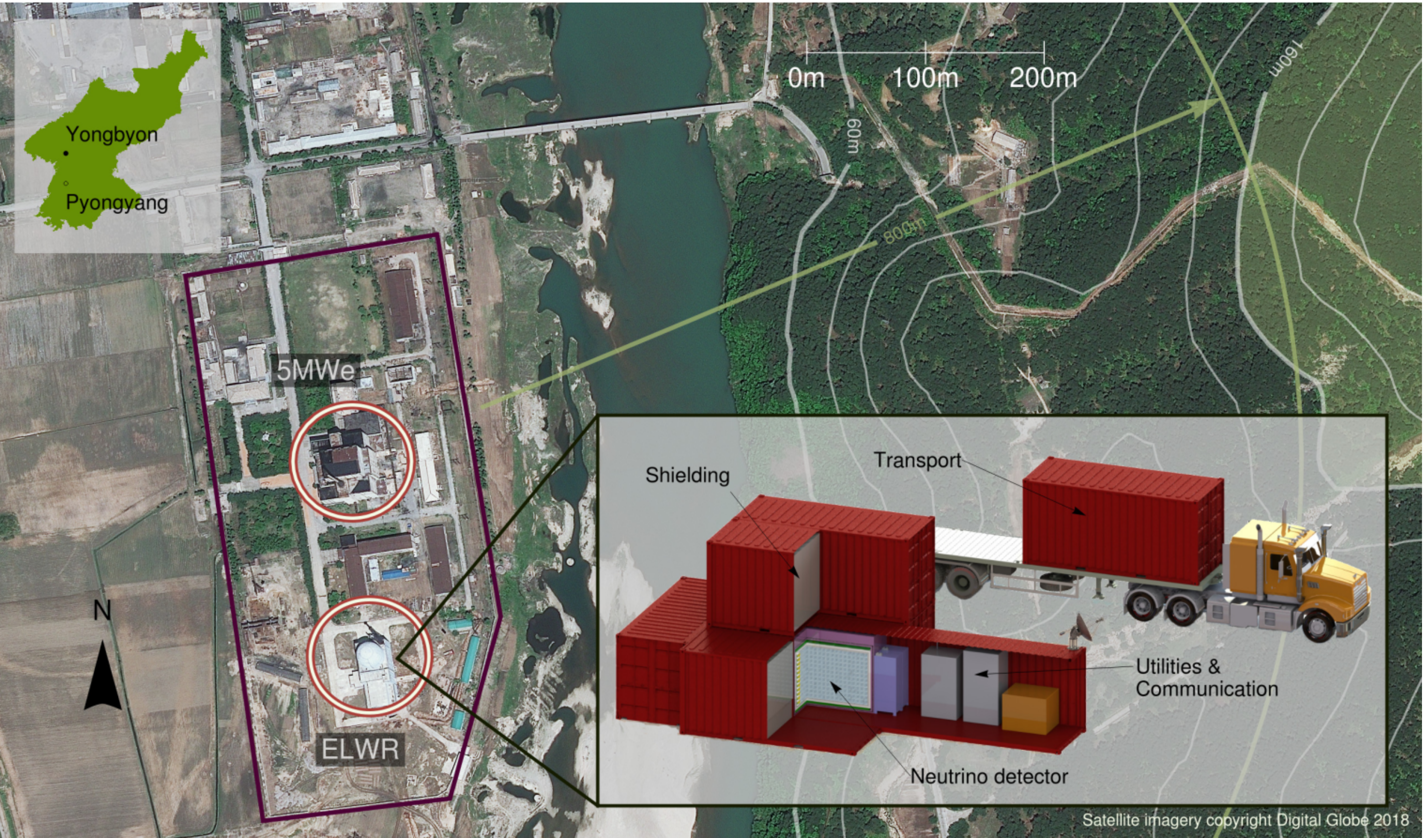
Global Project Overview –

Where do we go from here?



Satellite imagery copyright Digital Globe 2018

Patrick Huber
Center for Neutrino Physics
Virginia Tech

Applied Antineutrino Physics
September 18 – 21, 2023,
York, UK

Special nuclear materials

For a nuclear explosion a chain reaction of fast neutrons is required – only very few materials have this property of being fissile

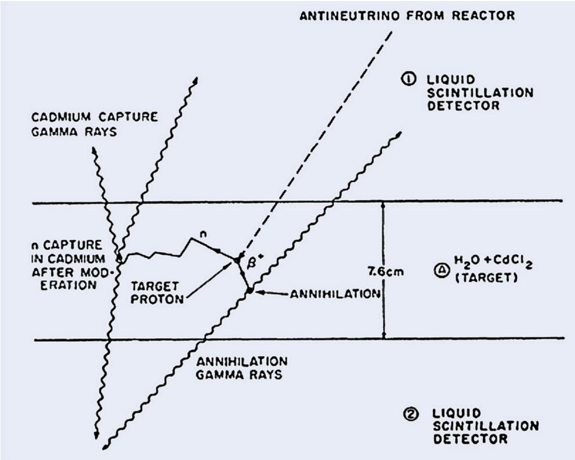
Isotope	235U	233U	239Pu	241Pu
Half-life	700 Million years	160,000 years	24,000 years	14 years
Natural abundance	0.72%	0%	0%	0%

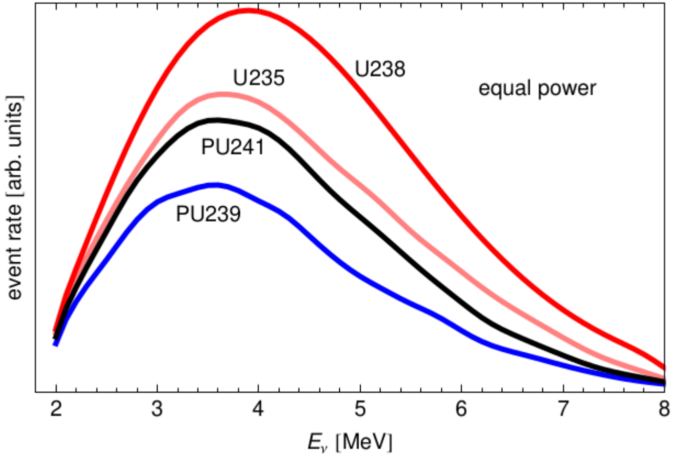
This is **the major barrier** to obtaining nuclear weapons

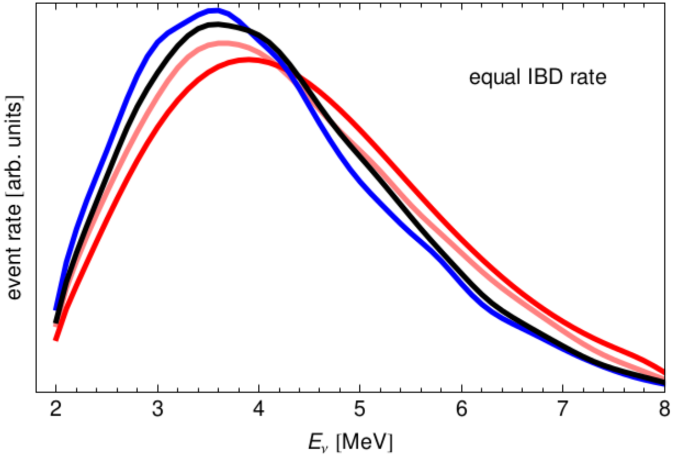
Neutrinos for reactor safeguards

Neutrinos offer unique safeguards opportunities:

- measure reactor power
- detect undeclared production of fissile material
- independent verification of fuel burn-up

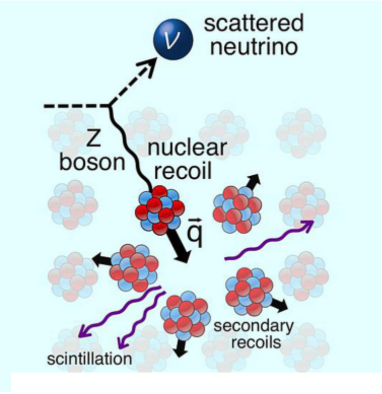






see talk by L. Hayen

CEvNS studies



Large cross section

→ small detectors

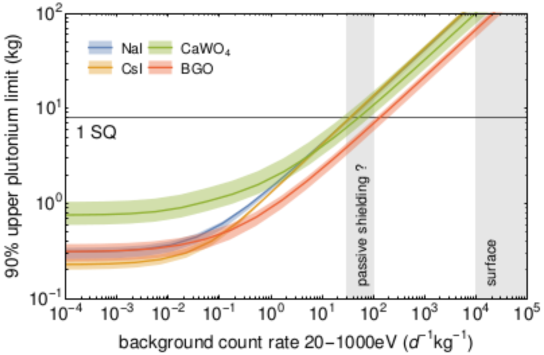
→ lots of ideas

Need observation!

