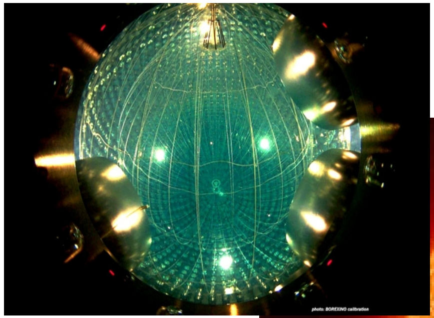
The SoLid experiment

Neutrino physics at a Belgian reactor

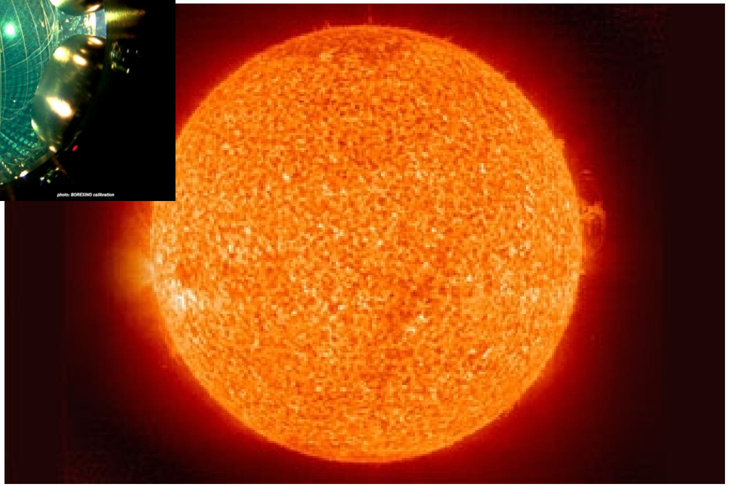
Petra Van Mulders

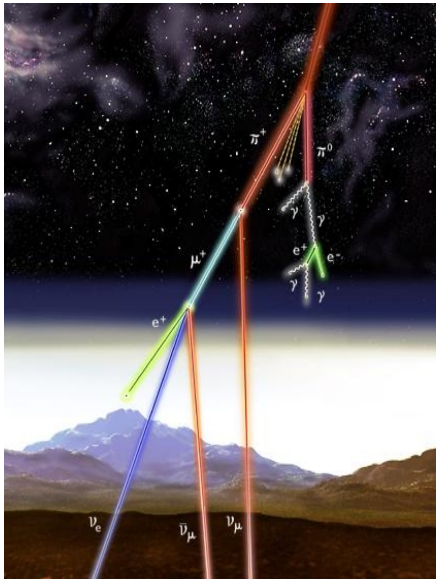
April 17, 2015

Sources of neutrinos and experiments

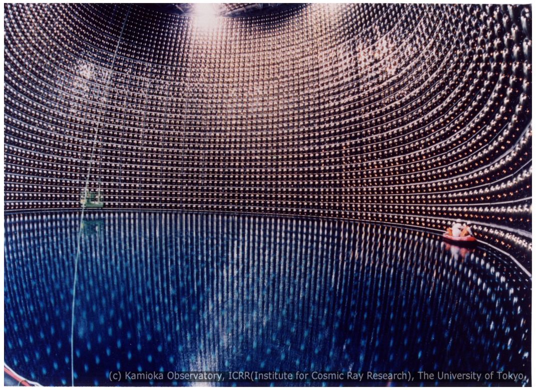


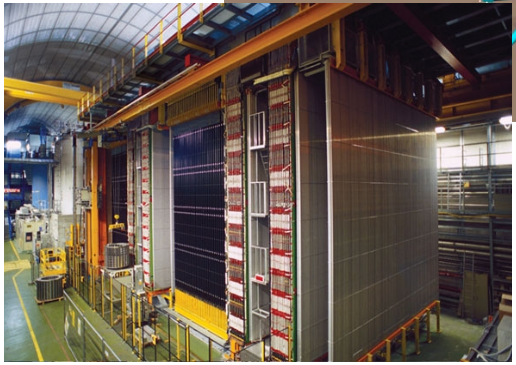
e.g. Borexino





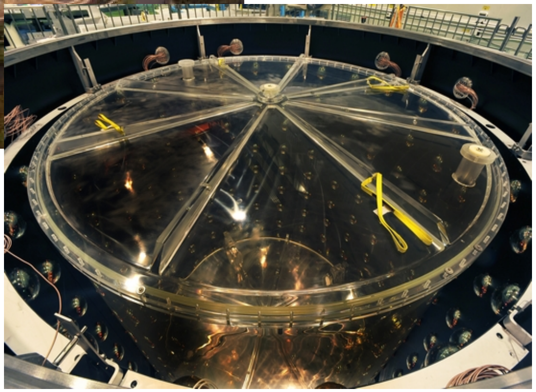
e.g. super kamiokande



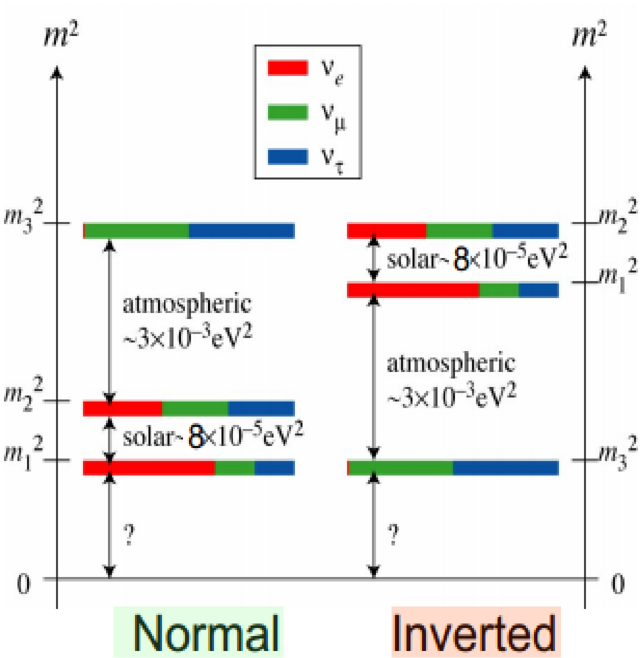


e.g. OPERA

e.g. Daya Bay



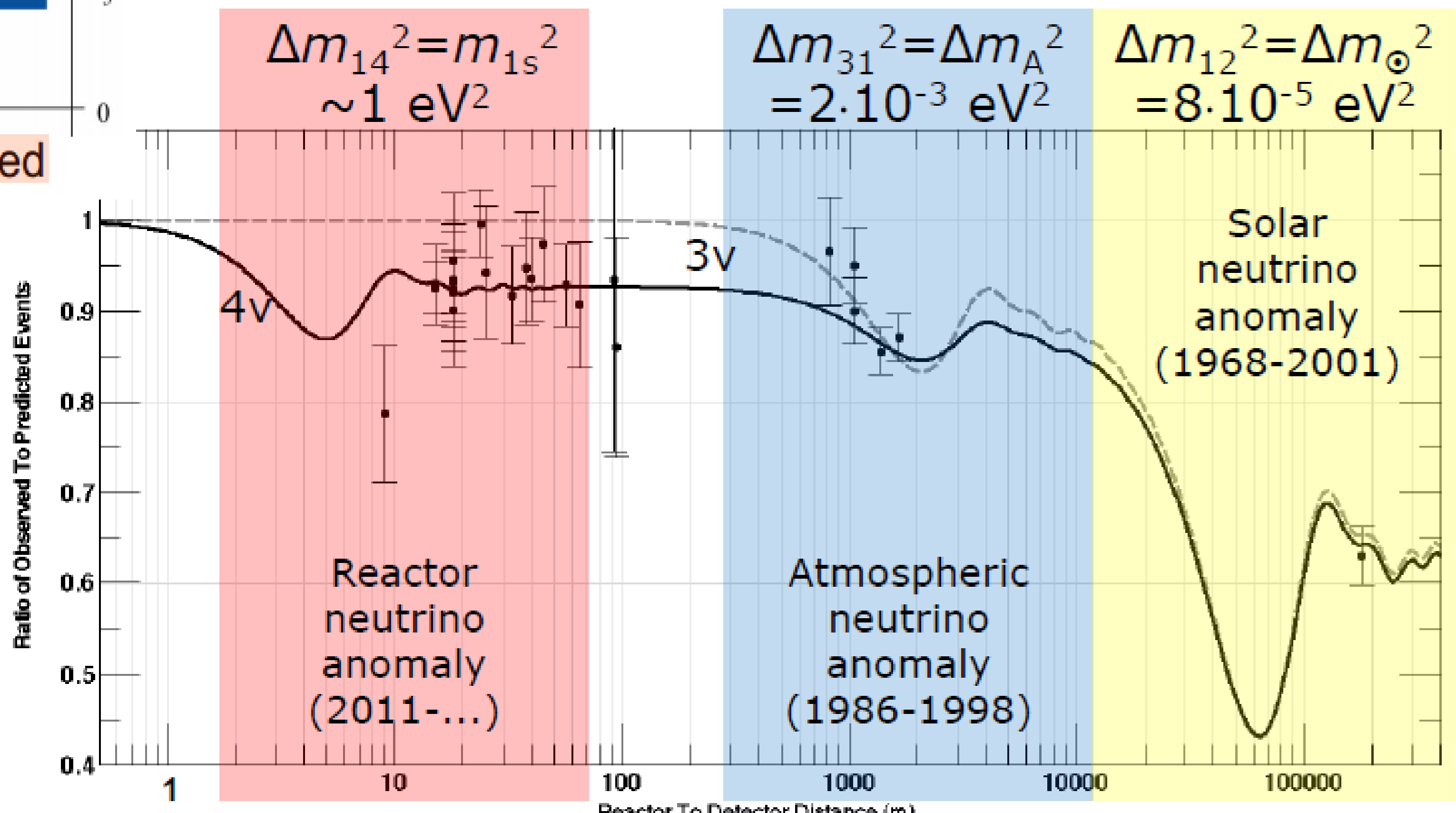
Experimental findings on neutrino properties



- 2 differences between squared masses (Δm^2)
- 3 mixing angles ($\sin^2\theta$) → PMNS matrix

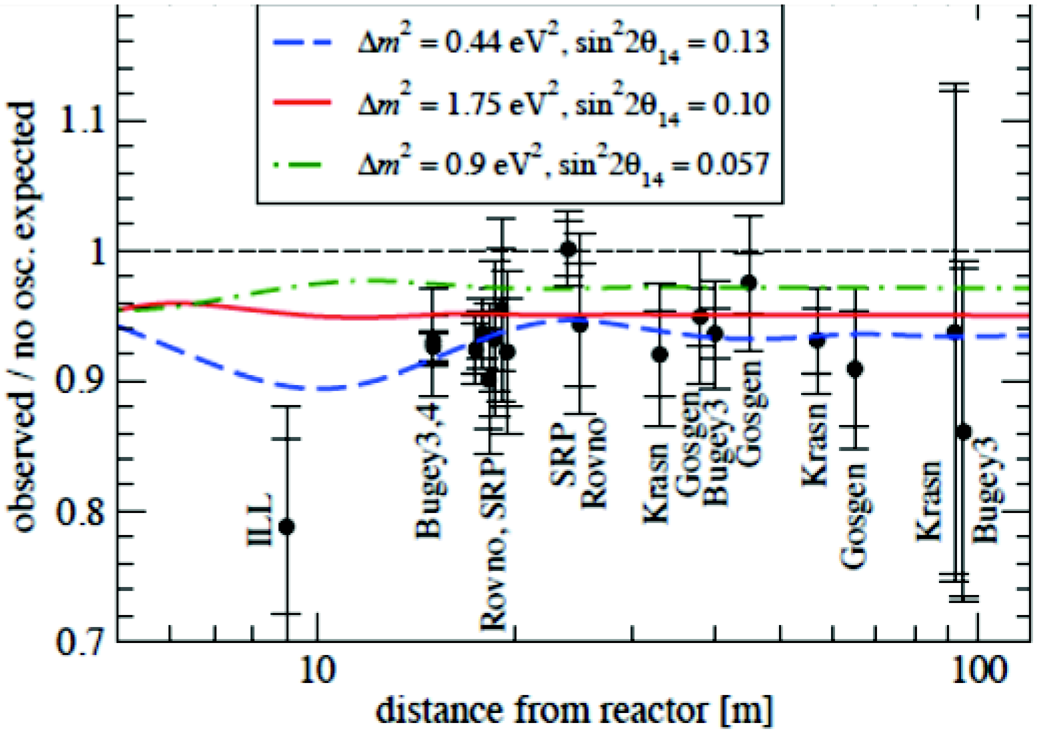
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

- We don't know
  - Mass hierarchy
  - CP violation
  - How to explain the anomaly at short distance



Graph from Th. Lasserre, (

The reactor antineutrino anomaly

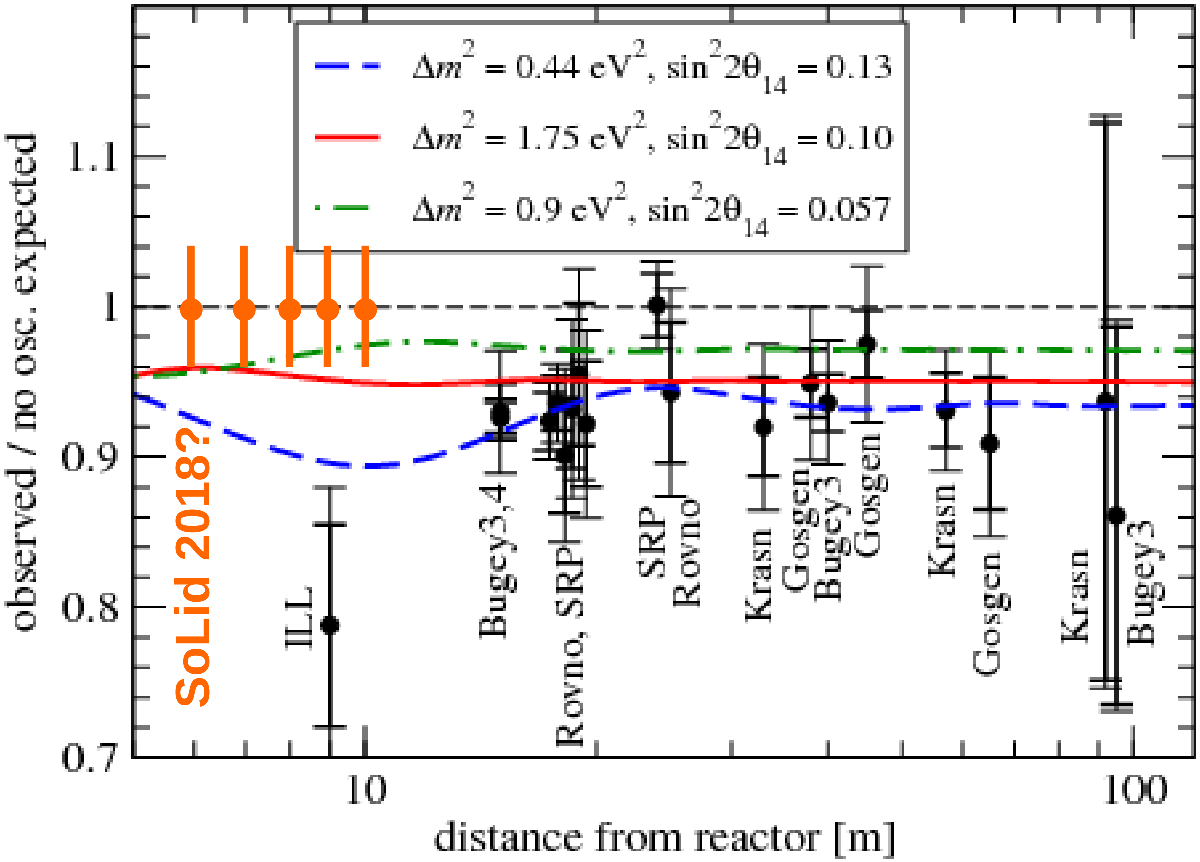


From J. Kopp, et al.
JHEP 05 (2013)050

- Deficit in the observed number of antineutrinos with respect to the expected number (5-10% or ~3σ) for short baseline experiments
  - Predicted flux could be wrong (see also A. Hayes, invited seminar March 12)
    → very hard calculation with lot of assumptions / large uncertainty
  - New physics (e.g. antineutrinos oscillate to a ~1eV 'sterile' neutrino)

Aim of the SoLid experiment

- **S**hort baseline **O**scillation search with **Li**thium-6 **D**etector
  - Confirm or rule out the reactor anomaly within the next 3 years
  - Measure and calculate precisely the electron anti-neutrino flux at very short distance from the reactor core



The SoLid experiment:

Sensitivity to the oscillation to a new unseen neutrino species with $\Delta m^2 \sim 1 eV^2$ with respect to the known mass states over a wide range of mixing angles

The SoLid collaboration

- 3 countries, 9 institutes, ~45 people (IIHE: Jorgen, Simon, Petra)

