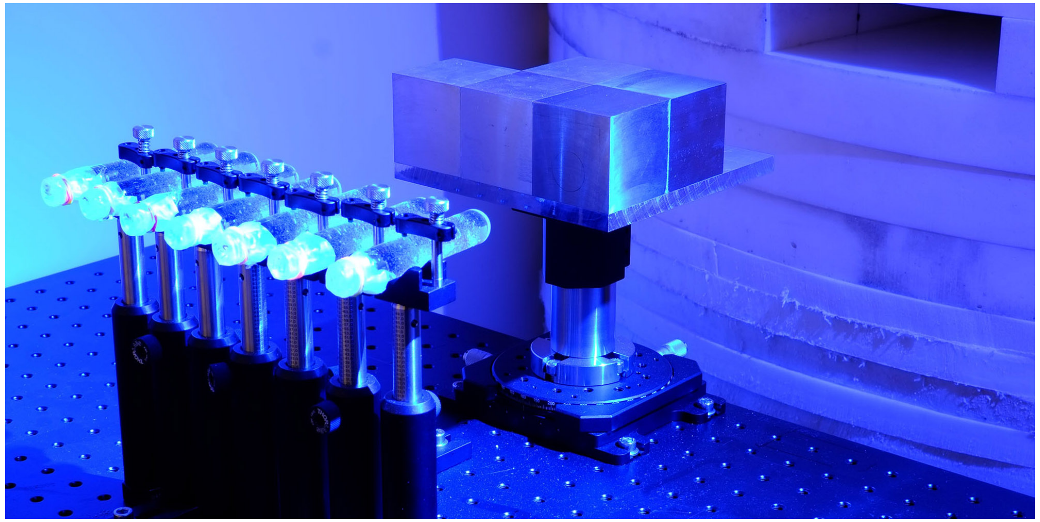
So-called zero knowledge proof – ideal for verifying that an object belongs to the same equivalence class as a template

Application to a warhead could look like this



Detector needs

Experimental proof-of-concept



Philippe, Glaser, Goldstone, d'Errico,
Nature Commun. 7 (2016) 12890.

Uses super-heated emulsion detectors
(think PICO)

Detector needs to be

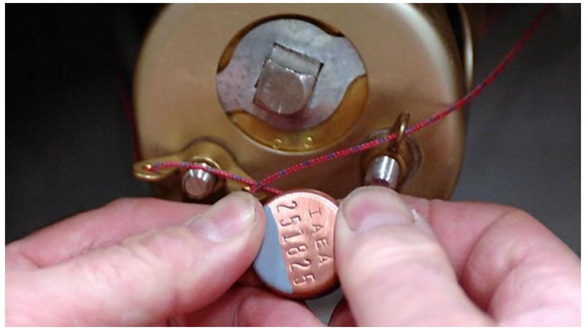
- pre-loadable
- pre-load must be persistent
- pre-load must be verifiable by host
- insensitive to gammas
- non-electronic
- un-spoofable

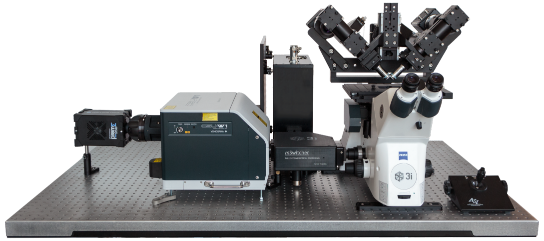
Color center-based detectors check all these boxes.

MeV neutrons are much easier to detect than reactor CEvNS.

Expected Impact

- Non-spoofable: neutrino signal unique, distinction to neutrons by different scaling with atomic mass, pre-existing point defects fingerprint a given detector.
- Passive detectors of ~100g likely can be incorporated into safeguards operations without disruption.
- Detector materials are commercially available.
- Light sheet microscopes are commercially available.





Summary

- Passive CEvNS detection based on color centers seems theoretically feasible based on detailed simulations
- Resulting detector sizes & deployment footprints appear promising:
- No cryogenics, detectors less 1kg
- Possible application to dark matter and neutron detection

Thanks to my collaborators:

Dr. Bernadette K. Cogswell

Apurva Goel