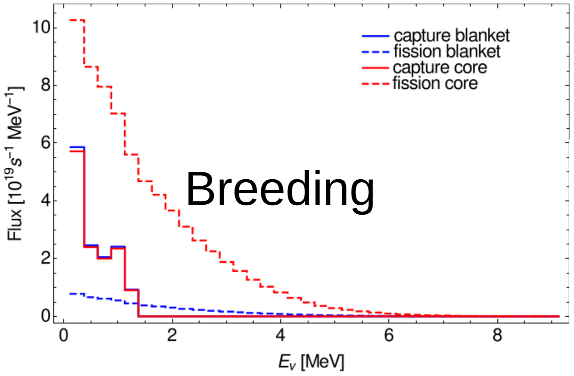
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} N^2 M_N \left(1 - \frac{M_N T}{2E_\nu^2}\right)$$

T recoil energy, N neutron number

Cogswell *et al.* 2021



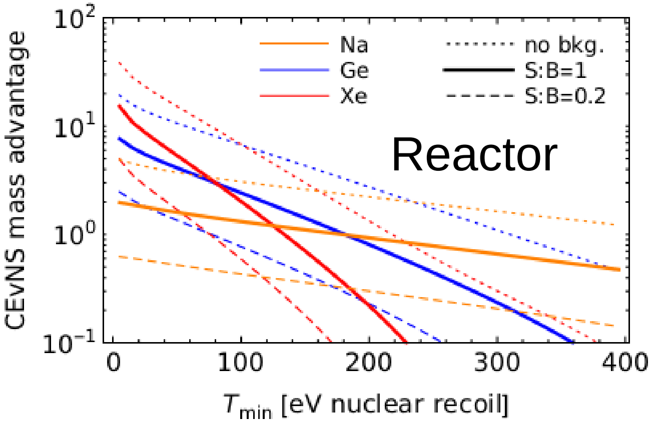
Cogswell, PH 2016

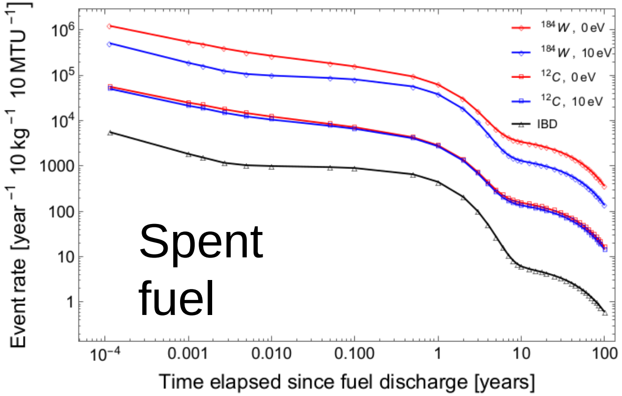


PALEOCCENE

Passive color center-based detectors

Bowen, PH, 2021



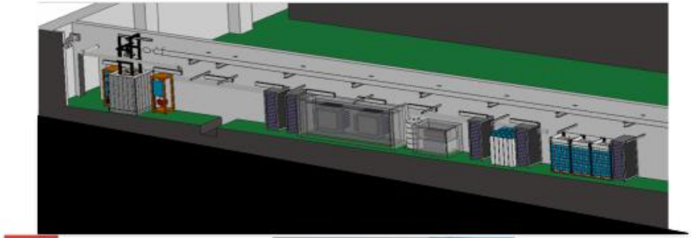


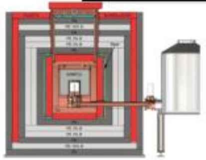
v. Raesfeld, PH 2022

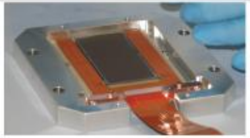
see talk by R. Carr

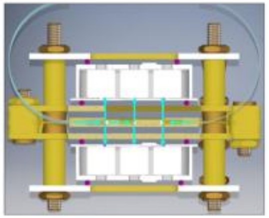
Many CEvNS Efforts Worldwide [incomplete]

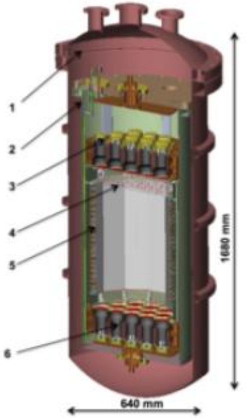
Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
ESS	CsI, Si, Ge, Xe	Sweden	πDAR
BULLKID	Si/Ge	Italy	Reactor
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
NEWS-G	Ar+2%CH4	Canada	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NEON	NaI(Tl)	Korea	Reactor
NUCLEUS	CaWO$_4$, Al$_2$O$_3$ cryogenic	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn, Al, Sn cryogenic	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor
Dresden II	PCGe	USA	Reactor
SBC	Scintillating Bubble Chamber	Fermilab (R&D)	Reactor

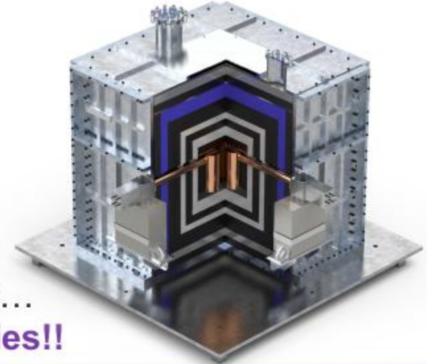


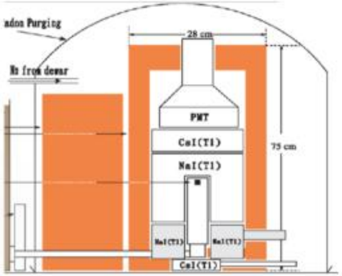








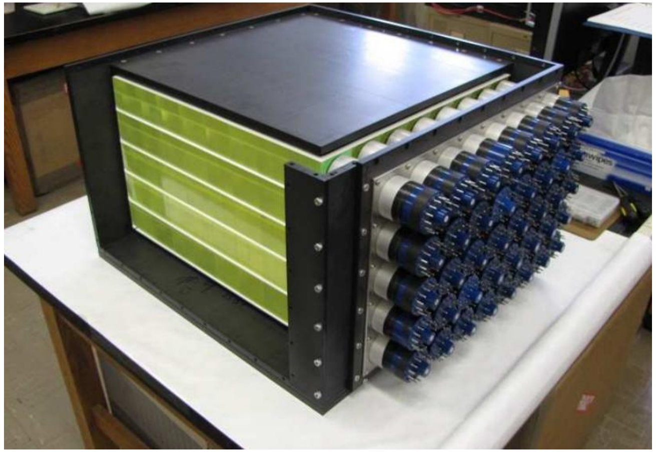




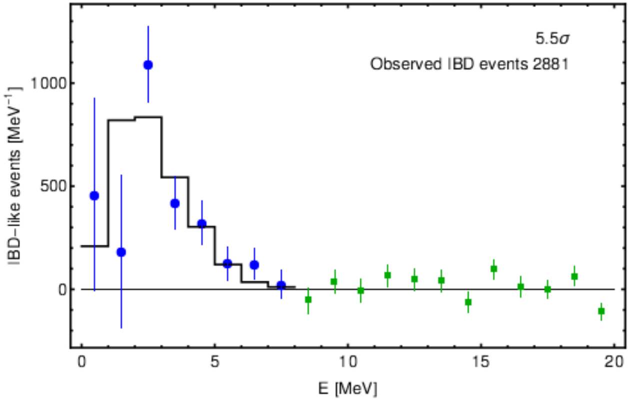
+DM detectors, +directional detectors +Solar/SN detectors…

many novel low-background, low-threshold technologies!!

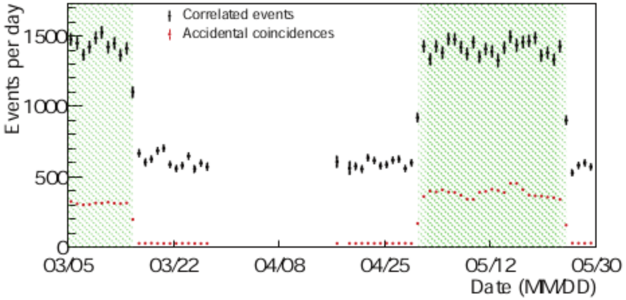
Surface detection

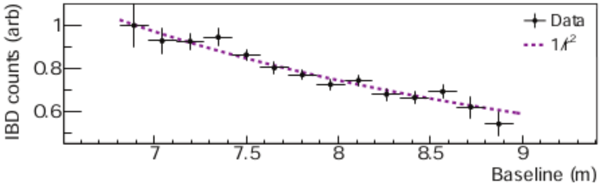


CHANDLER 2018
3D segmentation
solid plastic scintillator
topology



Essential step towards applications!