UK — University of Oxford, University of Bristol

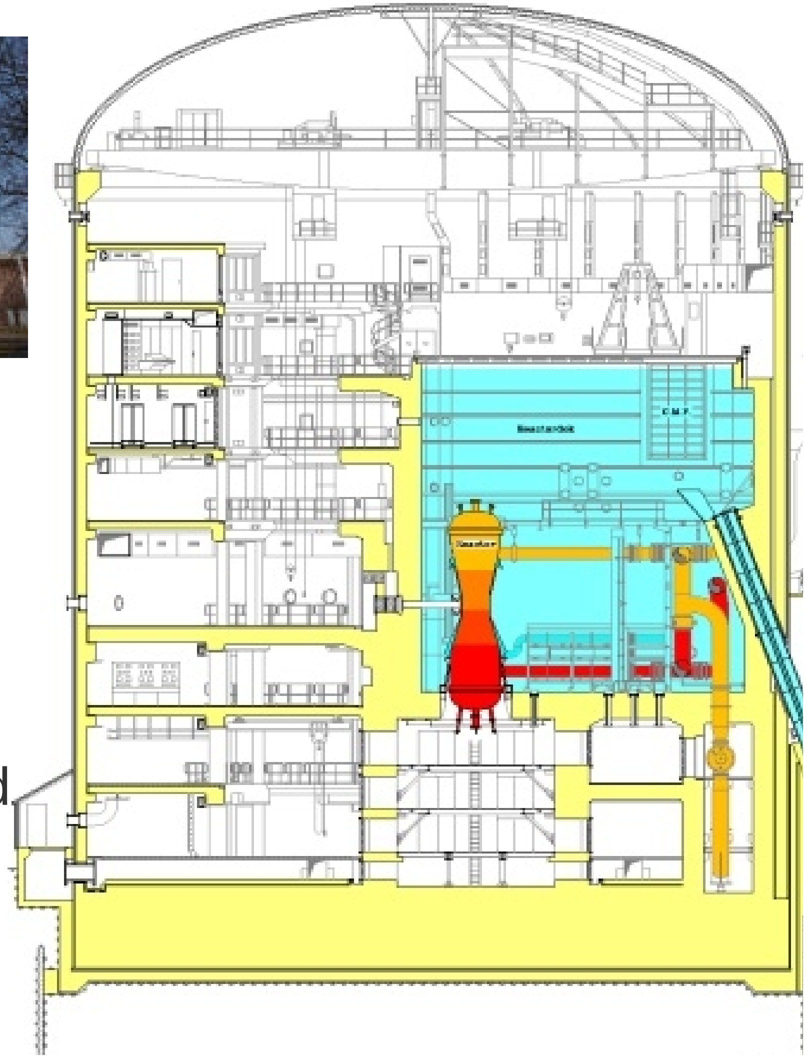
Belgium — SCK•CEN (Studiecentrum voor Kernenergie / Centre d'Etude de l'Energie Nucléaire), Universiteit Antwerpen, Vrije Universiteit Brussel, Universiteit Gent

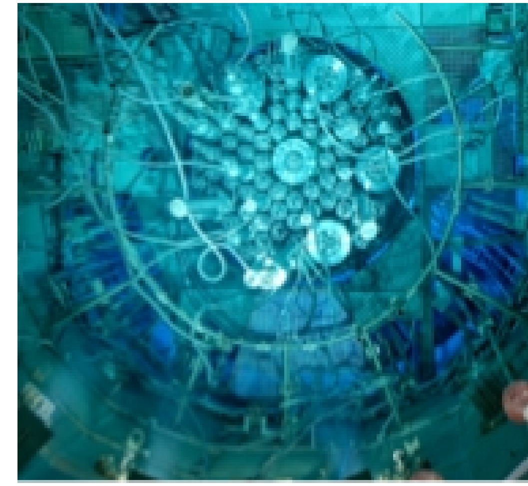
France — LPC Caen, LAL (Laboratoire de l'Accélérateur Linéaire), Subatech

SCK-CEN

https://www.sckcen.be/

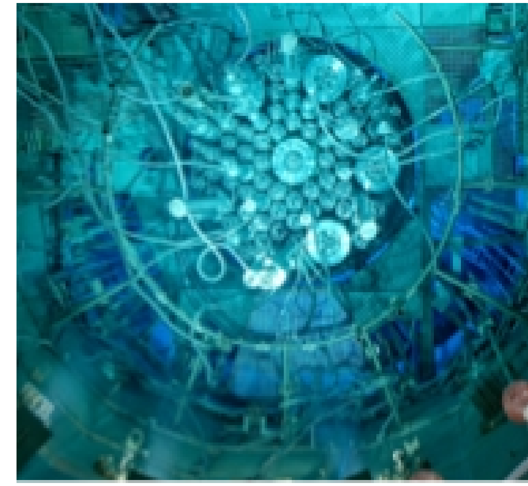
The BR2 reactor at SCK-CEN





- Tank in pool reactor for material irradiation
- Compact core
- Low background
- Highly enriched uranium
- 45 – 75 MW thermal power

The BR2 reactor at SCK-CEN



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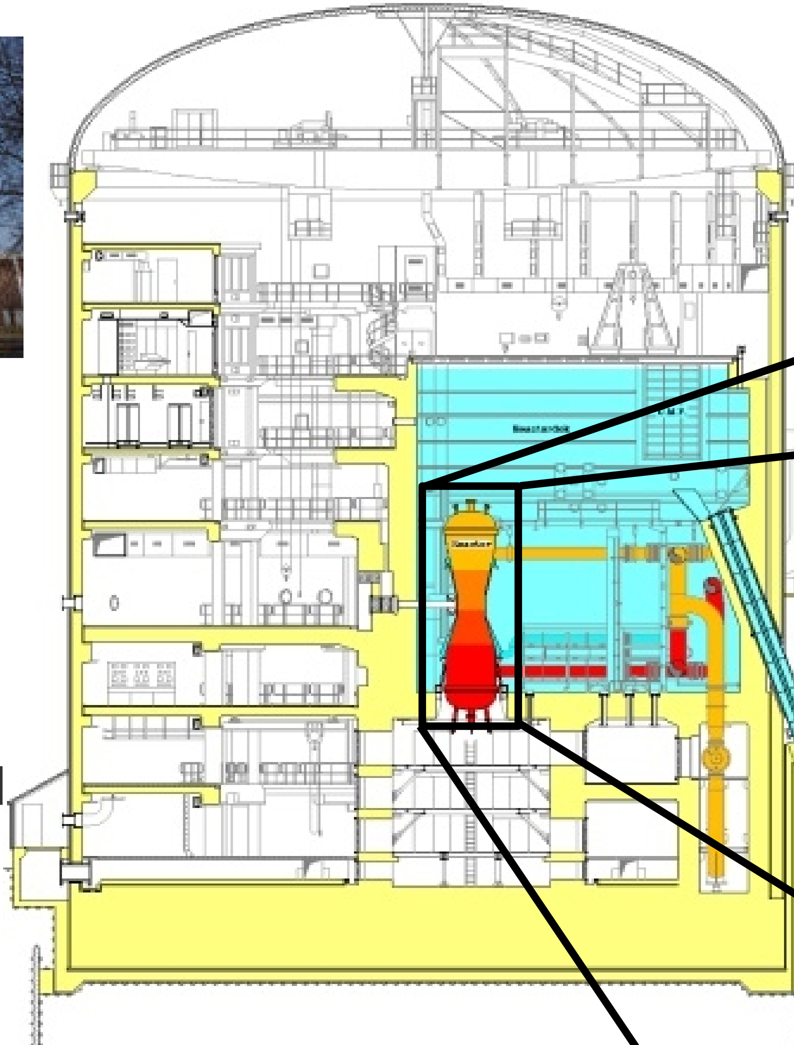

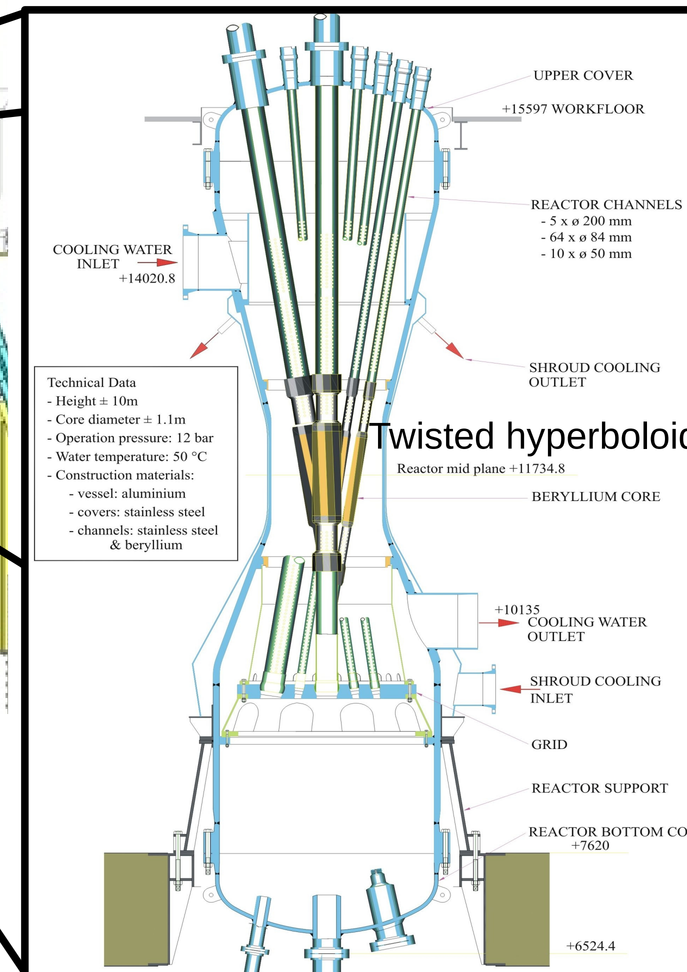

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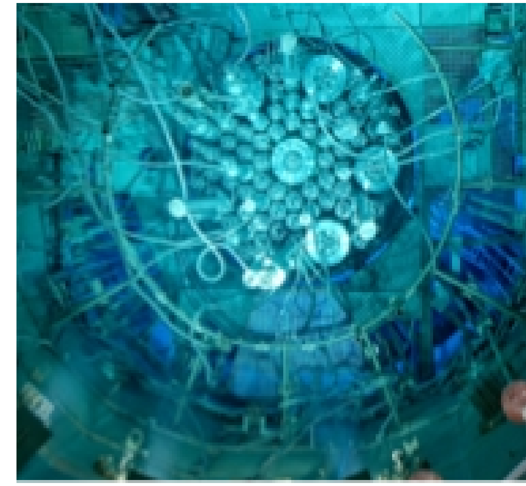

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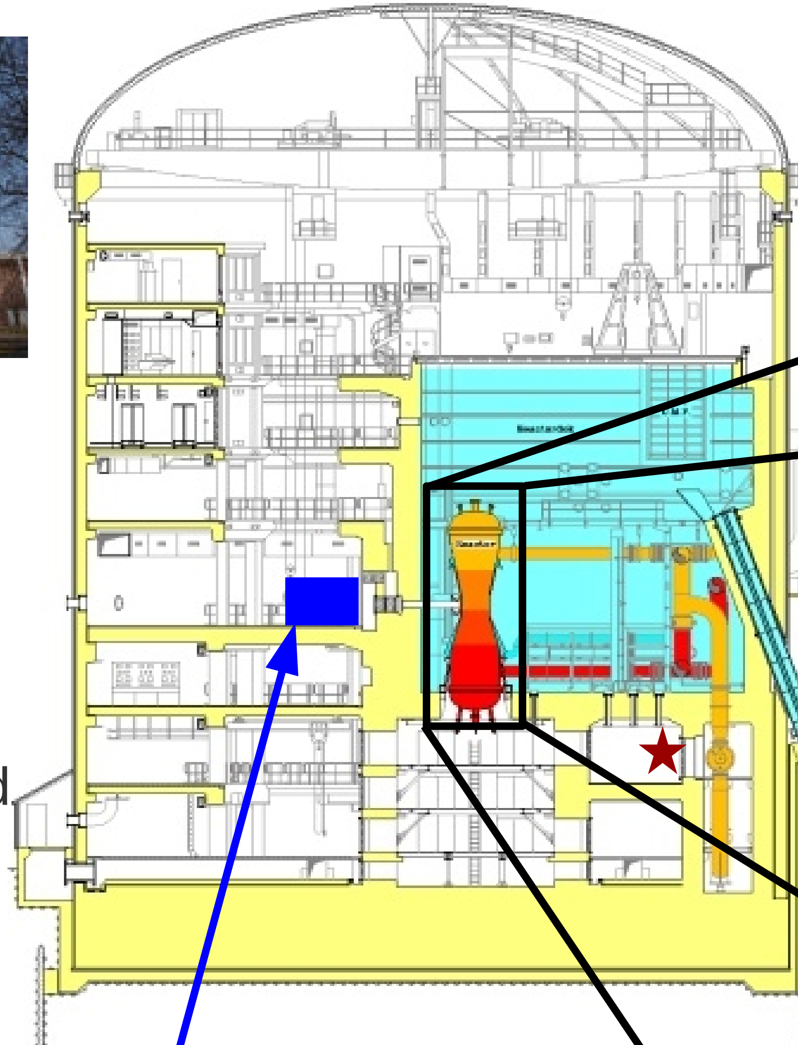
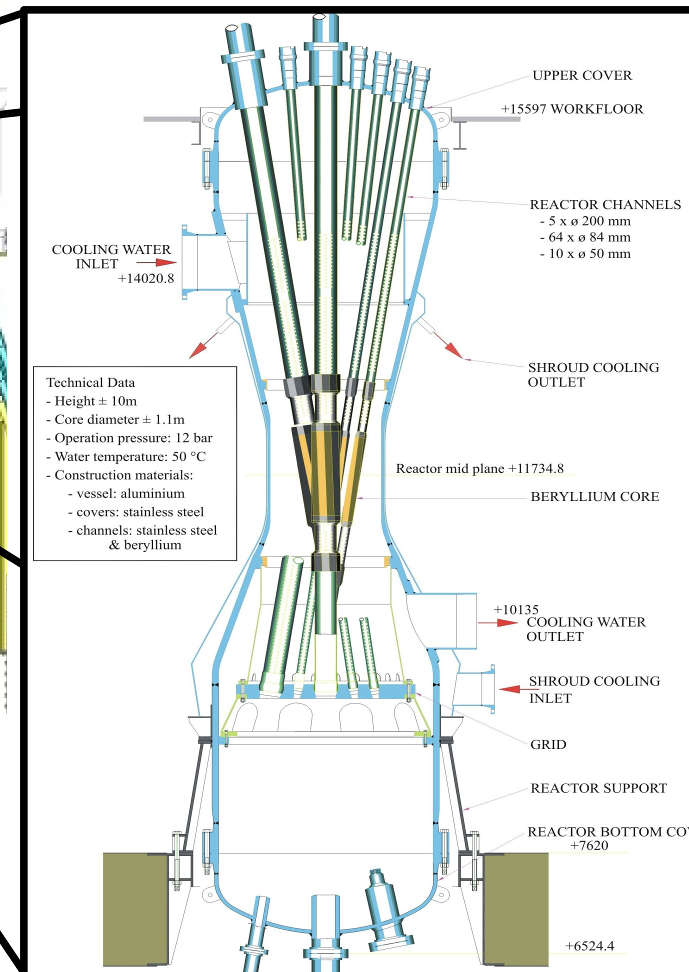


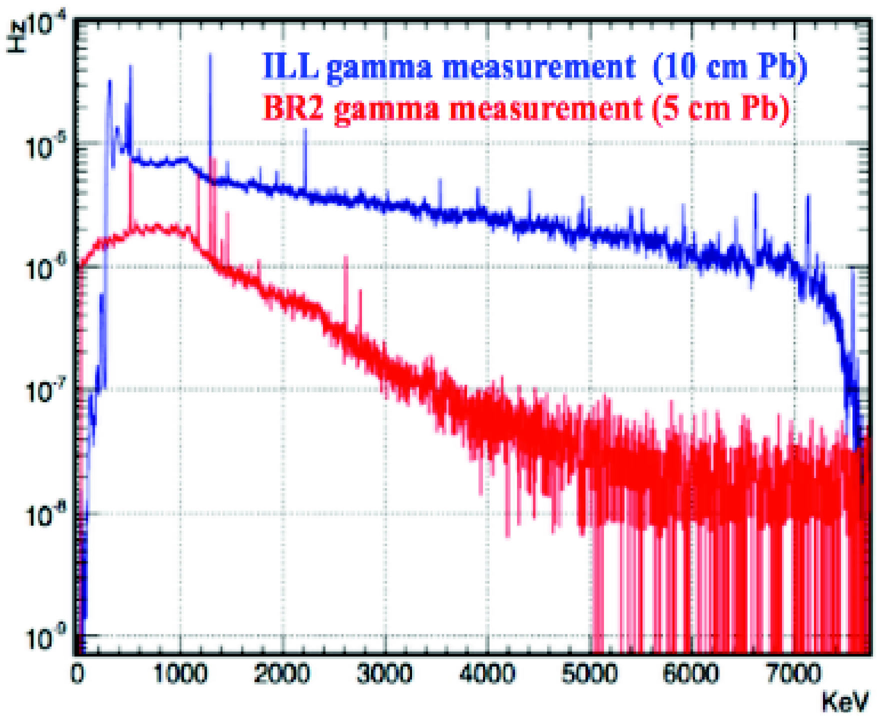


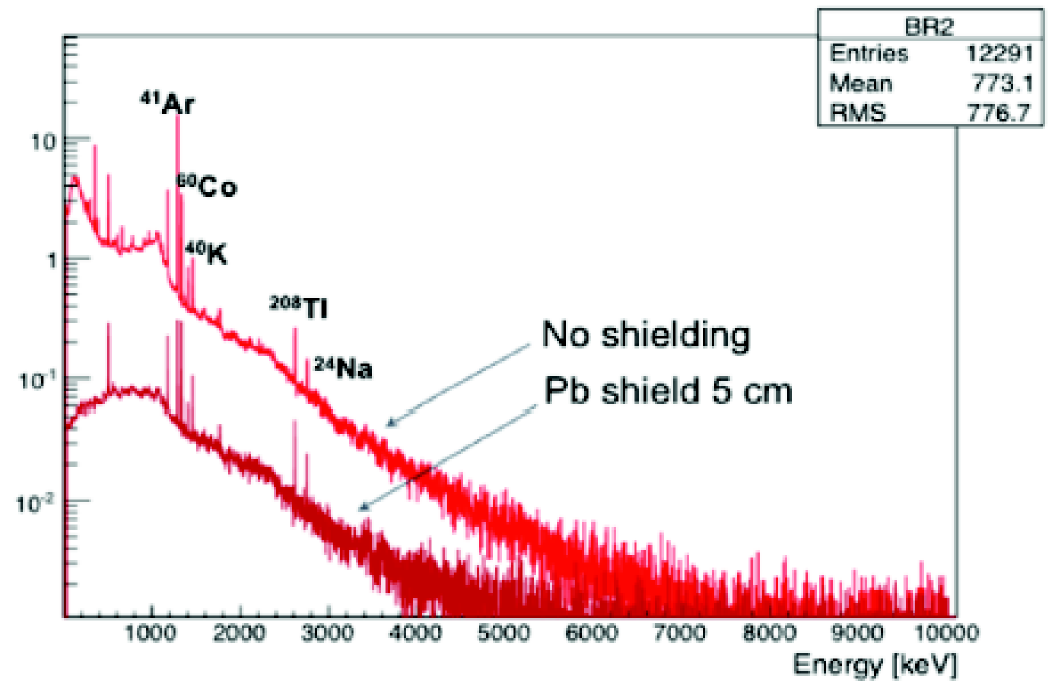
SoLid experiment on axis with reactor core (minimal distance of 5.5 meters)