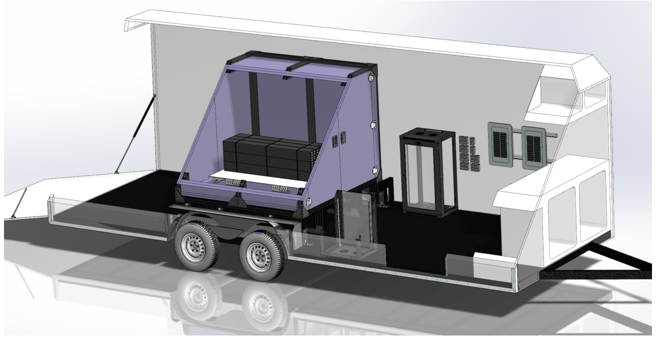


PROSPECT 2018
2D segmentation
liquid scintillator
pulse-shape discrimination

see talk by S. Dazeley

U.S. surface detector R&D

ROADSTR – 100kg

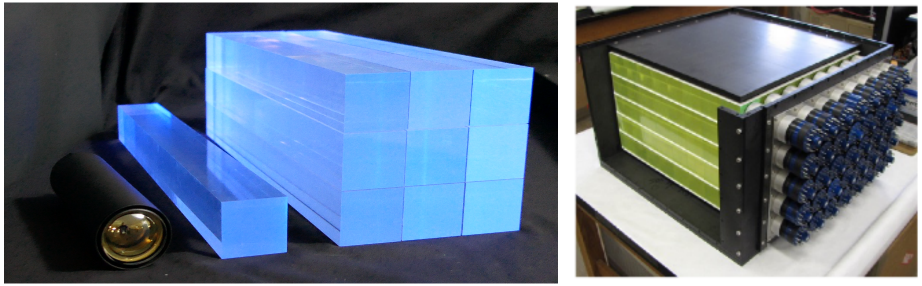


Lawrence Livermore National Laboratory

Technology testbed, test of concepts and neutron background characterization

Mobile Antineutrino Demonstrator – ton scale

Detector Technology Options



2D segmentation with ^{6}Li-doped PSD plastic scintillator

3D segmentation with ^{6}LiZnS & WLS plastic scintillator

Lawrence Livermore National Laboratory

Oak Ridge National Laboratory

NIST

Georgia Tech

Illinois Institute of Technology

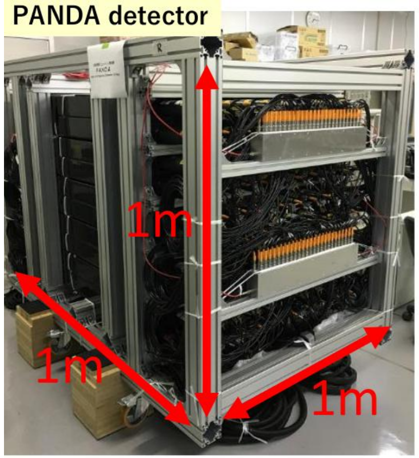
Virginia Tech

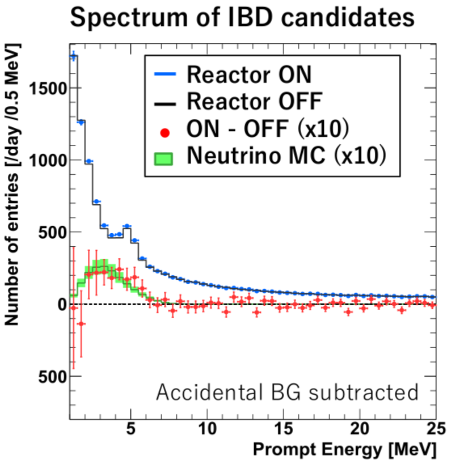
Yale

U.S. Naval Academy

Goal is to advance the technical readiness of reactor neutrino detection

Global detector R&D efforts



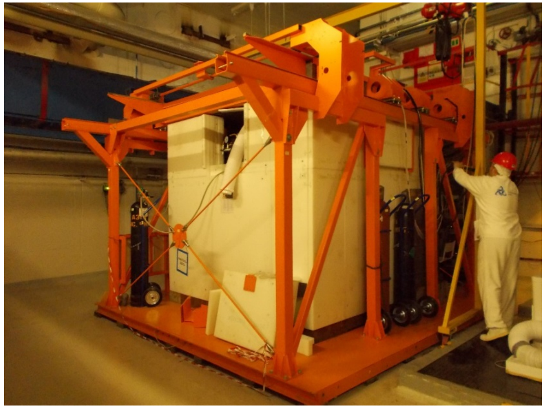


PANDA at Ohi NPP (Japan) 2018/2019
2D segmented, plastic scintillator

ISMRAN installed at 100MW Dhruva reactor (India), 2D segmented, plastic scintillator

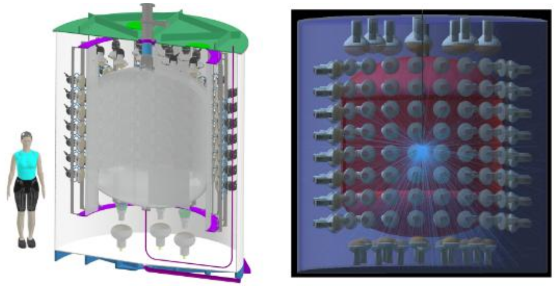
VIDARR Detector developed at the University of Liverpool, re-visit of supplementary Wylfa data underway (UK), 2D segmented, plastic scintillator

iDREAM has been installed and commissioned in 2021 at Kalinin NPP (Russia), 20m from 3GW reactor core, single volume, liquid scintillator



Water Cerenkov R&D

EOS 4 ton prototype



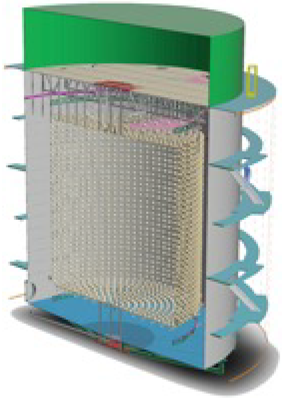
Closely coupled to BNL effort to construct 30-ton tank for demonstration of WbLS production, transparency and stability

Together these prototypes will demonstrate the feasibility and capabilities of hybrid detectors for nonproliferation and fundamental physics applications

Multi-kton detectors can provide reactor monitoring and exclusion over 10’s of km distance.

Potential role in future agreements.

WATCHMAN – 1kton



A candidate conceptual design for a kiloton-scale aqueous detector demonstrating remote sensitivity to reactor operations. Shown is a 12 m diameter cylindrical tank.

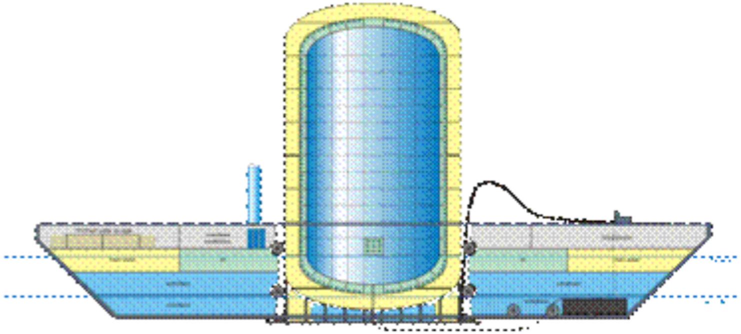
Possible early shutdown of original UK reactors motivates reconsideration of sites in the US.

Ocean deployed detector

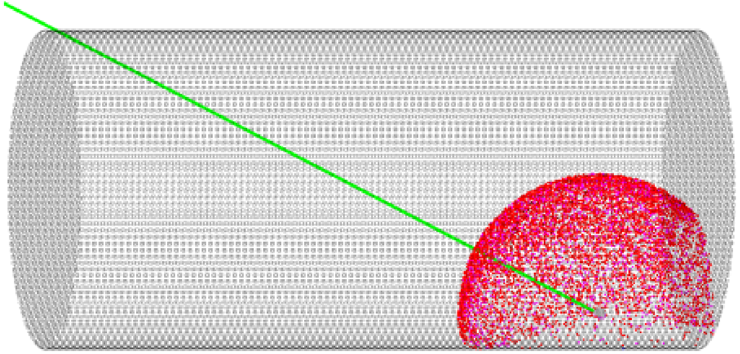
Deploying a 10kt liquid scintillator detector has been proposed to study geoneutrinos.

It also has been considered for long-range reactor detection.

Lasserre, *et al.*, 2010
Jocher, *et al.*, 2013



Learned, Dye, Pakvasa 2008
Sakai, *et al,* 2021

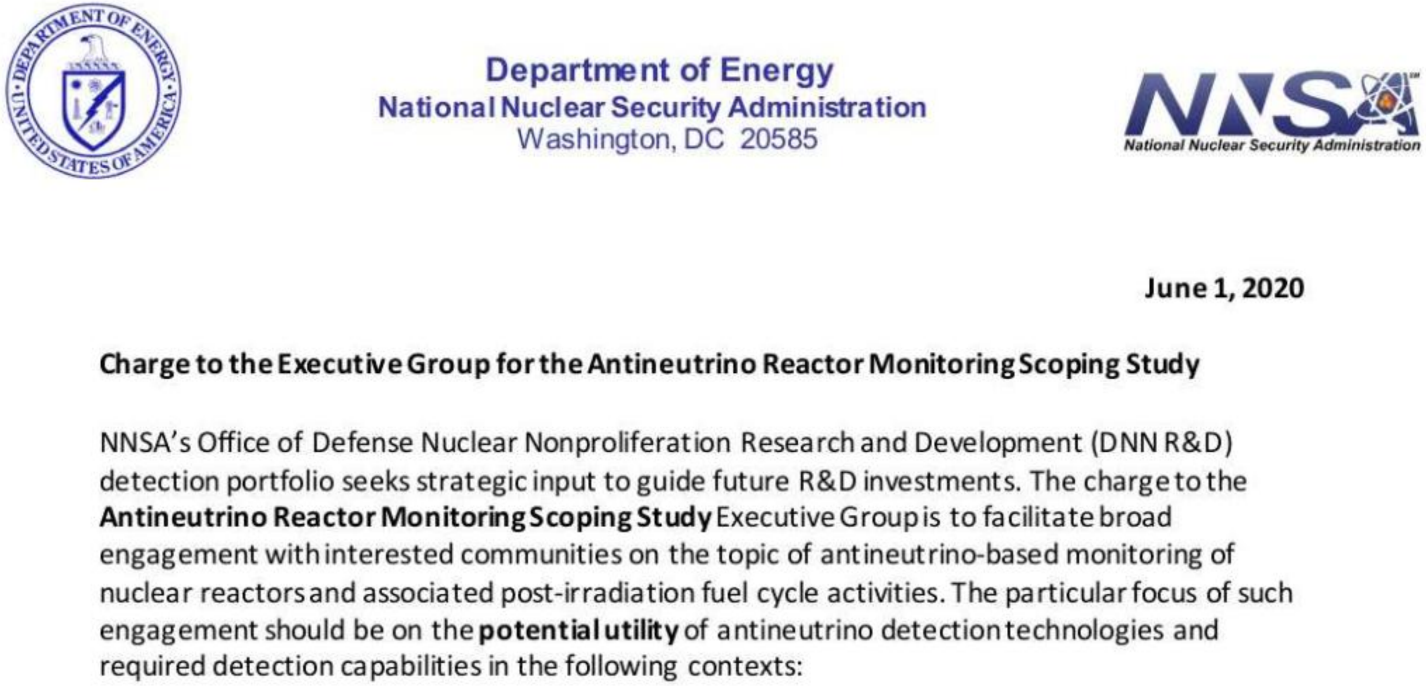



NuTools

Exploring Practical Roles for **Neutrinos** in **Nuclear Energy and Security**

see talk by A. Conant.

P0706 Michael Foxe


Department of Energy
National Nuclear Security Administration
Washington, DC 20585

June 1, 2020

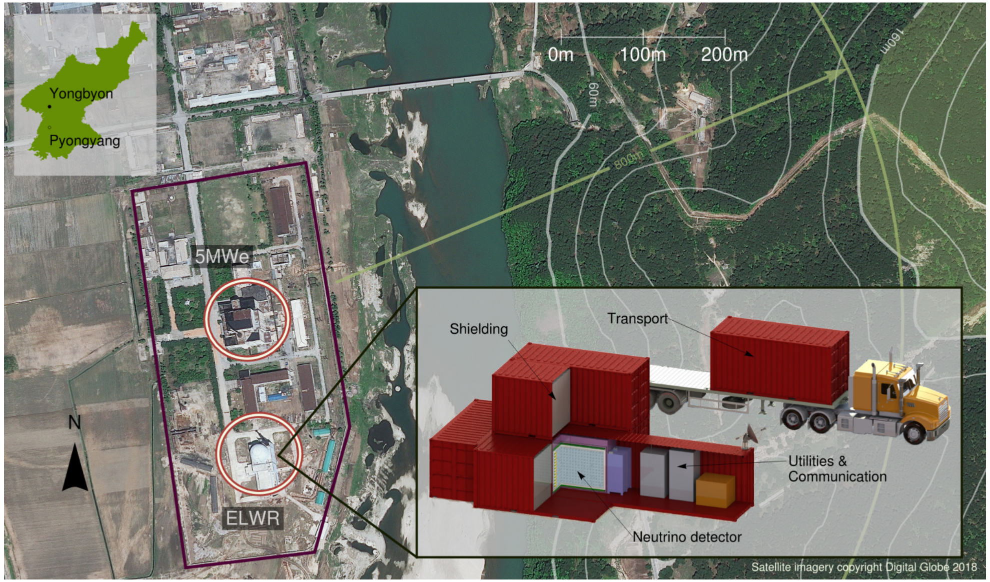
Charge to the Executive Group for the Antineutrino Reactor Monitoring Scoping Study

NNSA's Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) detection portfolio seeks strategic input to guide future R&D investments. The charge to the **Antineutrino Reactor Monitoring Scoping Study** Executive Group is to facilitate broad engagement with interested communities on the topic of antineutrino-based monitoring of nuclear reactors and associated post-irradiation fuel cycle activities. The particular focus of such engagement should be on the **potential utility** of antineutrino detection technologies and required detection capabilities in the following contexts:

Focus on **utility**

Method is end-user engagement **not** technical analysis

Confronting backgrounds with previous case studies



Satellite imagery copyright Digital Globe 2018

Carr, *et al.* 2018

5MWe	IR40	ELWR
20 MWth	40MWth	150MWth
graphite moderated	D2O moderated	H2O moderated
natural U	natural U	3% enriched U

Simple scaling model derived from PROSPECT-I data

$$S = 771\left(\frac{m}{2\,[\mathrm{ton}]}\right)\left(\frac{P}{85\,[\mathrm{MW}_{th}]}\right)\left(\frac{7.9\,[\mathrm{m}]}{L}\right)^2 \mathrm{d}^{-1}$$

$$B = \frac{771}{0.832}\left(\frac{m}{2\,[\mathrm{ton}]}\right)\mathrm{d}^{-1}\,.$$

The 1995 DPRK nuclear crisis and then JCPOA (Iran deal) are useful sandboxes.

Christensen, *et al.* 2013 & 2014

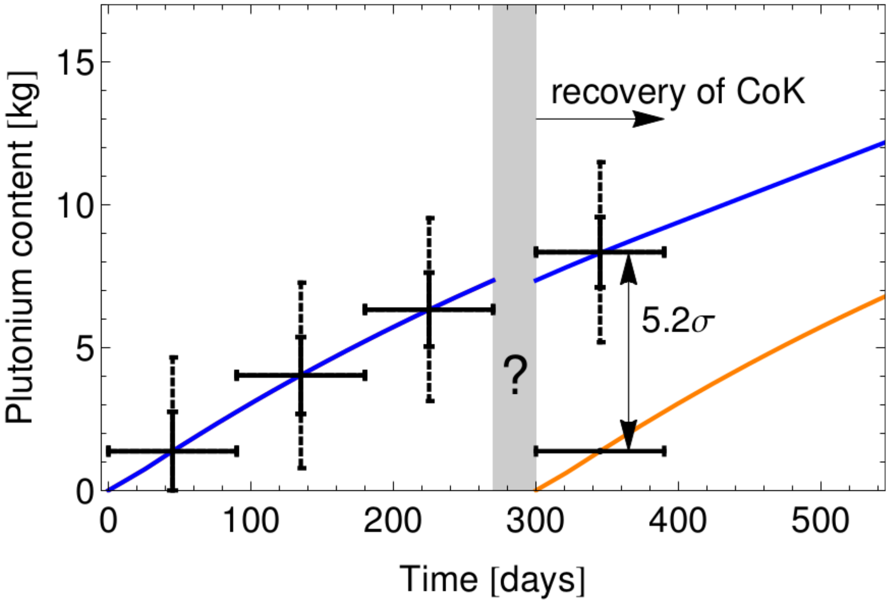
Confronting backgrounds – reactor on/off

5MWe	IR40	ELWR
1.2 days	8 hours	1.5 hours

95% CL to detection

20m standoff, i.e. directly outside of the reactor building.

Confronting backgrounds – reactor core/swap detection



BG level	5MWe	IR40	ELWR
1	1154	109	134
0.5	830	59	83
0.2	637	30	56
0	528	16	45

95% CL detection time in days

20m standoff, i.e. directly outside of the reactor building.