→ relatively low background from γ and neutrons

Relatively low background from γ rays @ BR2

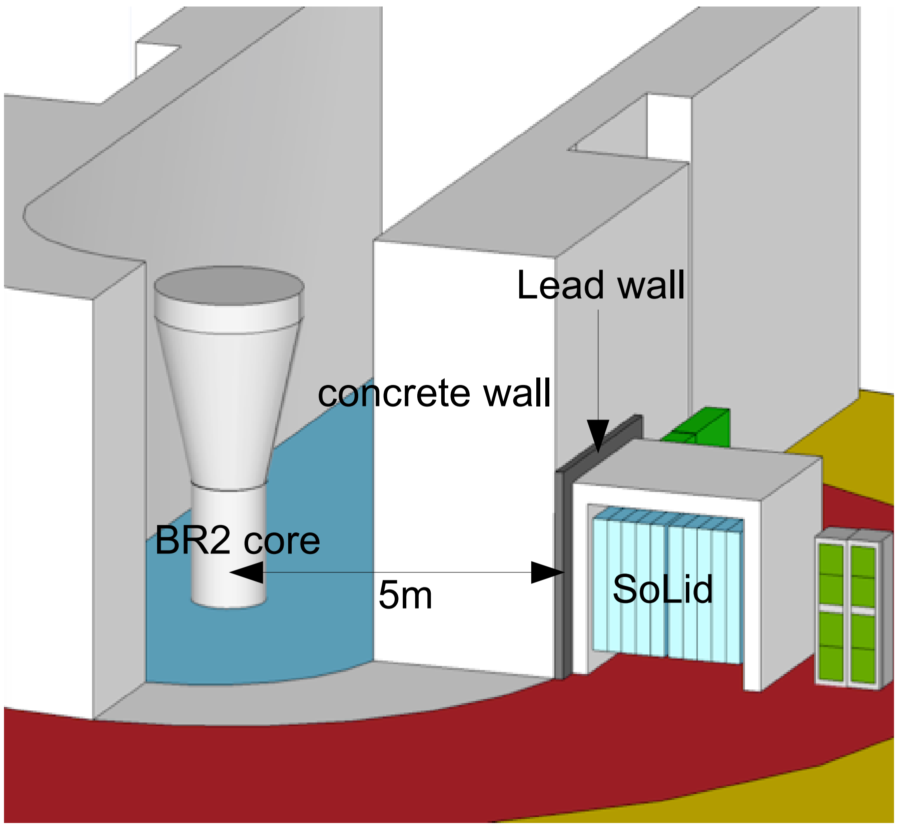
- Compared to other (research) reactors, the background is low:
  - Mostly low-energy (~1MeV) γ
  - Almost no reactor neutrons (stopped by the concrete wall)

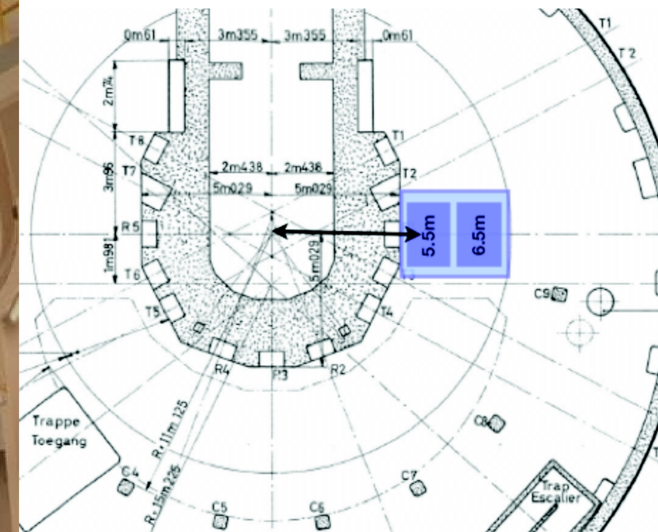




- Gamma-ray spectra measured with high-purity Ge detector
- Left: at level of SoLid detector, right: at level with low shielding

The SoLid experiment at BR2





- Baseline 5.5 – 11 meters
- Detector can be moved or extended
- Shielding (overburden) from cosmic rays is about 10 mwe
- ~150 days of data per year (4 – 6 cycles of about 25 days) from Spring 2016 onwards

Outline

- Production and detection of antineutrinos
- The SoLid detector technology
- The different phases of the SoLid experiment
  - Prototype: proof of concept
  - First submodule
- Reactor flux calculation
- Physics potential of the first submodule
- Towards the next phase of SoLid

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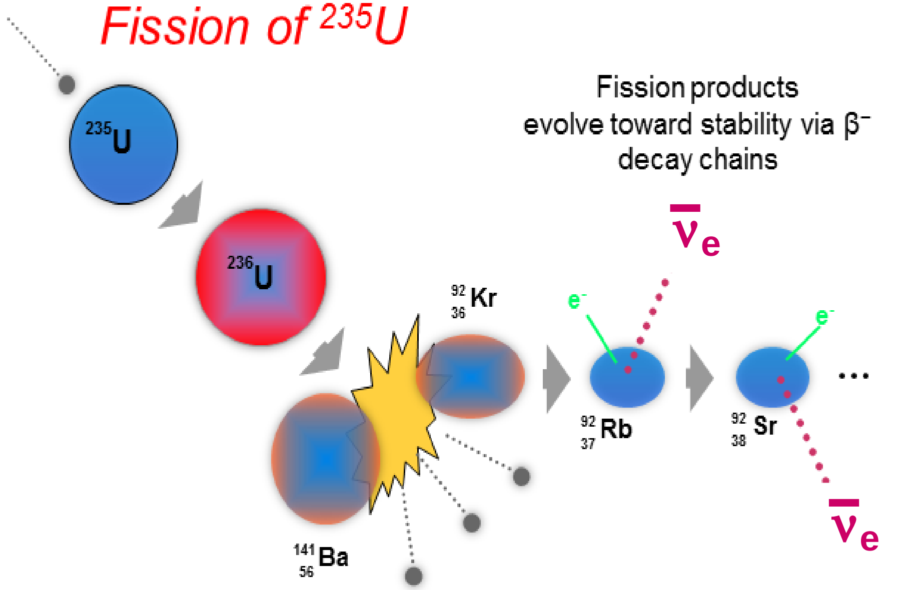
Production and detection of antineutrinos

- Antineutrinos are produced through beta decay:

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

Fission of ^{235}U

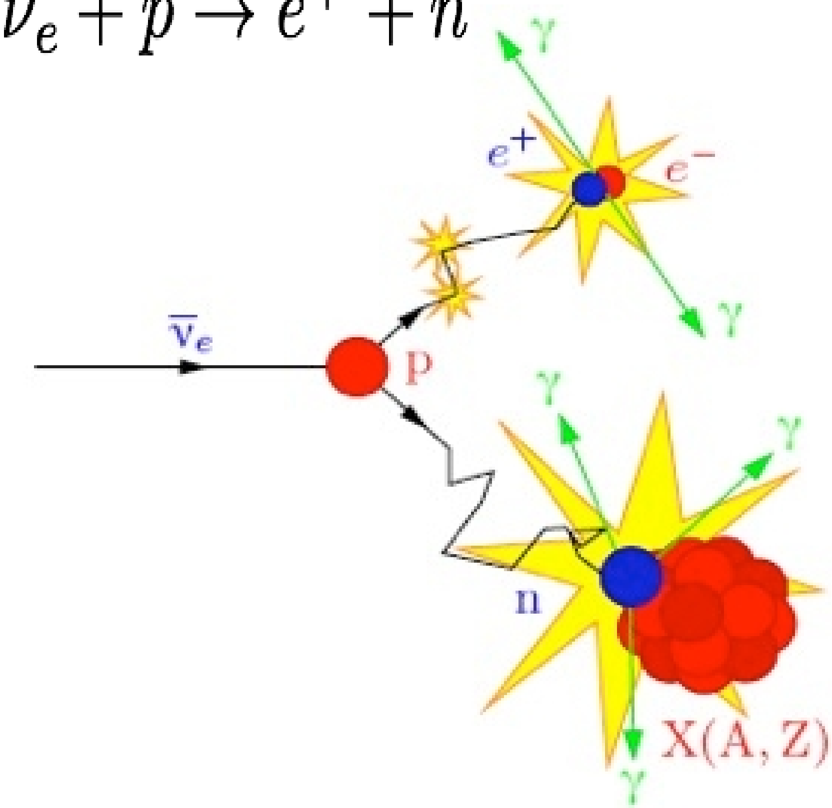


$$\langle N_{\bar{\nu}} \rangle / fission = 5.98 \quad \text{(no threshold)}$$

$$1GW_{th} \Rightarrow \approx 2.10^{20}\ \nu/s$$

- These antineutrinos can be detected through so-called inverse beta decay (IBD):

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

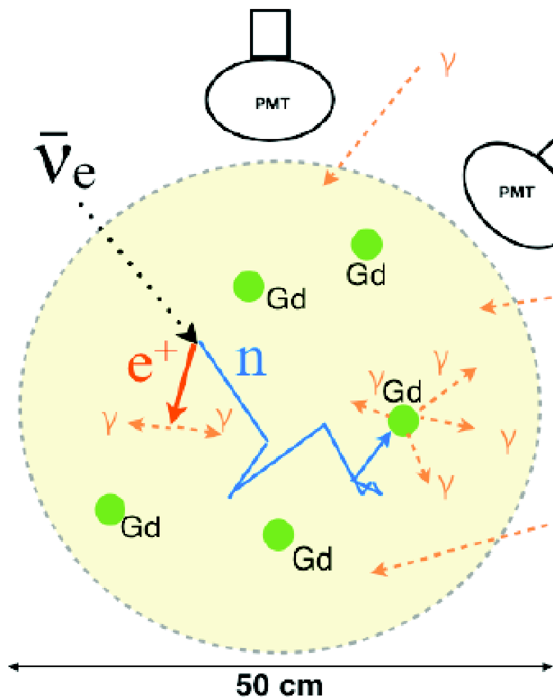


- BR2 uses highly enriched Uranium, Plutonium + decay products as fuel

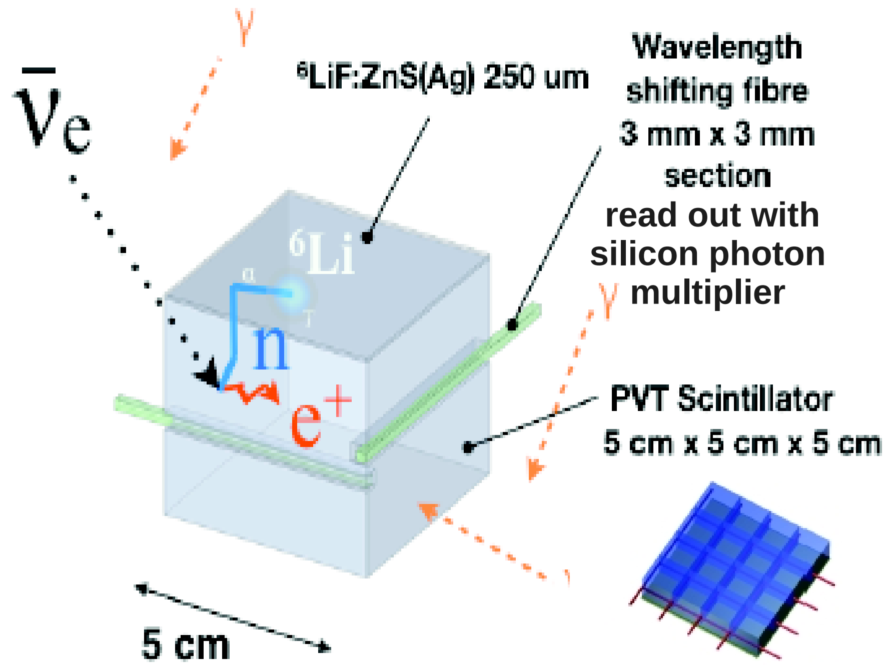
- In SoLid the neutron is captured by a Lithium-6 nucleus

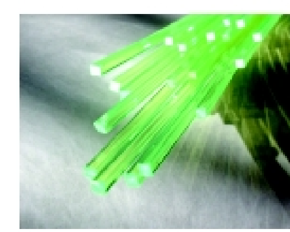
The SoLid detector technology

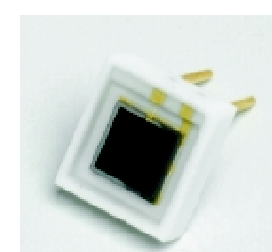
- Traditional approach: liquid scintillator doped with Gadolinium



- The SoLid detector: plastic scintillator with a Lithium-6 sheet

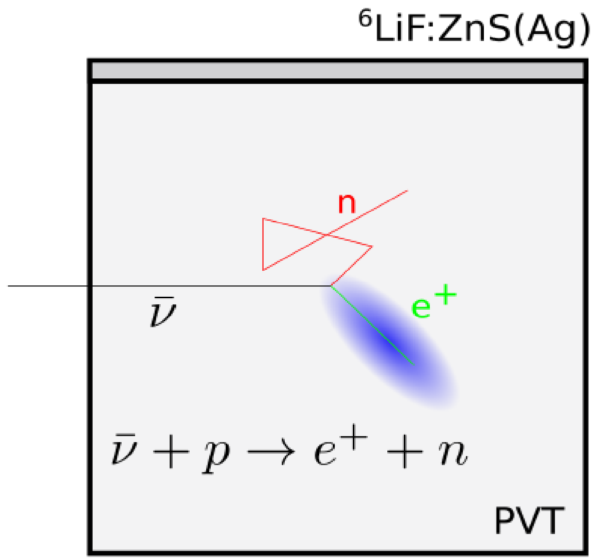




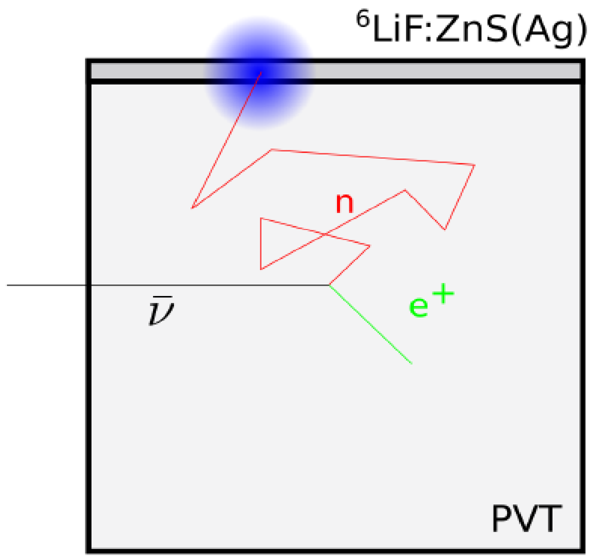


- Advantages of the SoLid detector:
  - Segmented → localize more precisely the antineutrino interaction (spatial resolution of 5 cm)
  - Better ID of inverse beta decay because of topological discrimination
  - Easily extensible

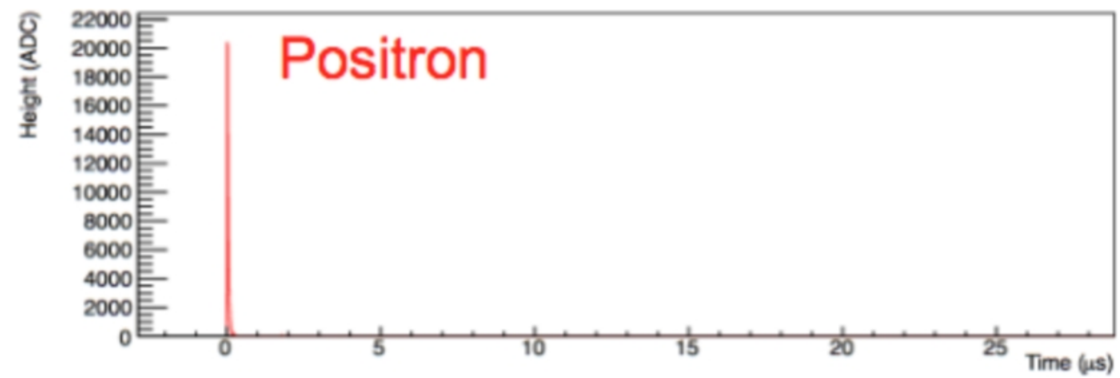
Detection principle: prompt+delayed signal