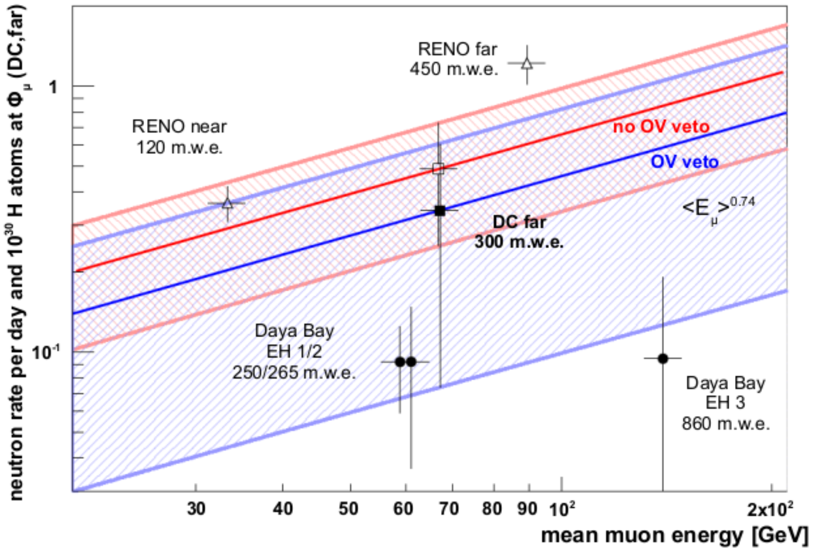
Confronting backgrounds – reprocessing waste

1 SQ Pu results in 2 mol of Sr90 = 11 IBD events at 10m in 1ton detector per year

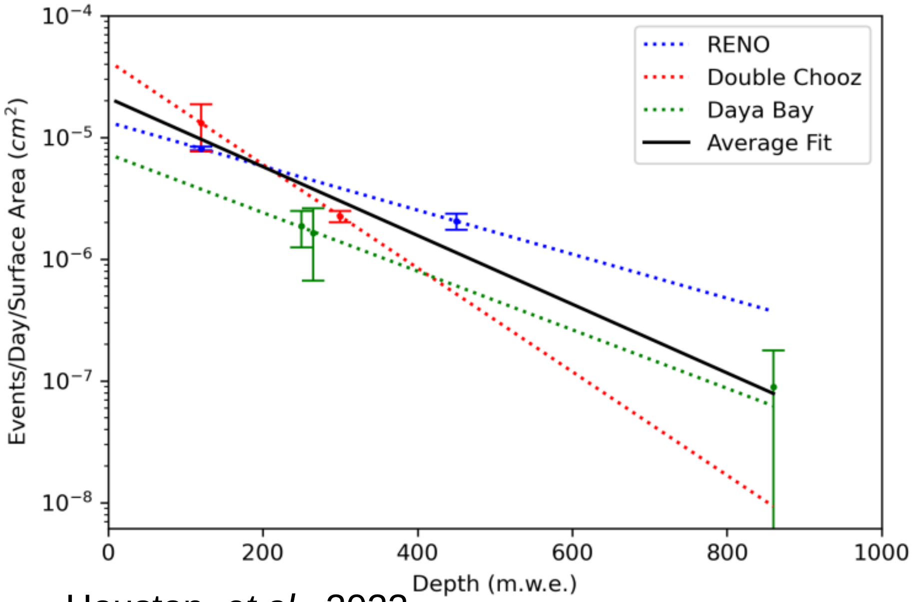
BG level	1SQ	10SQ	100SQ
1	170	1.7	0.018
0.1	17	0.18	0.0024
0.01	1.7	0.024	0.0009

95% CL to detection, time in years

Background models



Double Chooz 2012



Houston, *et al.*, 2023

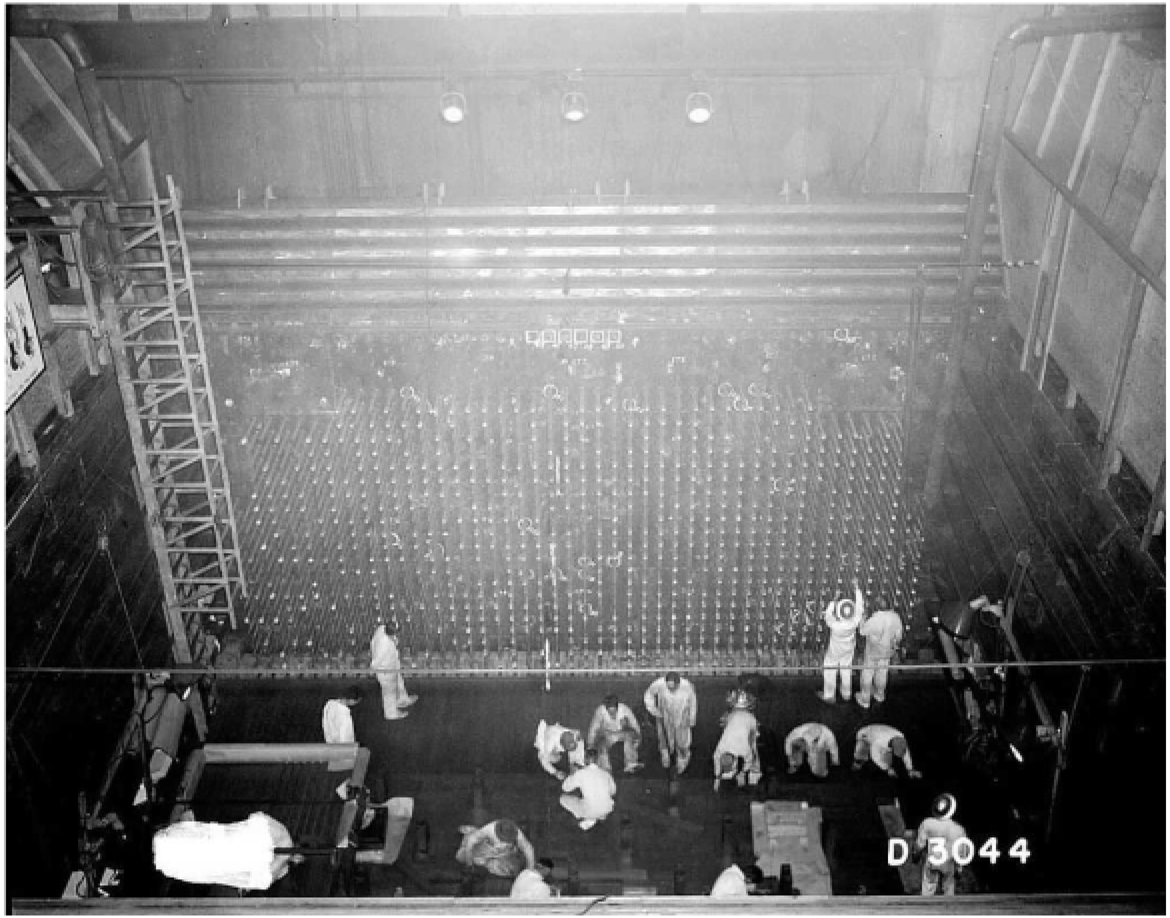
Predicting backgrounds is hard! – need to measure, but how *in situ*?

Reactor off periods may not be available

Historical weapons pathways

U.S.	Hanford, graphite
Russia	Mayak, graphite
U.K.	Windscale, graphite
France	Marcoule, heavy water
China	uranium enrichment
Israel	Dimona, heavy water
South Africa	uranium enrichment
India	CIRUS, heavy water
Pakistan	uranium enrichment
DPRK	Yongbyon, graphite

For smaller weapons programs typical reactor power is around **100MW – not your typical PWR**



Hanford B reactor making plutonium for the Trinity test

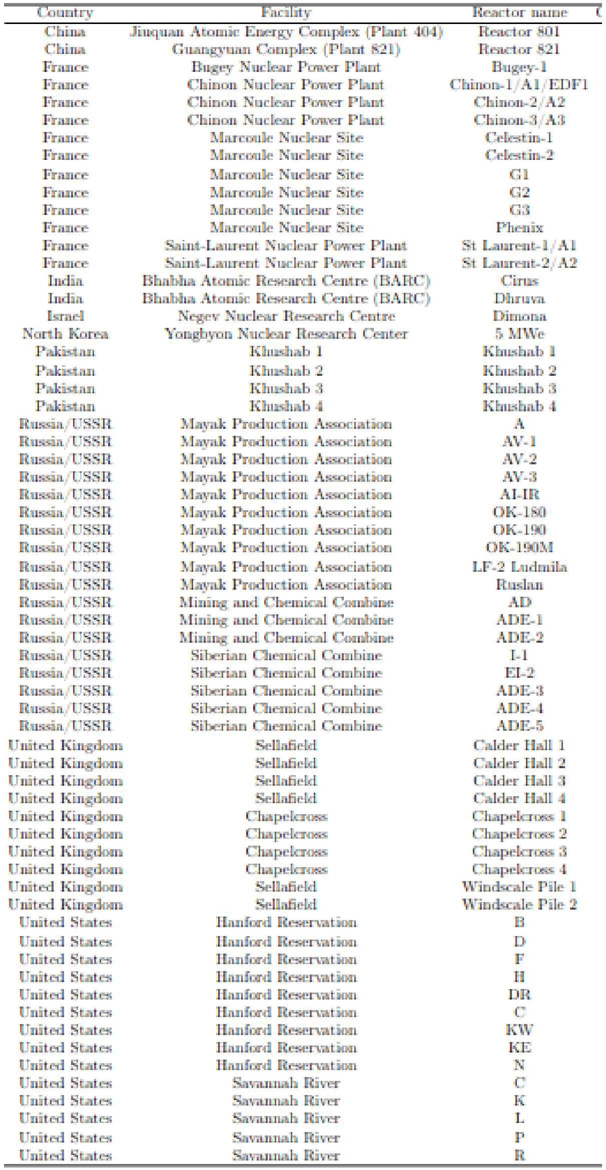
Historic plutonium production reactors

- 9 countries have produced plutonium for weapons use, and hence have or have had reactors for this purpose
- These 64 reactors and 18 facilities are known

This represents a data set

- spanning 7 decades
- small to very large weapons programs, 10s – 10,000s of weapons
- democracies and authoritarian states
- Cold War and post-Cold War