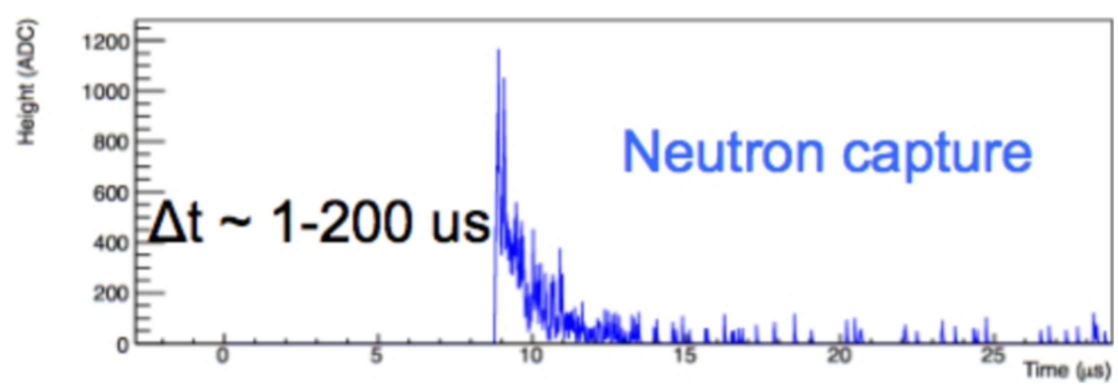
$$n +^6 \mathrm{Li} \rightarrow^3 \mathrm{He} + \alpha + 4.78\ \mathrm{MeV}$$



- Prompt signal from e^+ annihilation in PVT



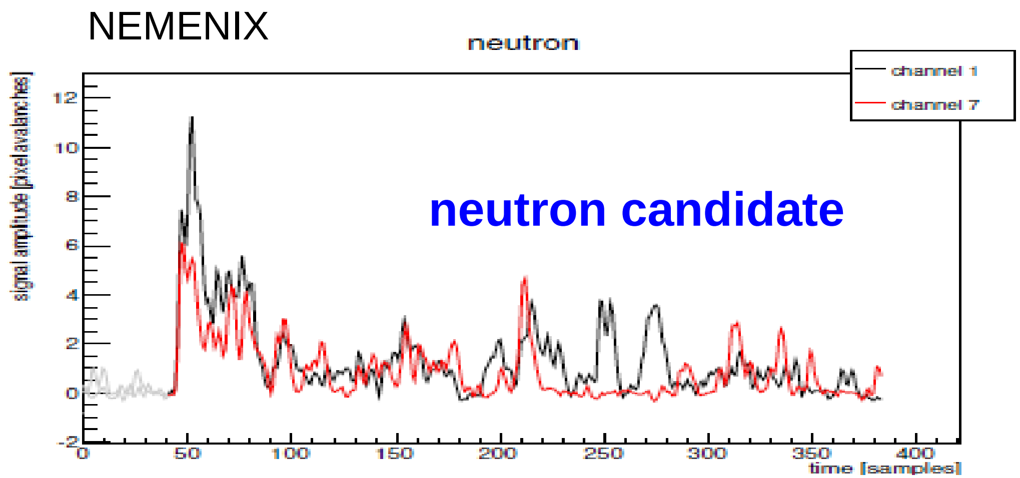
- Neutron thermalises in PVT
- Delayed capture in Lithium-6 (Δt<200 µs)
- Helium-3 and Helium-4 (α) absorbed in ZnS (inorganic scintillator)

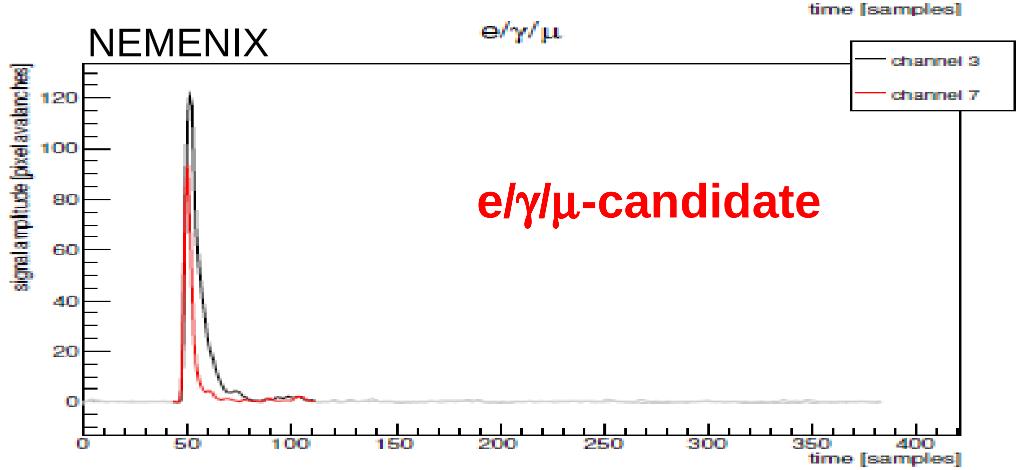


- PVT and ZnS have different photon emission time constants

Example of an inverse beta decay (IBD) event

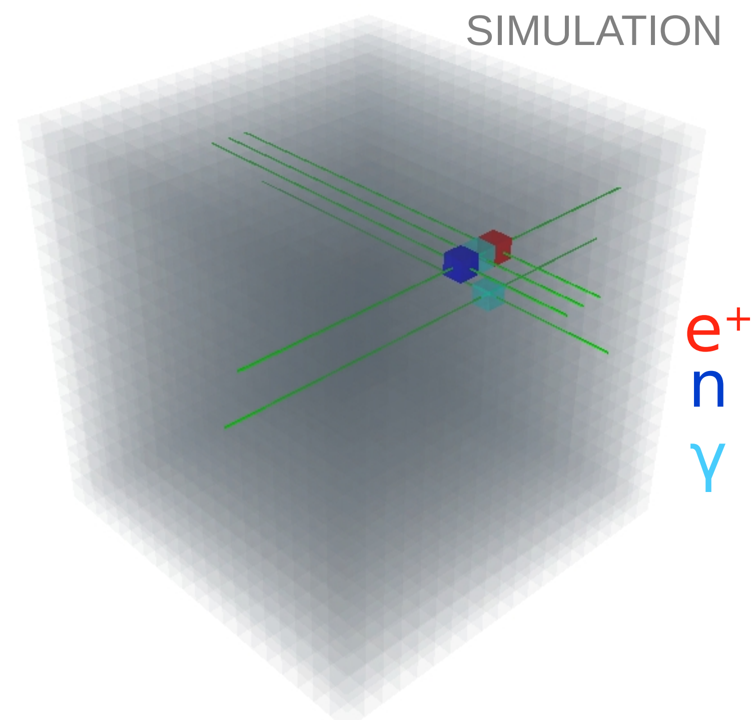
- A pulse shape analysis is performed to distinguish ZnS signals (neutrons) from PVT signals (e/γ/μ)





- Aim is to trigger on neutrons

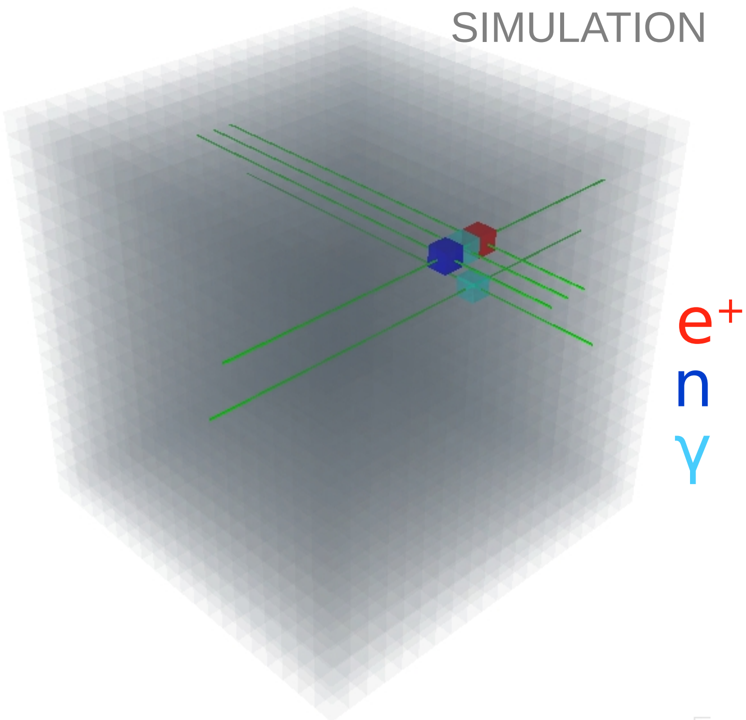
- Segmentation of the detector volume allows:
  - Location of IBD event
  - Efficient background rejection (n should be close to e^+)

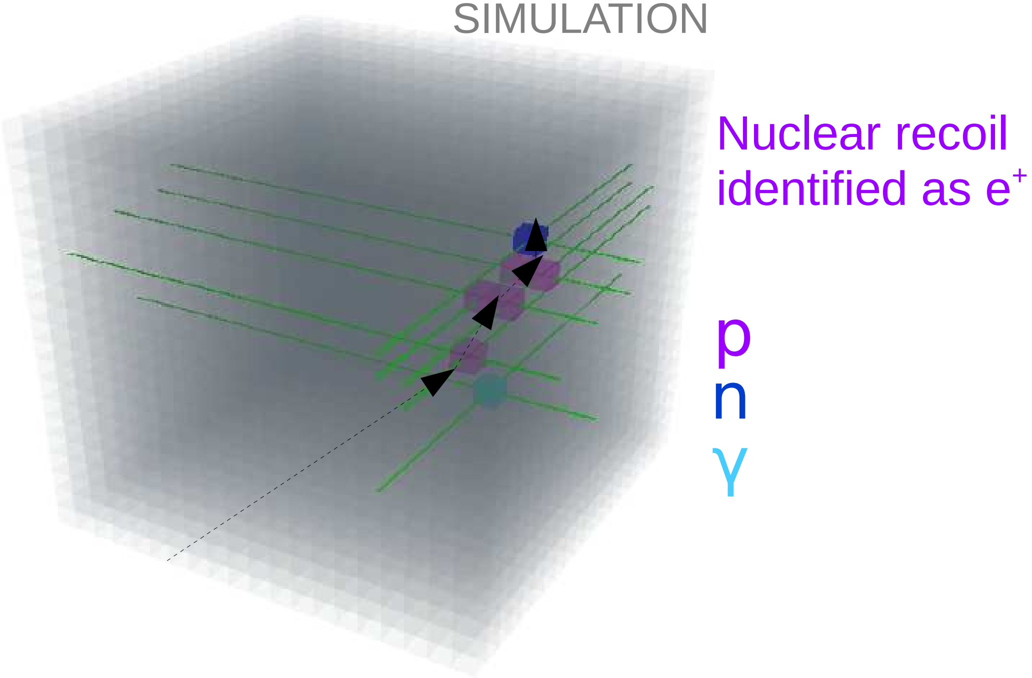


- Energy of e^+ gives $\bar{\nu}$ energy

Discrimination power of a topological cut

- An important background to control are high-energy (fast) neutrons
  - From the reactor (small at BR2)
  - Induced by cosmic muons





- New way to reject backgrounds, because of the different topology
- E.g. require neutron-like signal close to a positron-like signal (<2 cubes away)

Outline

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  - Prototype: proof of concept
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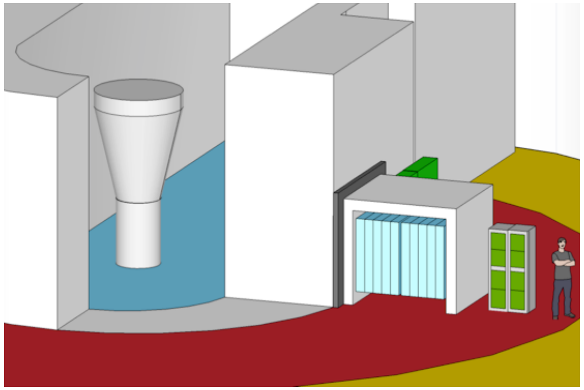
From R&D to a full-scale detector

- NEMENIX: 8kg prototype (R&D)
  - 20 x 20 x 20 cm^3
  - Summer 2013 → Spring 2015
  - Results expected by Summer 2015

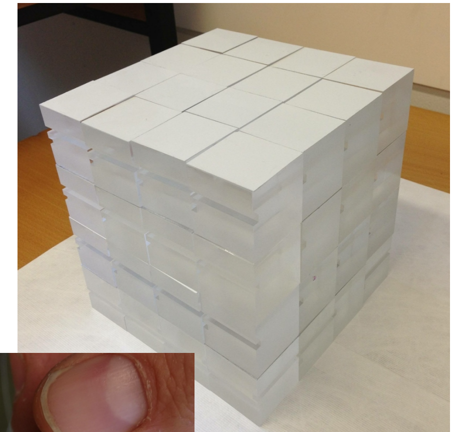
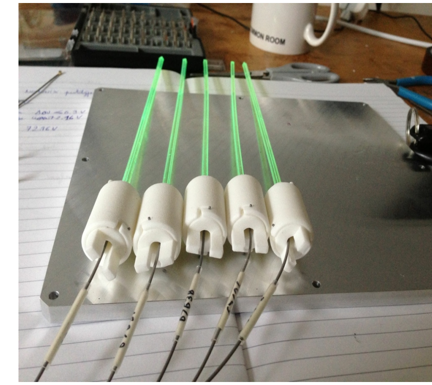
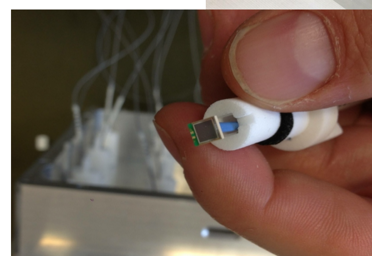
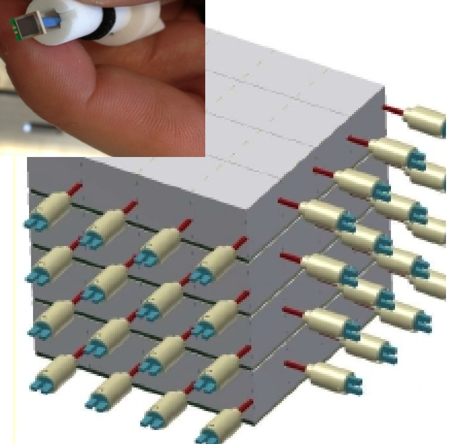
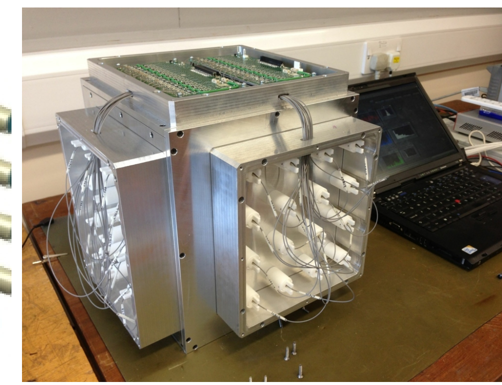
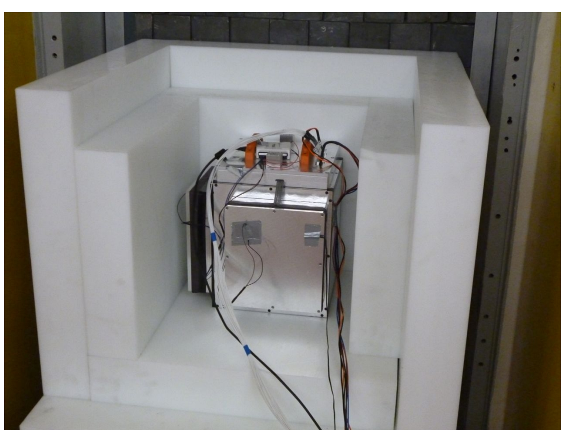
- SM1: 288 kg first module (Phase 1)
  - 80 x 80 x 45 cm^3
  - Winter 2014 → Summer 2015
  - Data taken with reactor on in February
  - Allows a measurement of the antineutrino flux with ~7% precision

- Full scale SoLid detector: 2.88 tonne
  - Funding available for 3 x 288kg (Phase 2)
  - Dimensions under discussion → production starting soon
  - 2016 → 2020+
  - Perform oscillation analysis



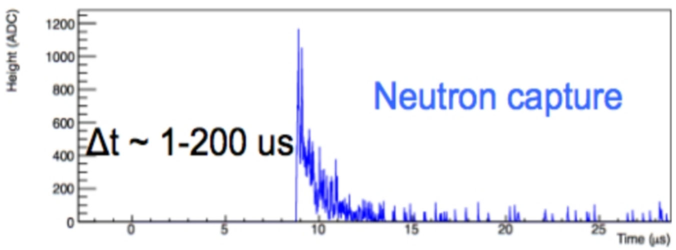
Detector technology tested with NEMENIX

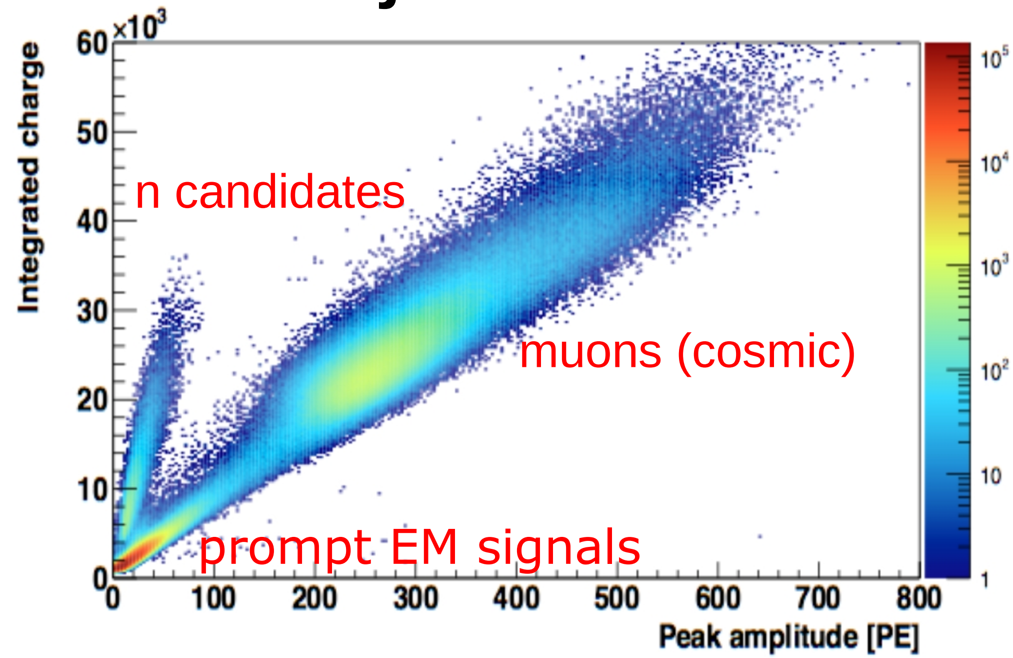
- 64 cubes optically isolated
- 32 read-out channels
- Proof of concept: segmentation, composite scintillator
- Develop reconstruction techniques
- Measure backgrounds at experimental location

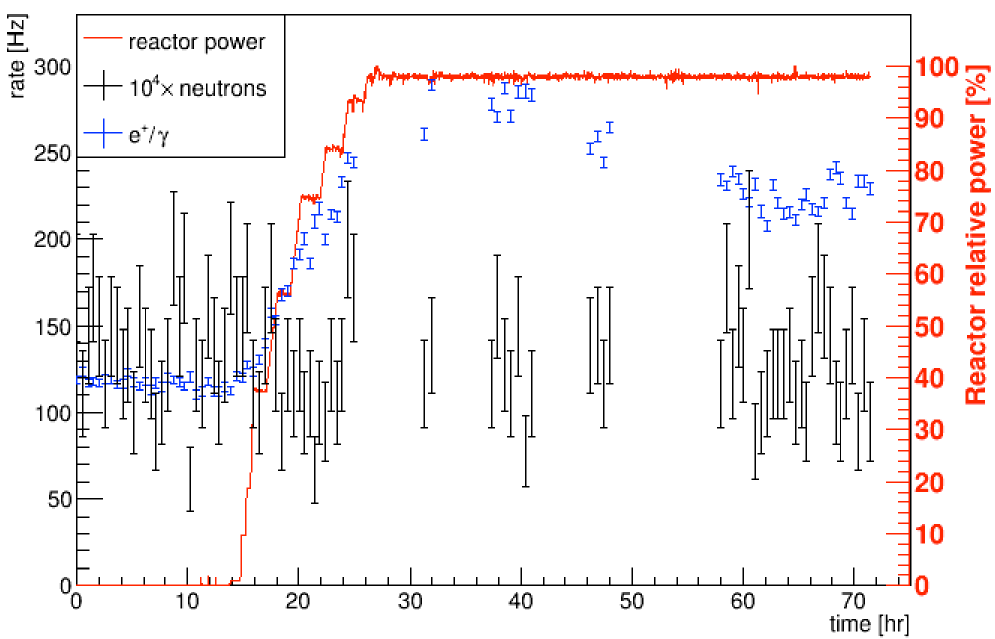
The prototype did an excellent job

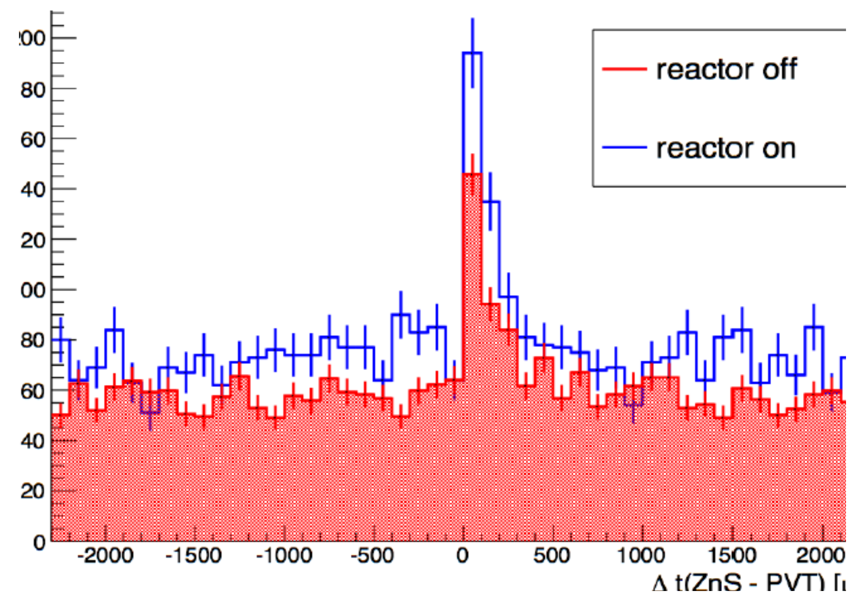
- Excellent particle ID
- Hint of inverse beta decay interactions





Reactor turn on





- Currently calibrating energy response, publish by Summer

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    - Construction
    - Commissioning
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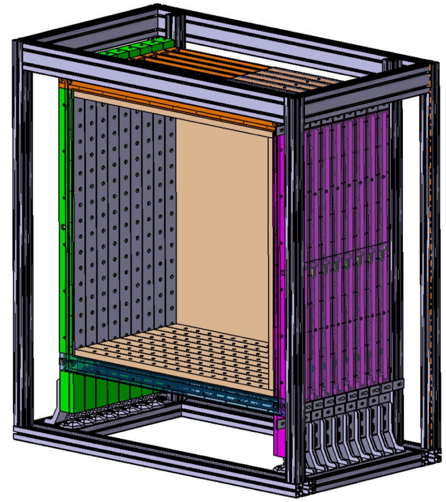
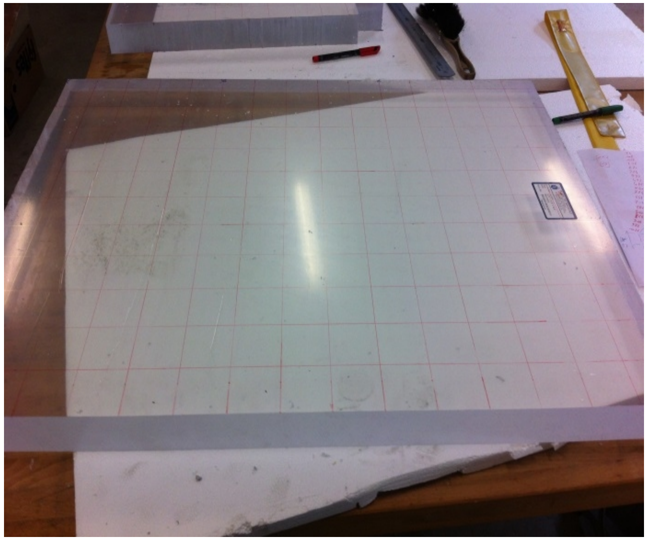
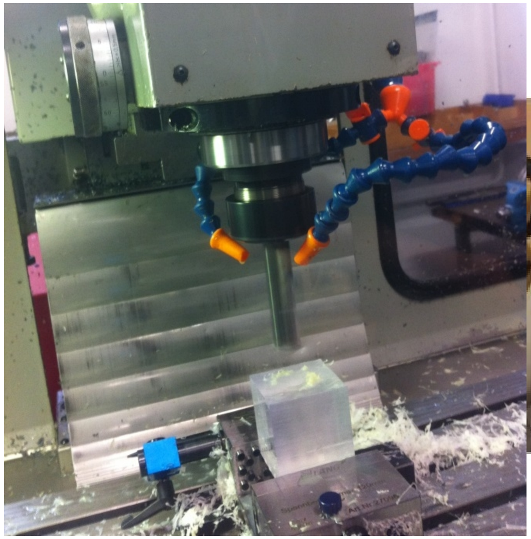
Construction of the first submodule (SM1)

- 2304 cubes:

  (cutting, washing, weighting, adding Lithium sheet (weighted), wrapping in Tyvec, weighing
- 9 aluminum frames

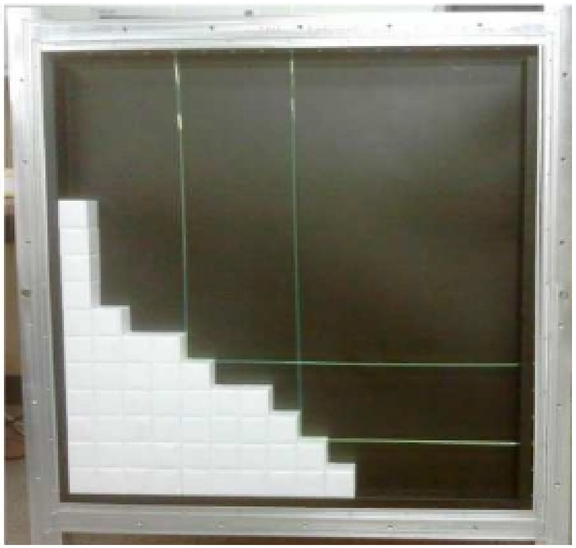


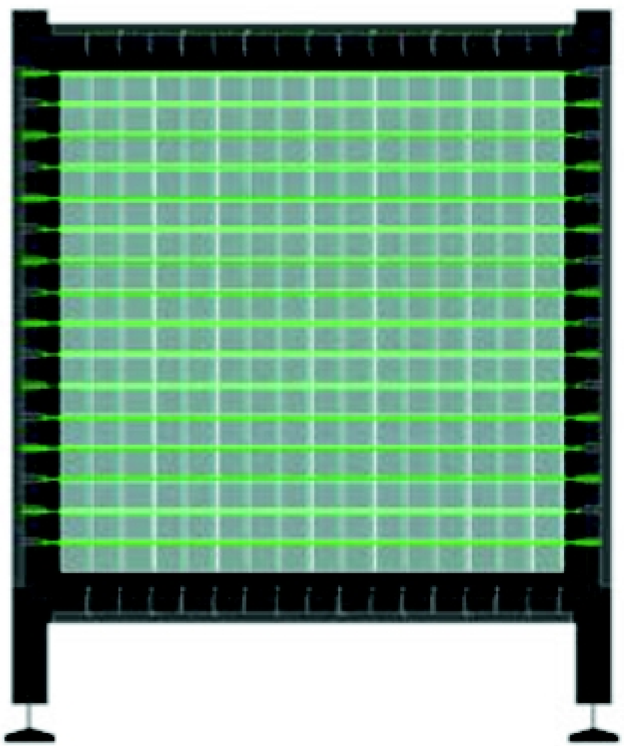


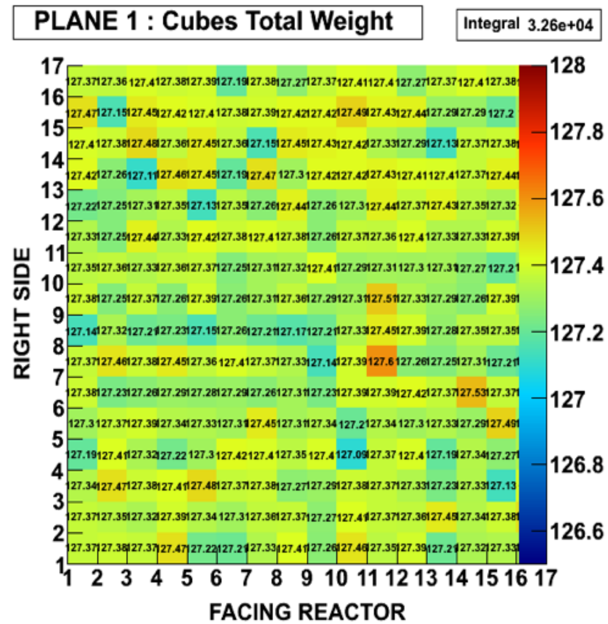


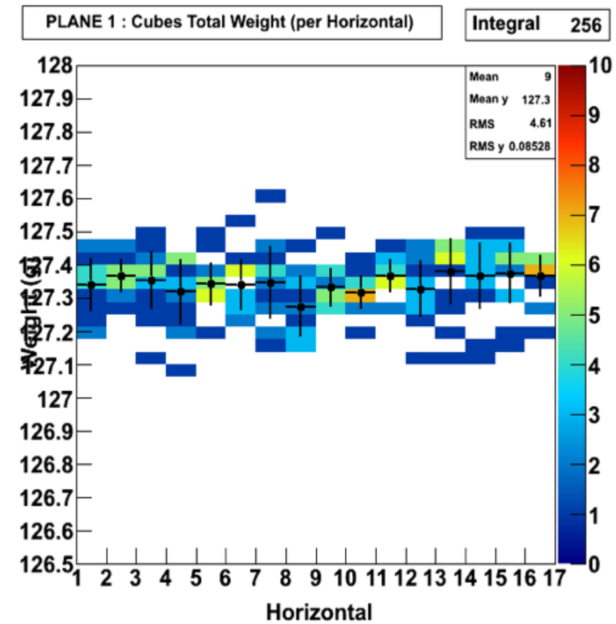
- 8 months from construction to commissioning

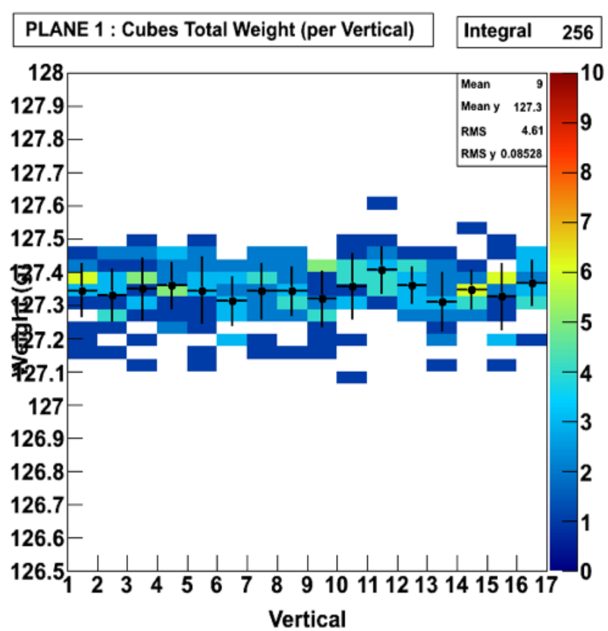
All material in the plane is weighted to <1%