The following is work in preparation with R. Carr & B. Cogswell



Country	Facility	Reactor name
China	Jiuquan Atomic Energy Complex (Plant 404)	Reactor 801
China	Guangyuan Complex (Plant 821)	Reactor 821
France	Bugey Nuclear Power Plant	Bugey-1
France	Chinon Nuclear Power Plant	Chinon-1/A1/EDF1
France	Chinon Nuclear Power Plant	Chinon-2/A2
France	Chinon Nuclear Power Plant	Chinon-3/A3
France	Marcoule Nuclear Site	Celestin-1
France	Marcoule Nuclear Site	Celestin-2
France	Marcoule Nuclear Site	G1
France	Marcoule Nuclear Site	G2
France	Marcoule Nuclear Site	G3
France	Marcoule Nuclear Site	Phenix
France	Saint-Laurent Nuclear Power Plant	St Laurent-1/A1
France	Saint-Laurent Nuclear Power Plant	St Laurent-2/A2
India	Bhabha Atomic Research Centre (BARC)	Cirus
India	Bhabha Atomic Research Centre (BARC)	Dhruva
Israel	Negev Nuclear Research Centre	Dimona
North Korea	Yongbyon Nuclear Research Center	5 MWe
Pakistan	Khushab 1	Khushab 1
Pakistan	Khushab 2	Khushab 2
Pakistan	Khushab 3	Khushab 3
Pakistan	Khushab 4	Khushab 4
Russia/USSR	Mayak Production Association	A
Russia/USSR	Mayak Production Association	AV-1
Russia/USSR	Mayak Production Association	AV-2
Russia/USSR	Mayak Production Association	AV-3
Russia/USSR	Mayak Production Association	AI-IR
Russia/USSR	Mayak Production Association	OK-180
Russia/USSR	Mayak Production Association	OK-190
Russia/USSR	Mayak Production Association	OK-190M
Russia/USSR	Mayak Production Association	LF-2 Ludmila
Russia/USSR	Mayak Production Association	Ruslan
Russia/USSR	Mining and Chemical Combine	AD
Russia/USSR	Mining and Chemical Combine	ADE-1
Russia/USSR	Mining and Chemical Combine	ADE-2
Russia/USSR	Siberian Chemical Combine	I-1
Russia/USSR	Siberian Chemical Combine	EI-2
Russia/USSR	Siberian Chemical Combine	ADE-3
Russia/USSR	Siberian Chemical Combine	ADE-4
Russia/USSR	Siberian Chemical Combine	ADE-5
United Kingdom	Sellafield	Calder Hall 1
United Kingdom	Sellafield	Calder Hall 2
United Kingdom	Sellafield	Calder Hall 3
United Kingdom	Sellafield	Calder Hall 4
United Kingdom	Chapelcross	Chapelcross 1
United Kingdom	Chapelcross	Chapelcross 2
United Kingdom	Chapelcross	Chapelcross 3
United Kingdom	Chapelcross	Chapelcross 4
United Kingdom	Sellafield	Windscale Pile 1
United Kingdom	Sellafield	Windscale Pile 2
United States	Hanford Reservation	B
United States	Hanford Reservation	D
United States	Hanford Reservation	F
United States	Hanford Reservation	H
United States	Hanford Reservation	DR
United States	Hanford Reservation	C
United States	Hanford Reservation	KW
United States	Hanford Reservation	KE
United States	Hanford Reservation	N
United States	Savannah River	C
United States	Savannah River	K
United States	Savannah River	L
United States	Savannah River	P
United States	Savannah River	R

Carr, Cogswell, PH, in preparation

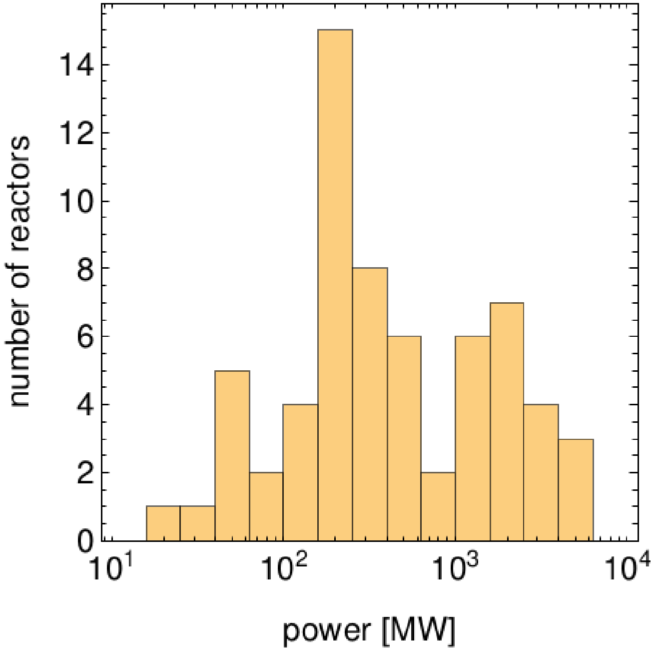
Historic plutonium production reactors – geotagging

Google Earth to determine the exact location and the distance to the fence.

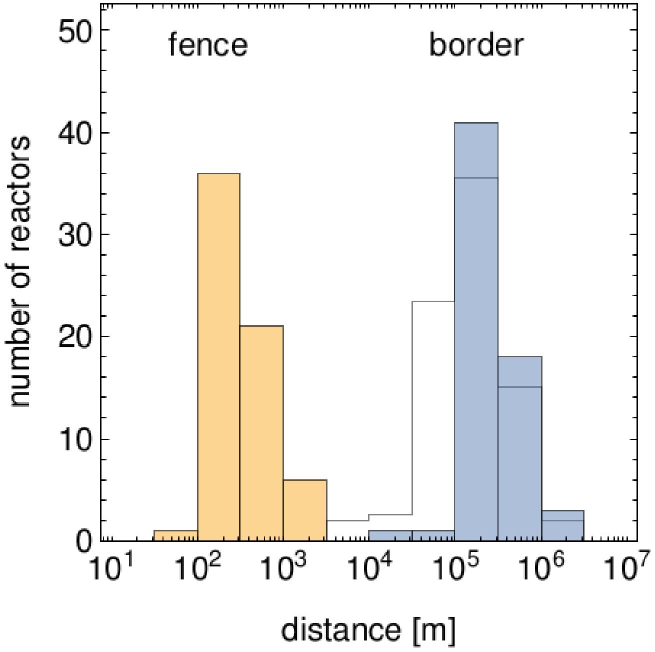
Mathematica geocomputation tools to determine the distance to closest land border or sea shore.

Carr, Cogswell, PH, in preparation

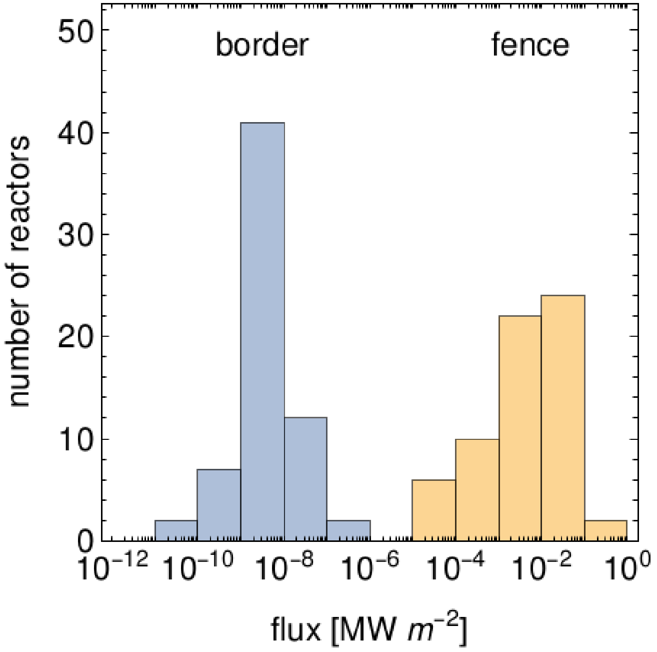
Power, fence & border distances



25 – 2500 MWth



75 – 1500m (fence)
20 – 1720km (border)