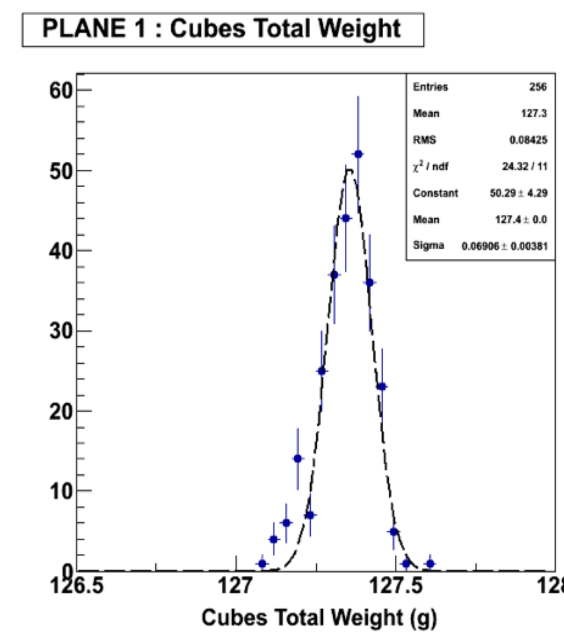




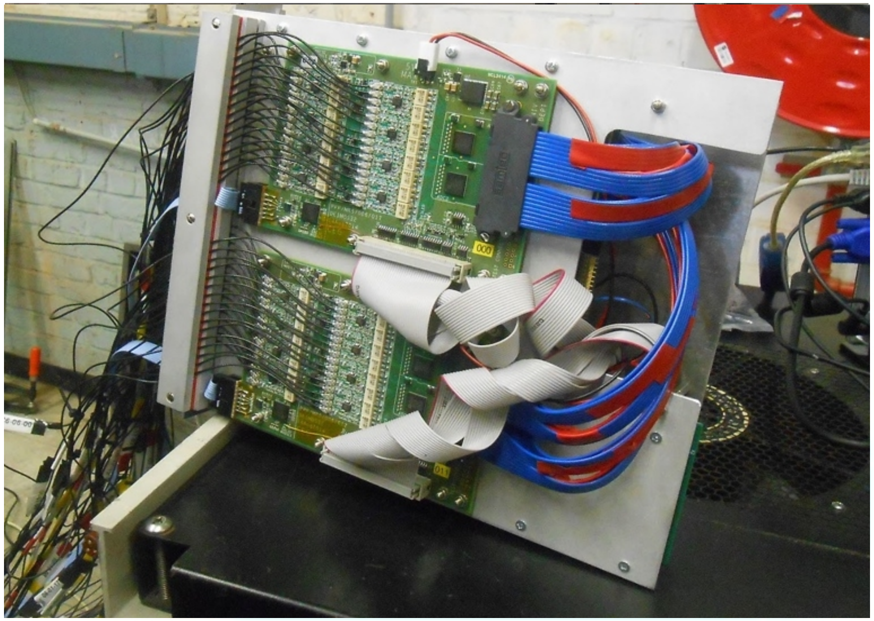


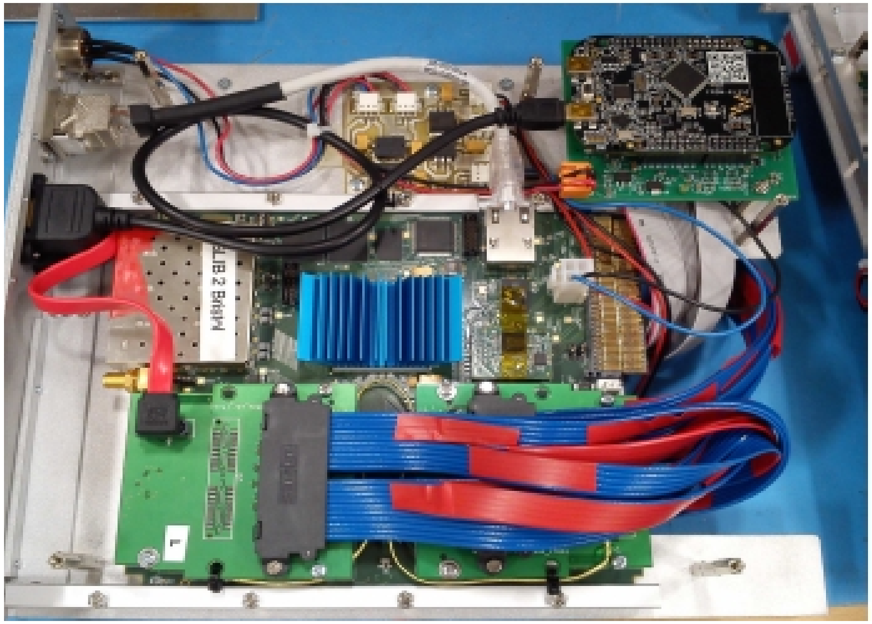


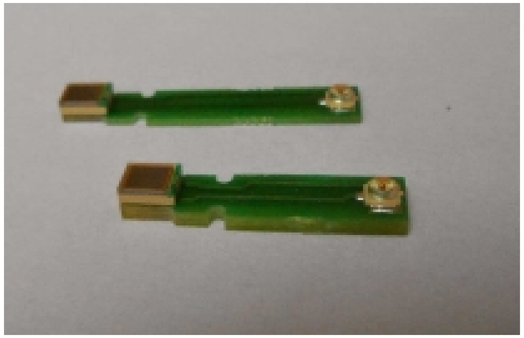


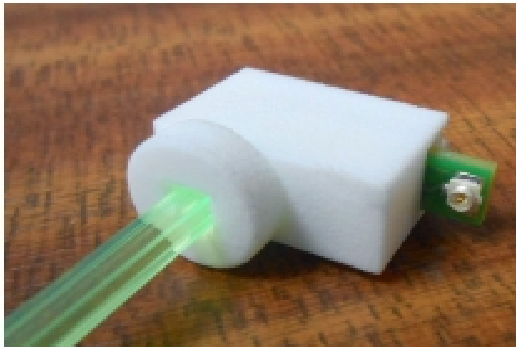


SM1 read-out system



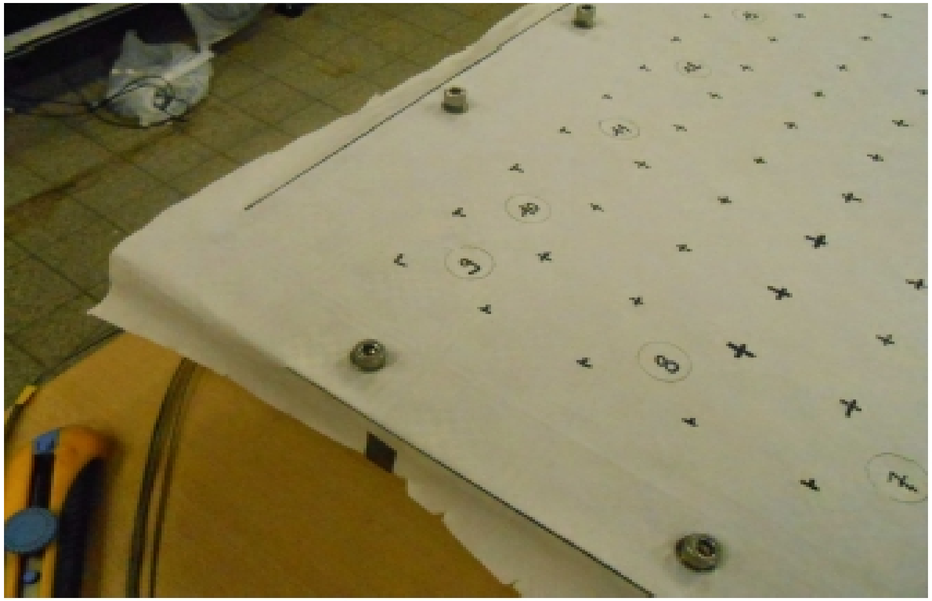


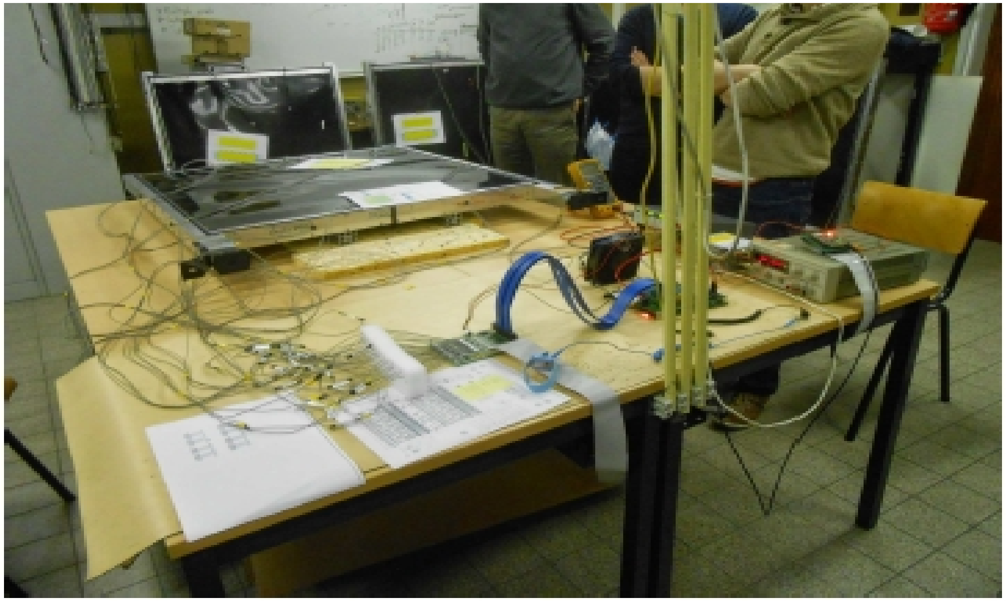


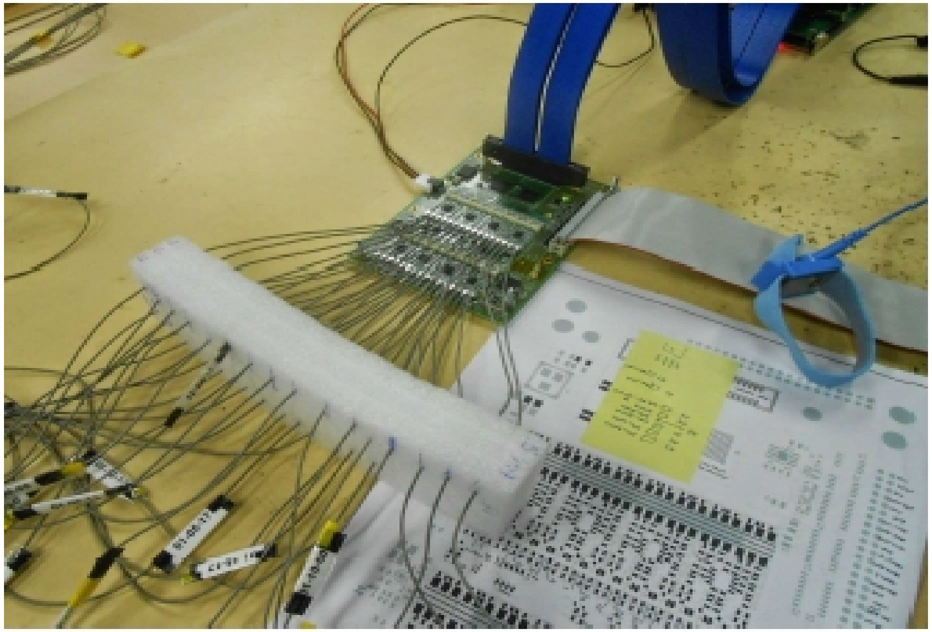


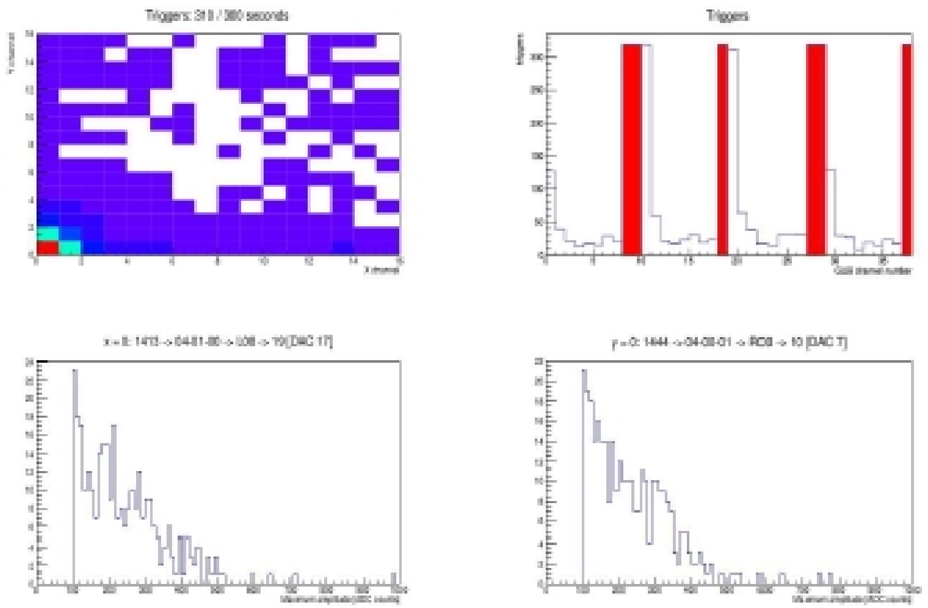
- Electronics

SM1 plane commissioning with Cobalt-60



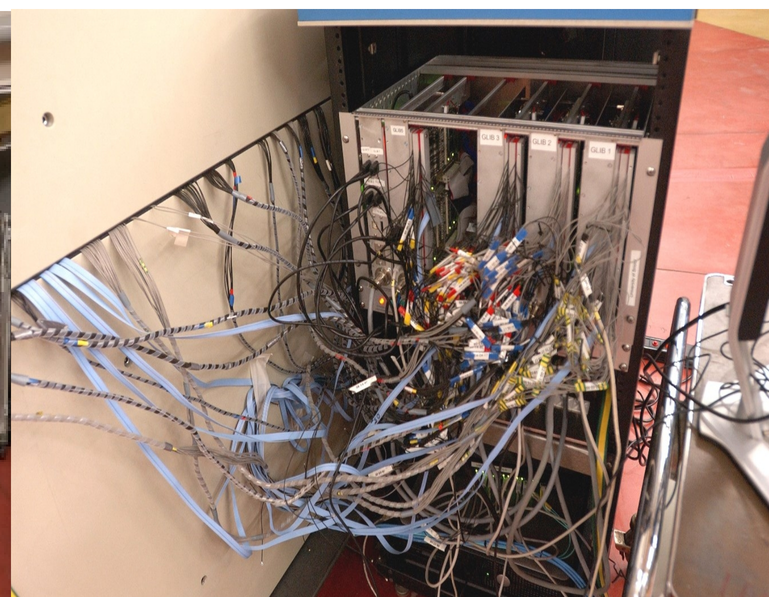






Check channel mapping, identify dead channels, measure attenuation

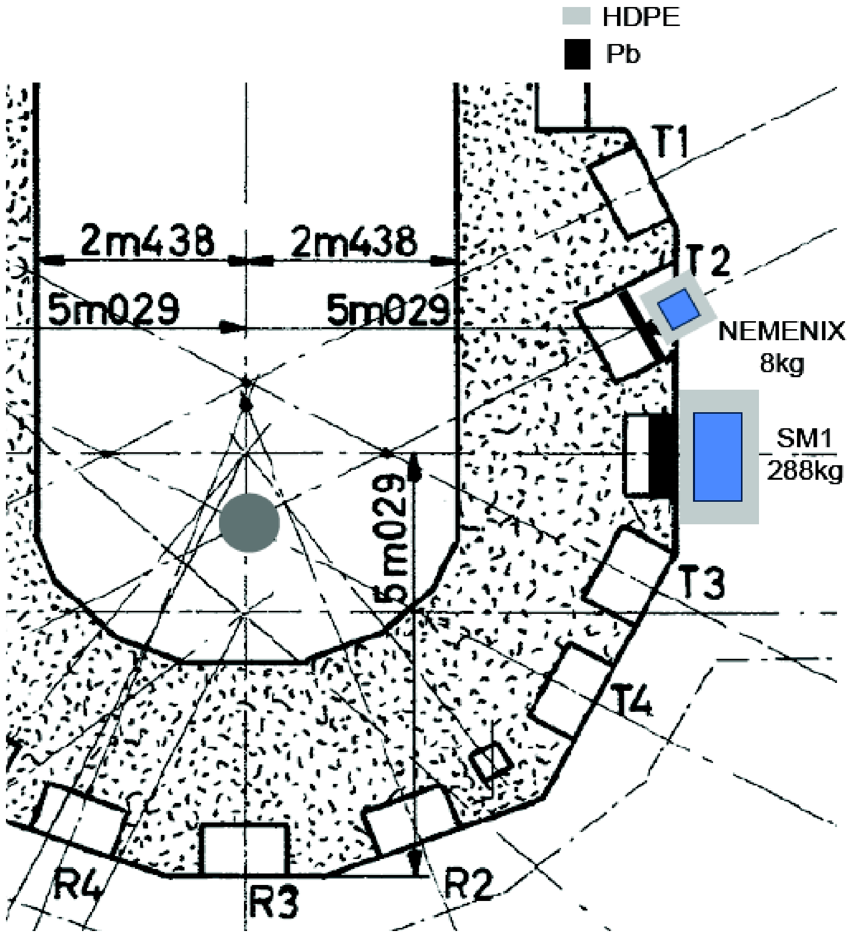
Plane loading in SM1 and deployment @BR2



SM1 in position: Nov. 27, 2014

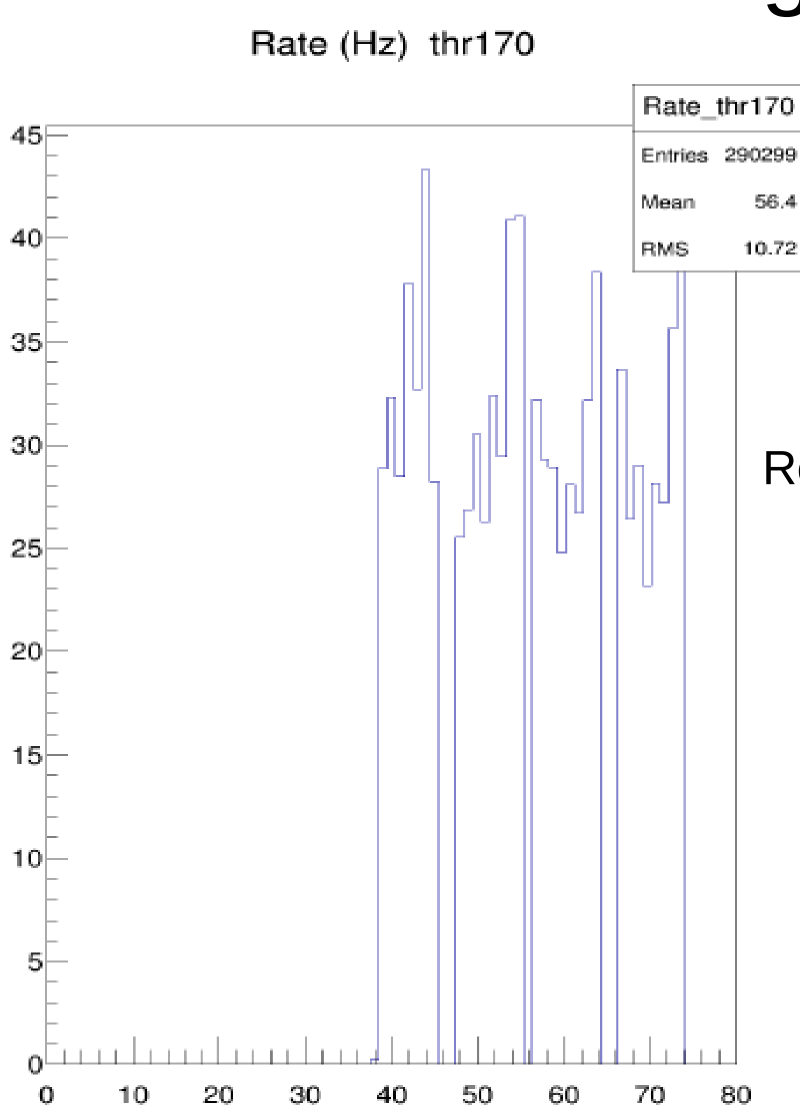
Alignment with respect to the reactor center is known to 2 mm