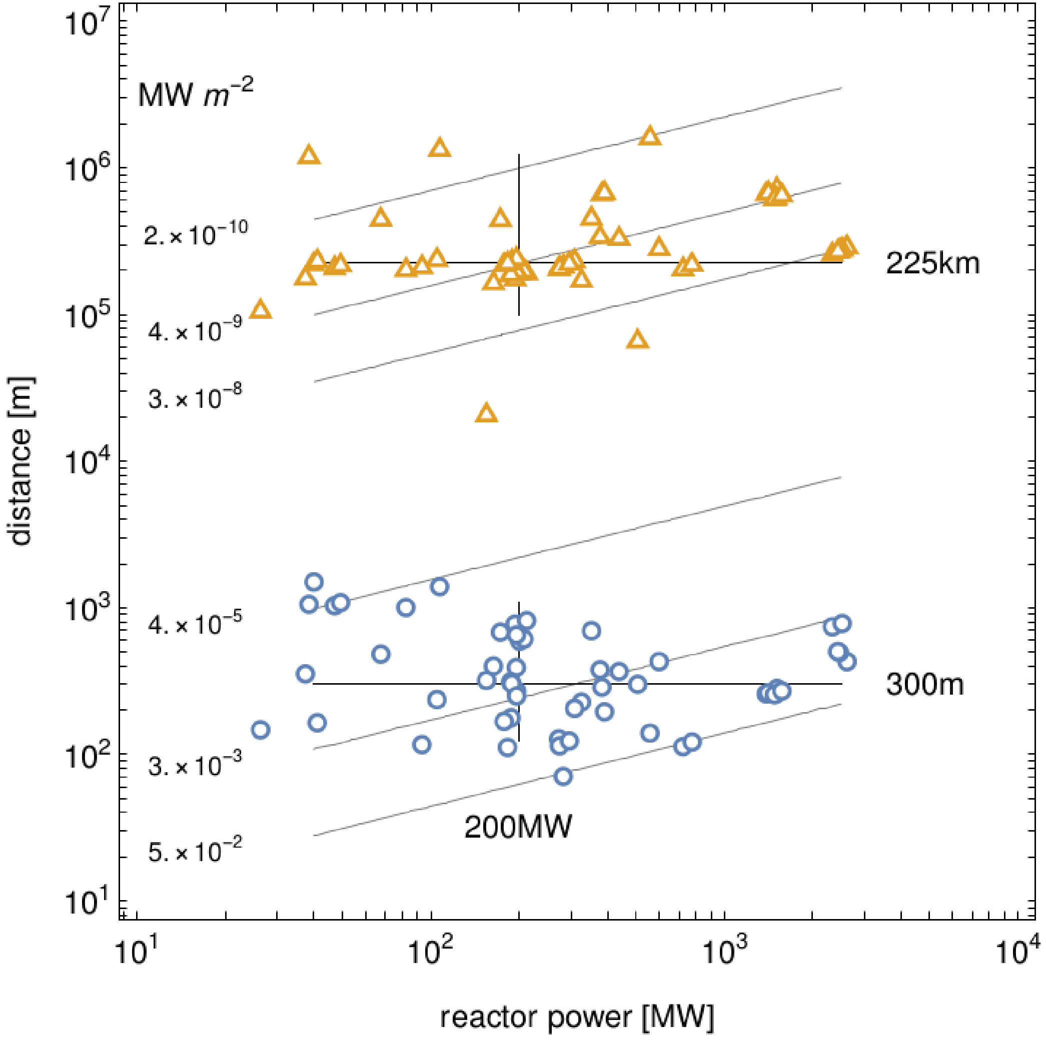
1.8E-5 – 5.3E-2 (fence)
2.6E-11 – 3.8E-7 (border)

Carr, Cogswell, PH, in preparation

Flux levels

For comparison

- PROSPECT 0.1 MW/m^2
- MiniCHANDLER 0.3 MW/m^2
- PANDA 0.1 MW/m^2



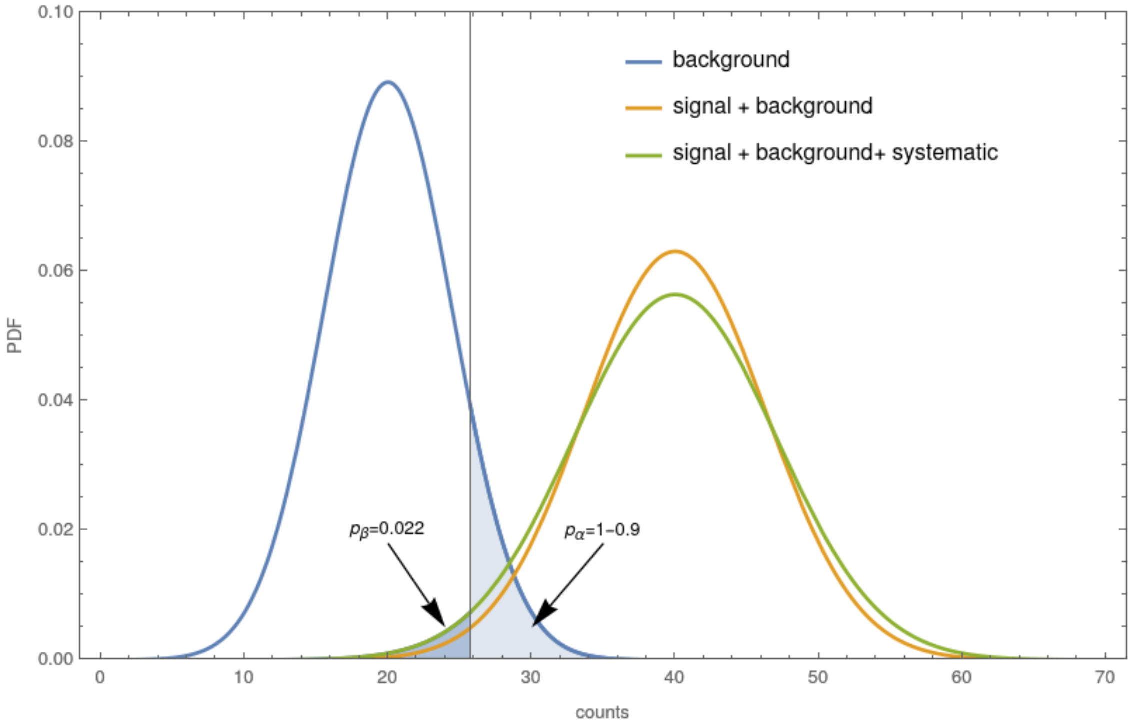
Carr, Cogswell, PH, in preparation

Statistics 101

The goal is to discern the presence/absence of a signal relative to a non-zero background. This is a hypothesis test.

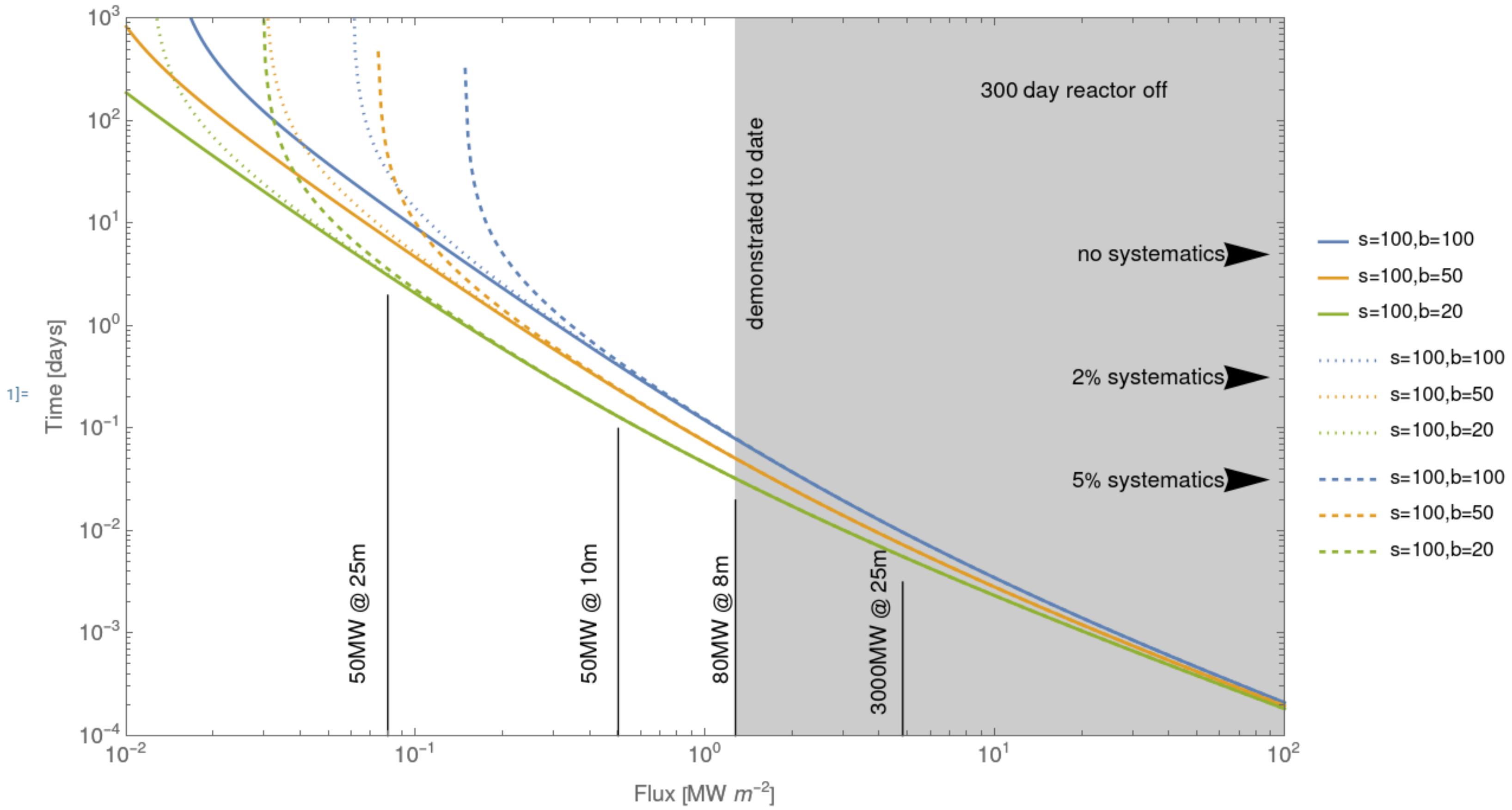
Assuming normal distributed counts, we can solve this analytically and fix for instance

- the error of first kind to 10%
- and find the error of second kind to be 2.2%



Systematics on either the background and/or signal make the variance of the distributions larger and in particular, may **prevent us from reaching certain error goals even in the case of infinite statistics**!

Backgrounds & systematics – toy example



Backgrounds & systematics

For IBD detection in segmented scintillator

- 40% signal efficiency
- Surface: 54 events/ton/day (PROSPECT II)
- Shallow underground: 0.5 events/ton/day (scaling model)

For IBD detection in monolithic large detector, Gd-doped

- 40% signal efficiency
- Deep underground: 0.3–0.6 events/ton/year (Super-K)

For ES detection in monolithic large detector we find that even with Borexino level backgrounds no gains over IBD are obtained.

For all cases we compute the global reactor neutrino background

We neglect oscillation, it suppresses signal and background at a very similar level.

We assume a **1% systematic** on the combined background.

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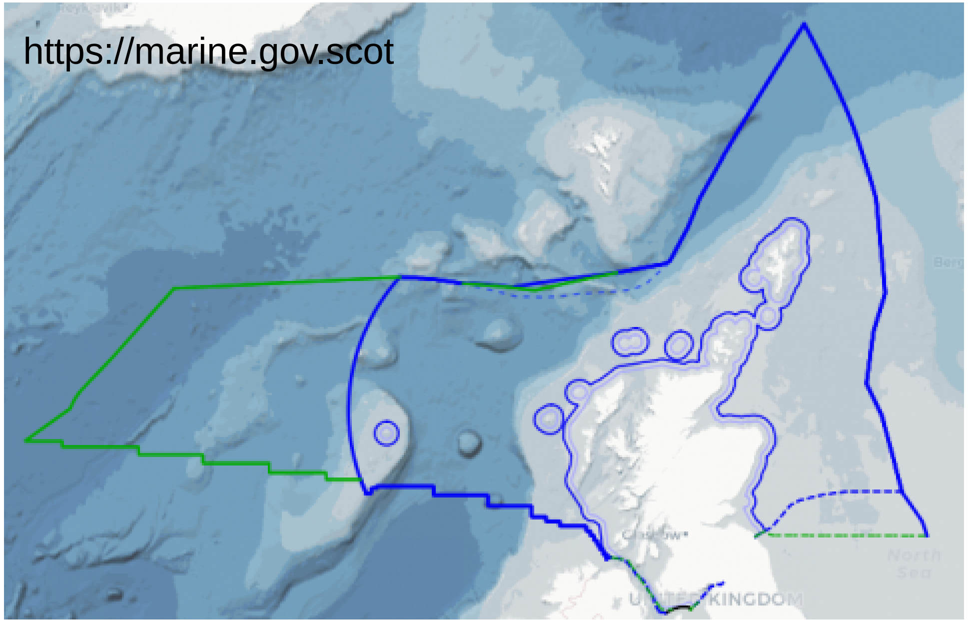
Note on sea shores and ocean deployed detectors

The sea shore is not the boundary of national territorial control, many countries use 12 nautical miles as definition – which we adopted for our study.

Facility	dry land distance [km]	sea floor distance [km]
Hanford	260	220
Annan	220	72
Sellafield A	180	27
Sellafield B	180	27
BARC	620	35



NB: The closest sites at 12 nautical miles all seem be in shallow water, we still use them since we did not make any allowance for overburden availability for dry-land detectors either.

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Figure of merit

It also requires detection of diversion of 1SQ within 90 days

In practice, for reactors, this leaves two choices:

- Detect when 1SQ has been produced, independent of how long this takes
- Measure for 90 days irrespective of how much plutonium is made

We chose as FOM the
Detection of the production of 1SQ irrespective of time at 95% C.L.

This results in smaller detector masses for smaller reactors and larger detector masses for larger reactors/facilities compared to a fixed 90 day time windosw.

IAEA specifies 90% detection probability with a 5% false positive rate as goal
IAEA Safeguards Glossary 2001

We find that this practically very close to the result obtained with the 95% C.L. criterion.

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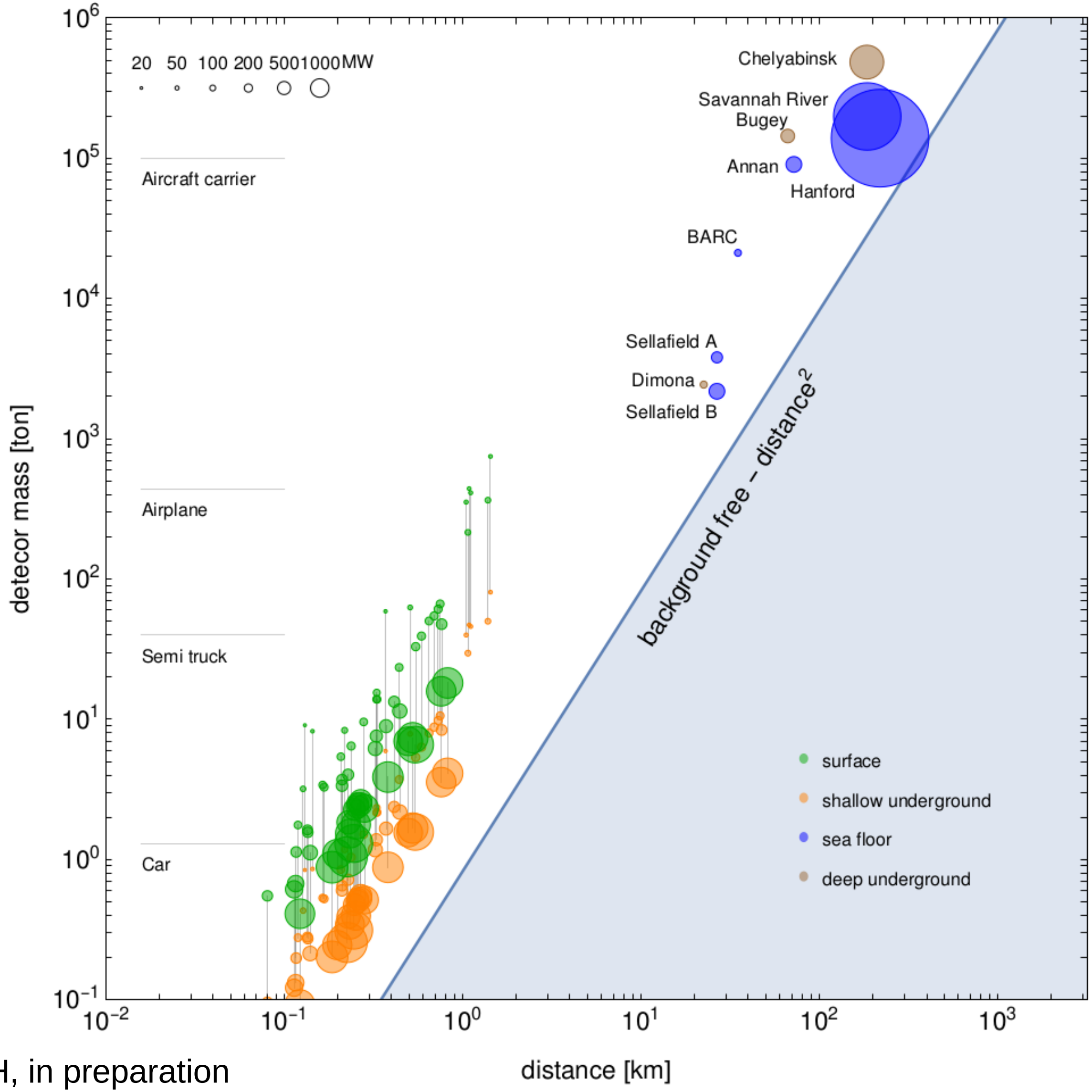
Resulting detector masses

Out of 64 reactors (fence case)
- 64 have finite mass detectors
- 58 have 20t shallow underground detector

Out of 18 facilities (border case)
- 4 have finite mass dry-land detectors
- 6 have finite mass ocean-deployed detectors
- 8 are inaccessible



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Summary

We have seen great progress in neutrino detection technology and case studies at all levels – reactor physics, end-user engagement.

For the simplest application case (Rx ON/OFF) at the reactor building current performance probably good enough.

For anything else we still need better S/B: reactor burnup verification, deployments at fence of facility, spent fuel, SMRs, fast reactors etc.

The question of how we know the background and how well we know it becomes critical, e.g. Rx OFF data may not be available.

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