The current situation at BR2

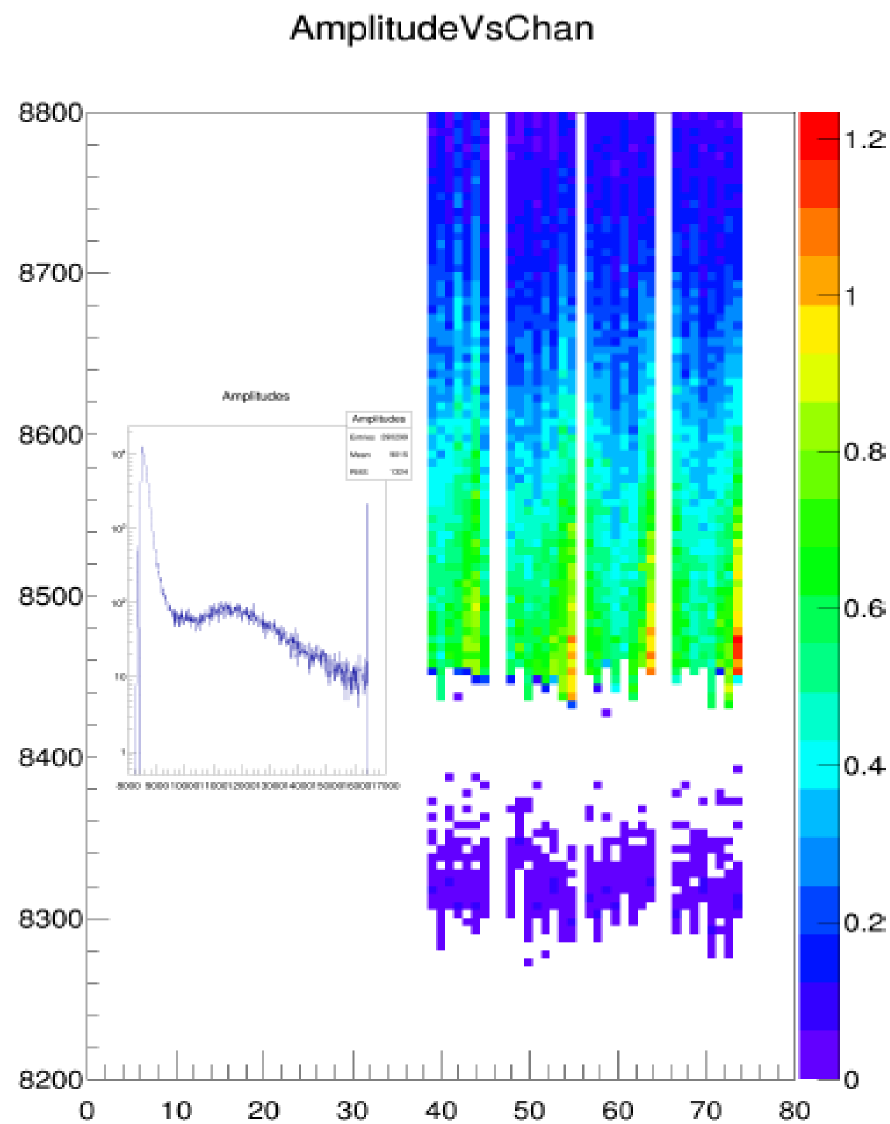


- As planned, BR2 is now in maintenance for 1 year (until Spring 2016)
- Last week NEMENIX was removed and transported to the UK (for calibrations)
- SM1 is taking data with radioactive source (to allow energy calibration)
- Detector has to be removed by the end of May

SM1 commissioning at BR2



Plane 2
Reactor ON



- Trigger on time-coincident signal above threshold in an x and y channel of the same plane → signal in a cube
- Monitor trigger rate for each plane (rate is 2x higher when reactor is on)
- Some channels are hot/noisy

Outline

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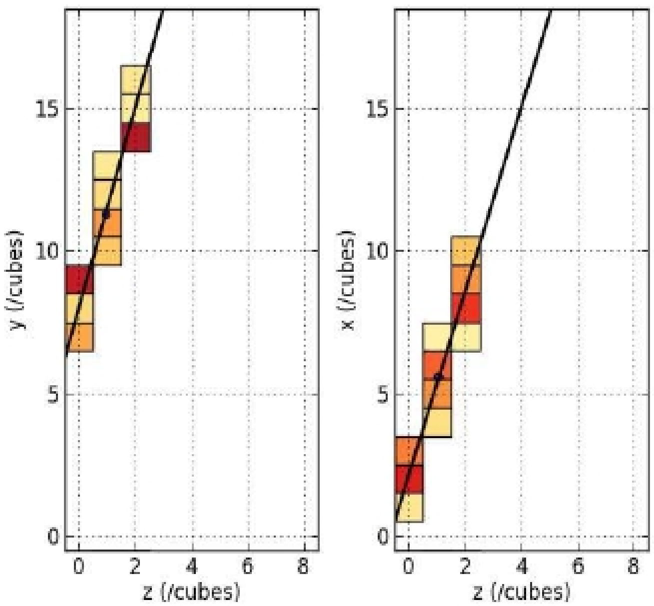
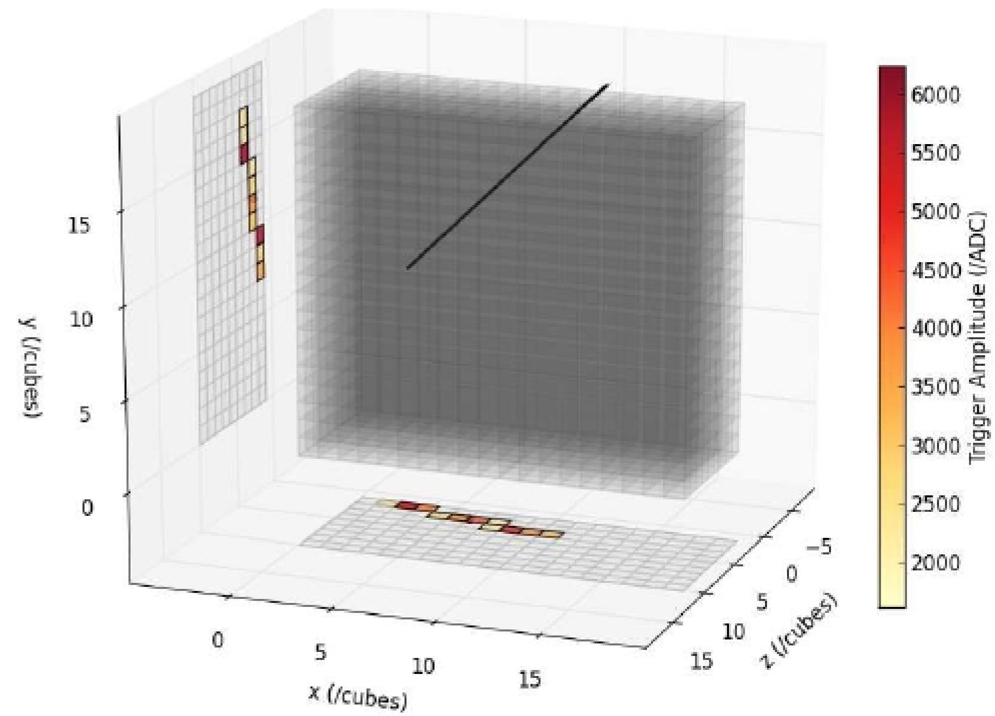
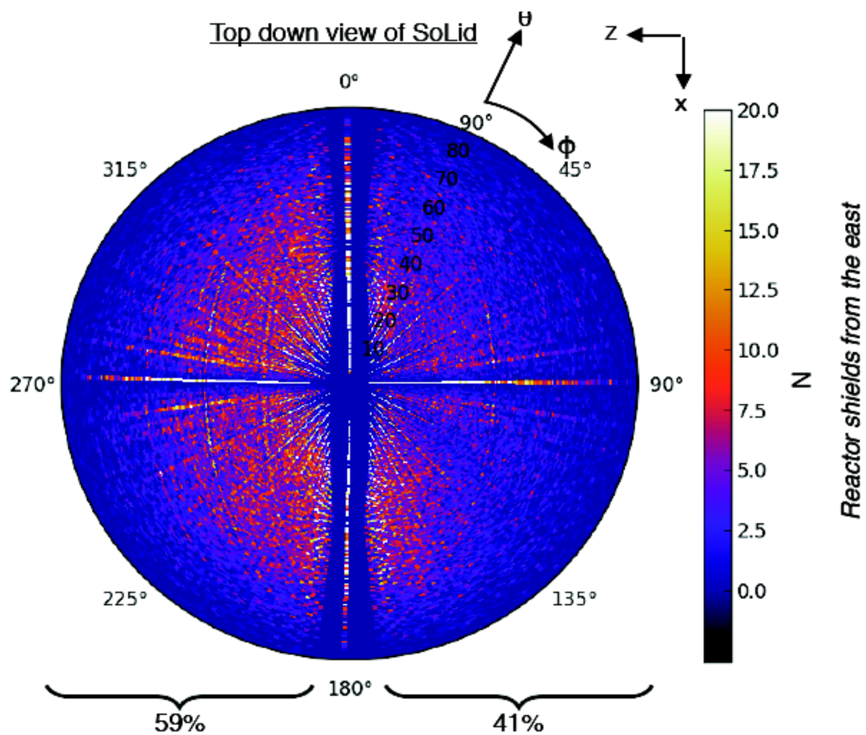
- The SoLid detector technology
- The different phases of the SoLid experiment
  - Prototype: proof of concept
  - First submodule
    - Construction
    - Commissioning
    - Reconstruction of particles
- Reactor flux calculation
- Physics potential of the first submodule
- Towards the next phase of SoLid

Muon tracking in SM1 works

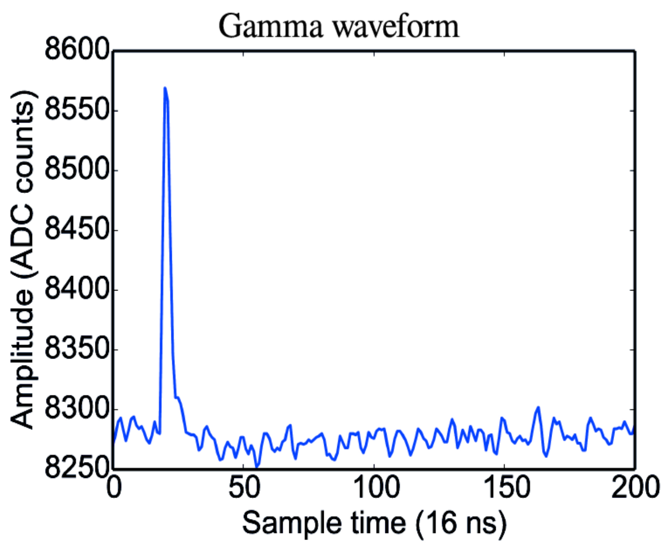


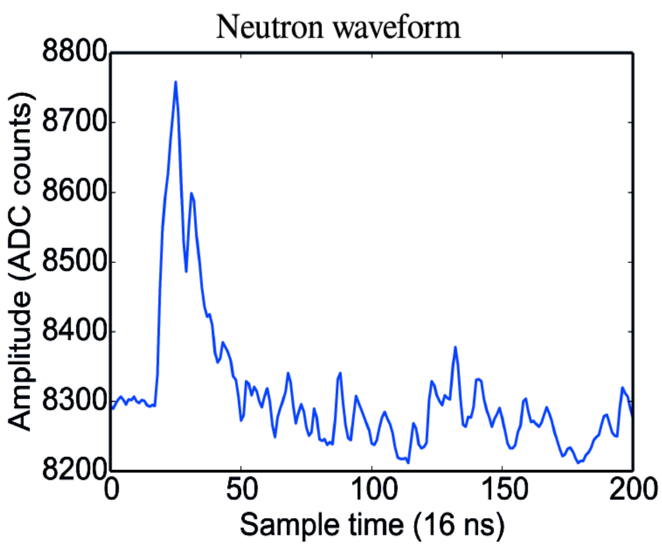




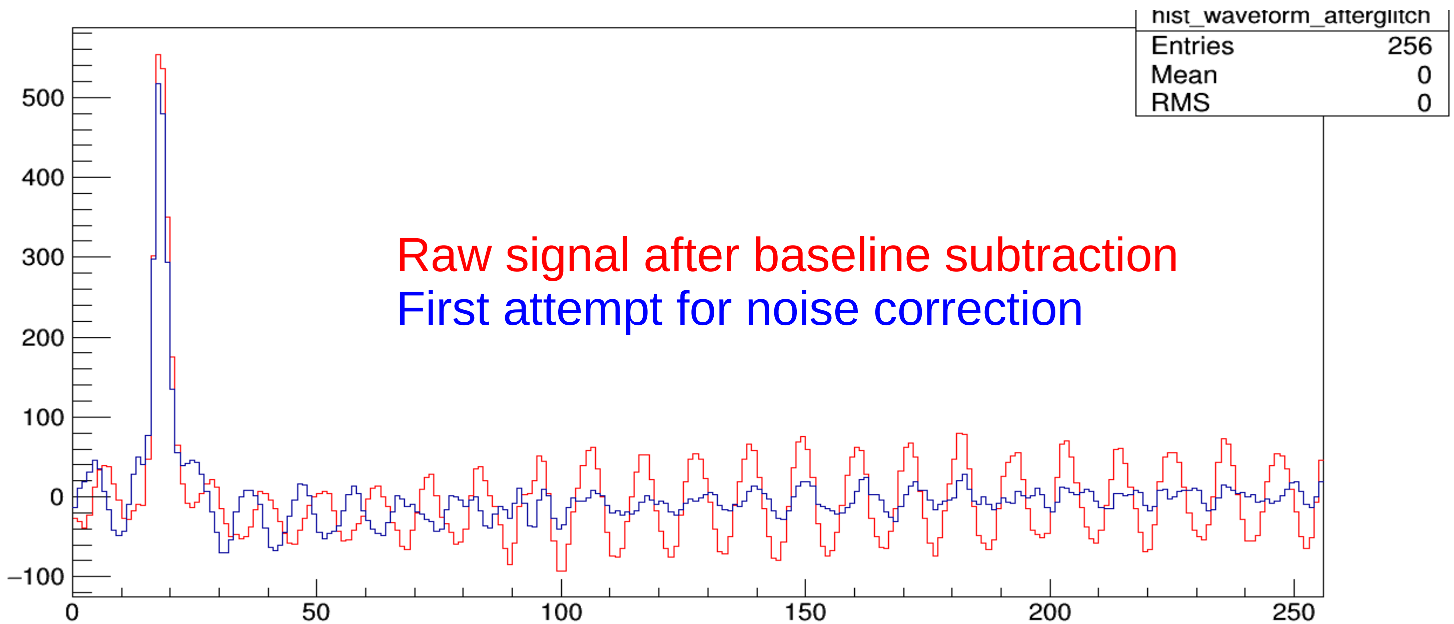
- Cosmic rays → known angular distribution
- Altered by shielding and detector sensitivity
- Clear shielding from the right (concrete wall around reactor)
- Discretisation is caused by the detector segmentation

We see prompt signals, neutrons and noise...

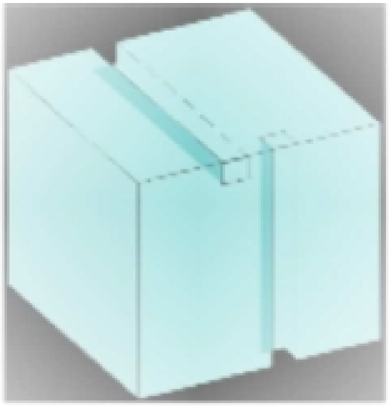


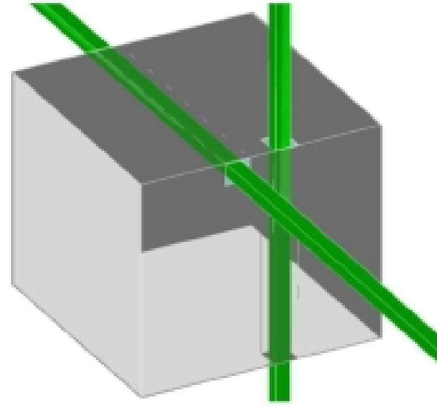


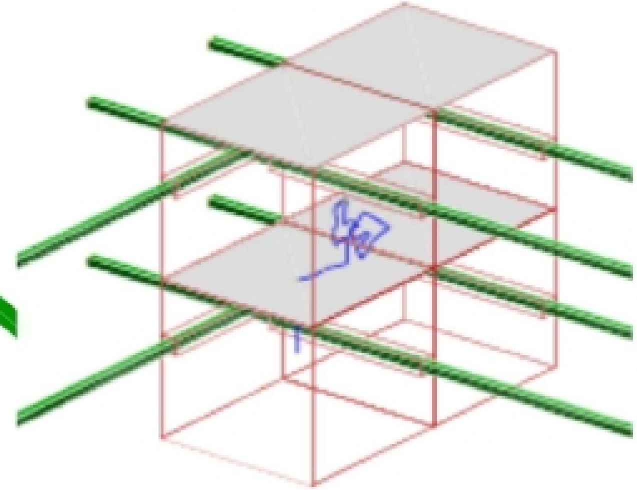
- But we are also fighting periodic noise in some channels, e.g.:

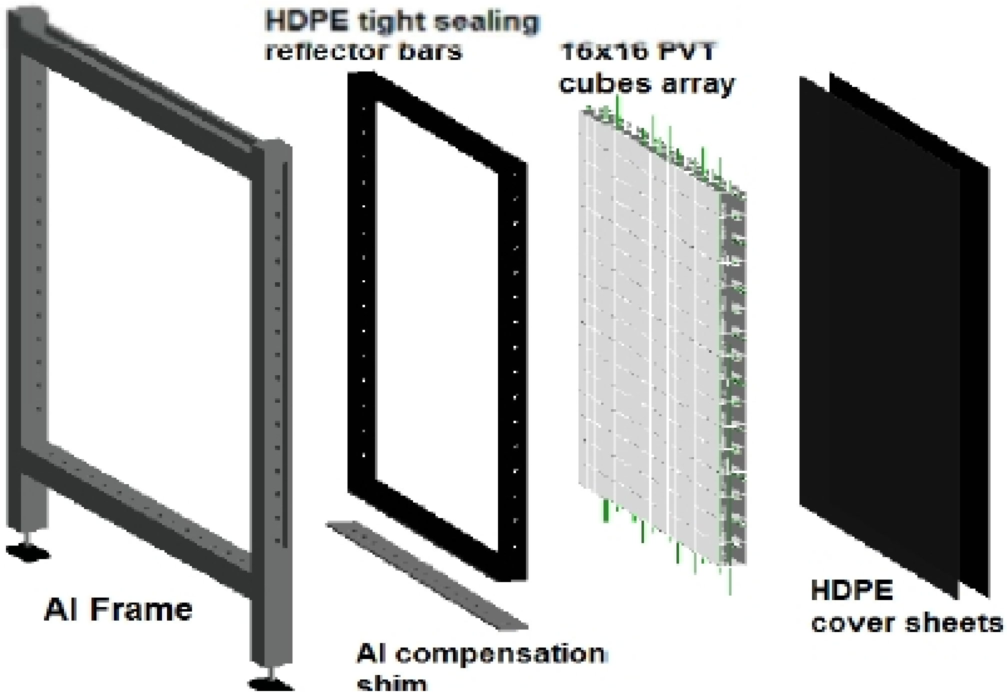


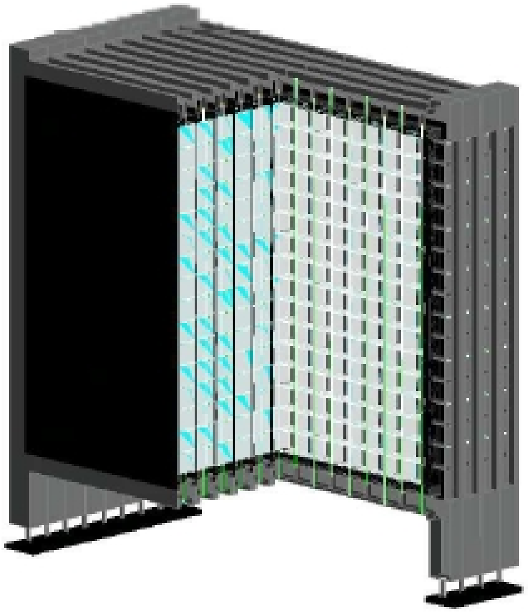
Also work ongoing from the simulation side











- SM1 geometry implemented in GEANT4

Outline

- Production and detection of antineutrinos
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  - Prototype: proof of concept
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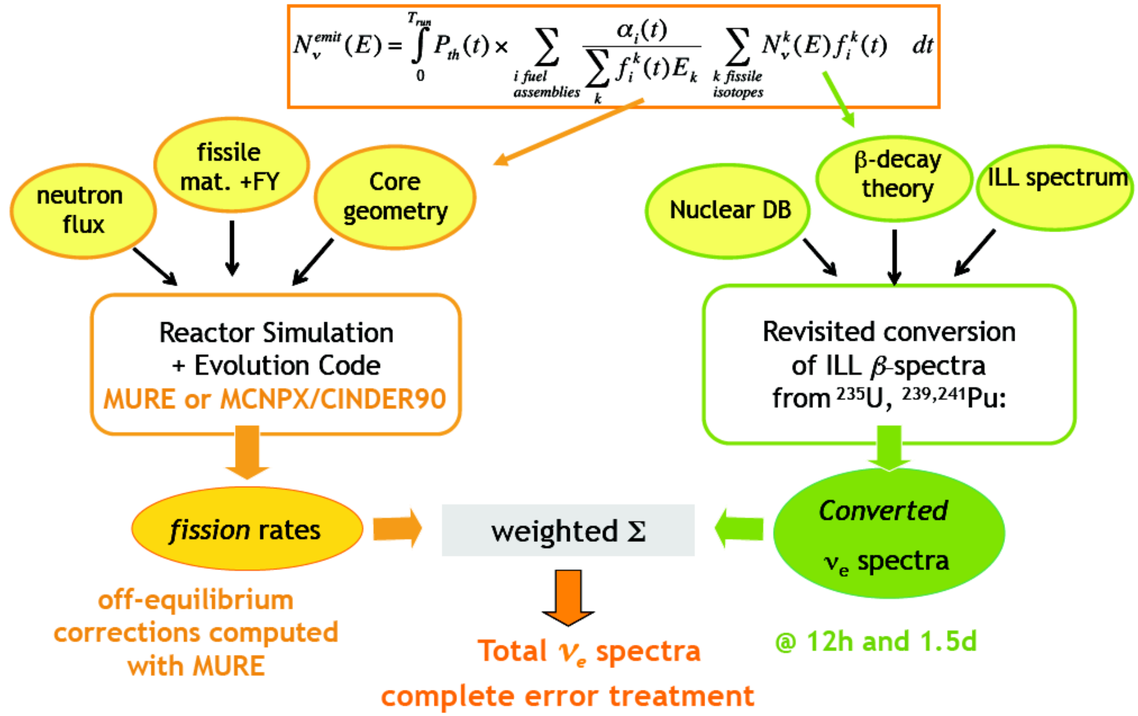
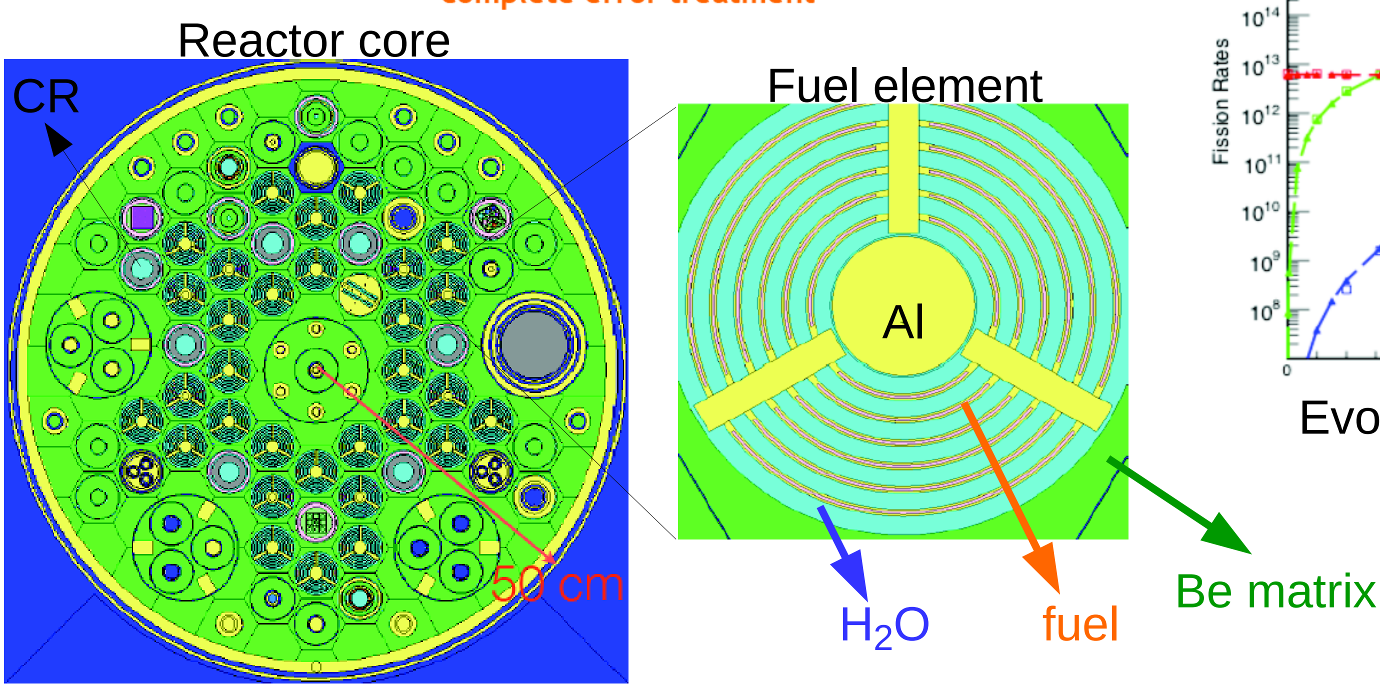
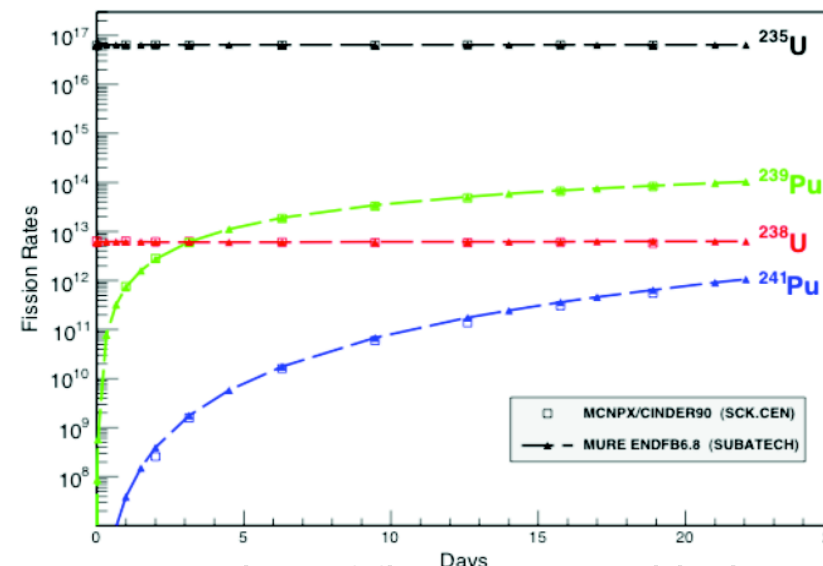
- Reactor flux calculation
- Physics potential of the first submodule
- Towards the next phase of SoLid

Calculating the number of neutrinos is tricky



- Conversion method is used to calculate the reactor flux
- Fission rates can be computed: good agreement between two codes (BR2 + SoLid) for the evolution of the fission rate

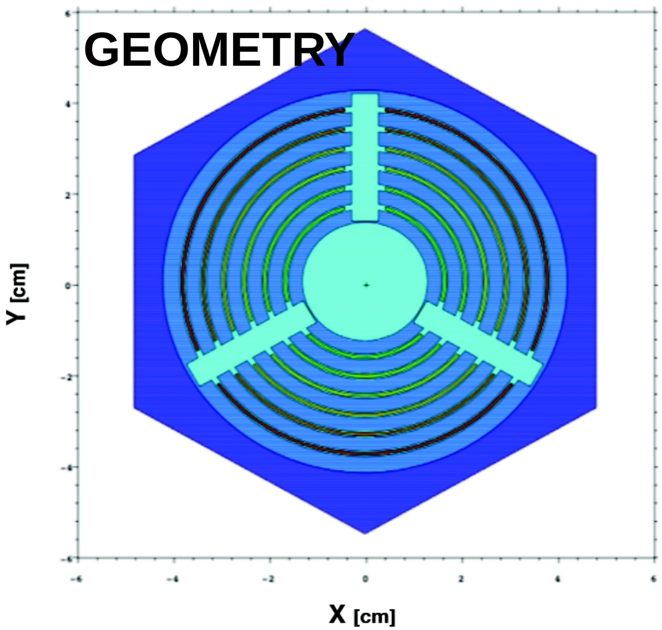


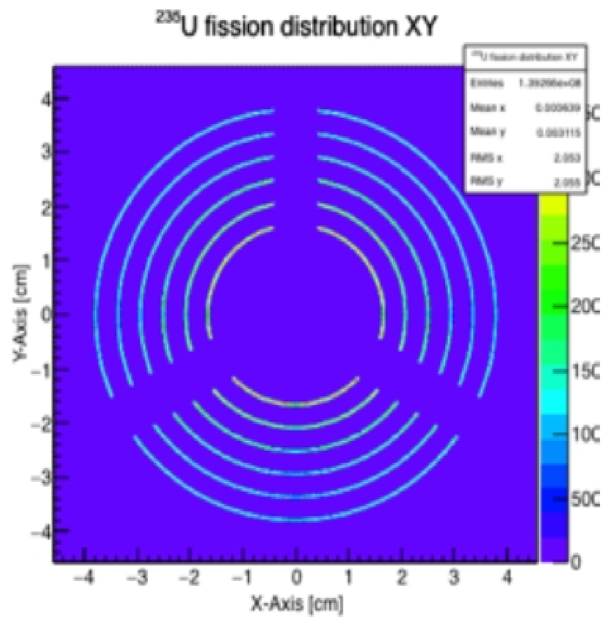


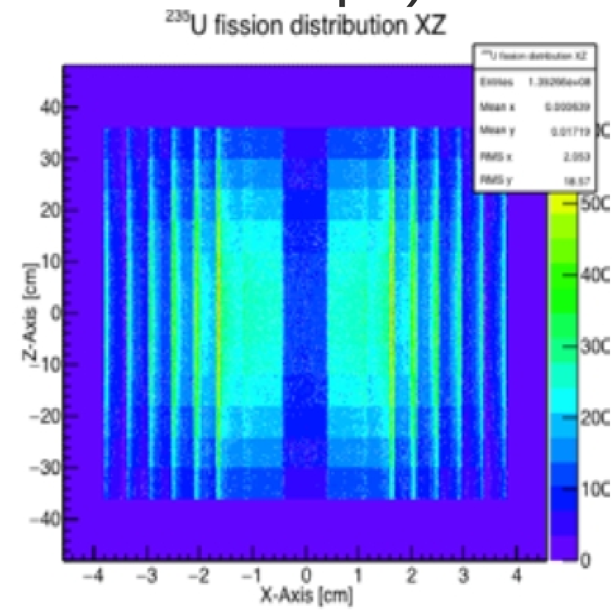
Evolution of fission rate with time

Simulation of the spatial distribution of the flux

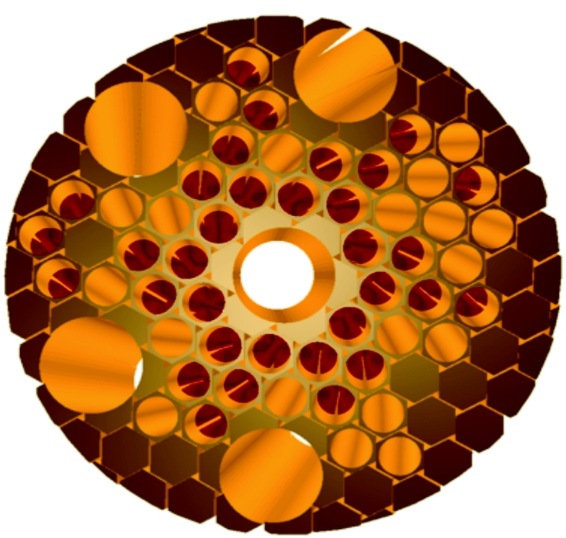
- We need also the spatial distribution of the flux
- Start with a single fuel element (example for U-235 isotope)

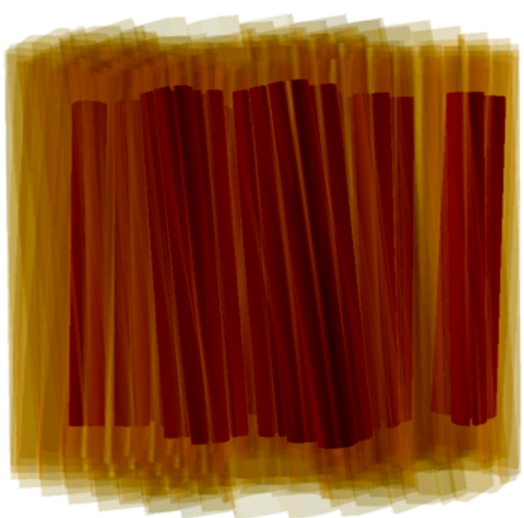






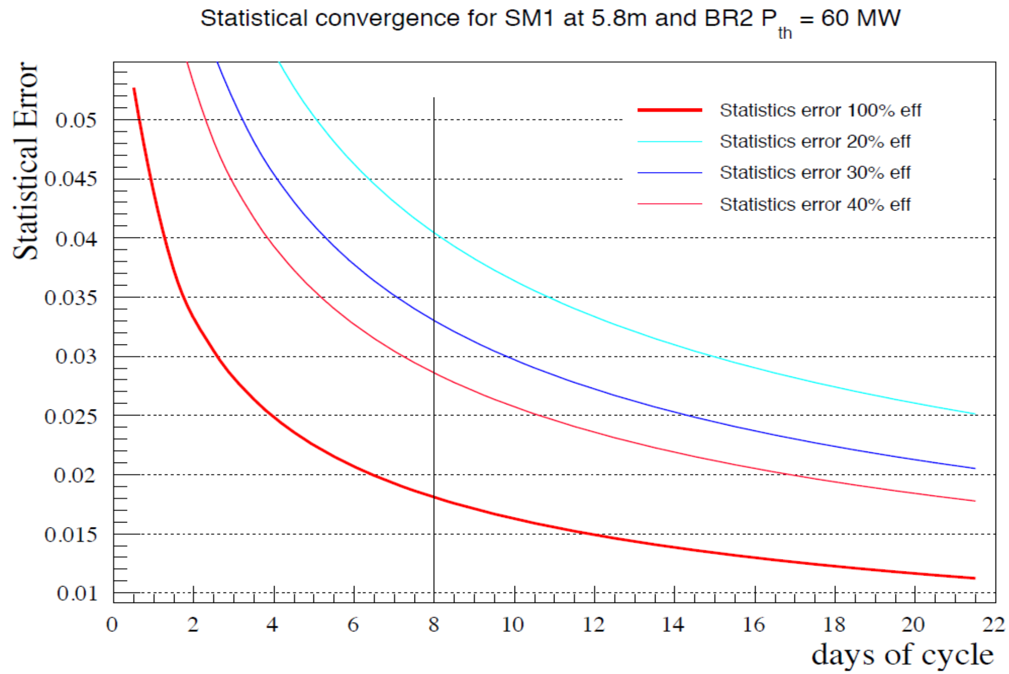
- Next step, do the same for the full core
- Core geometry now implemented in Root

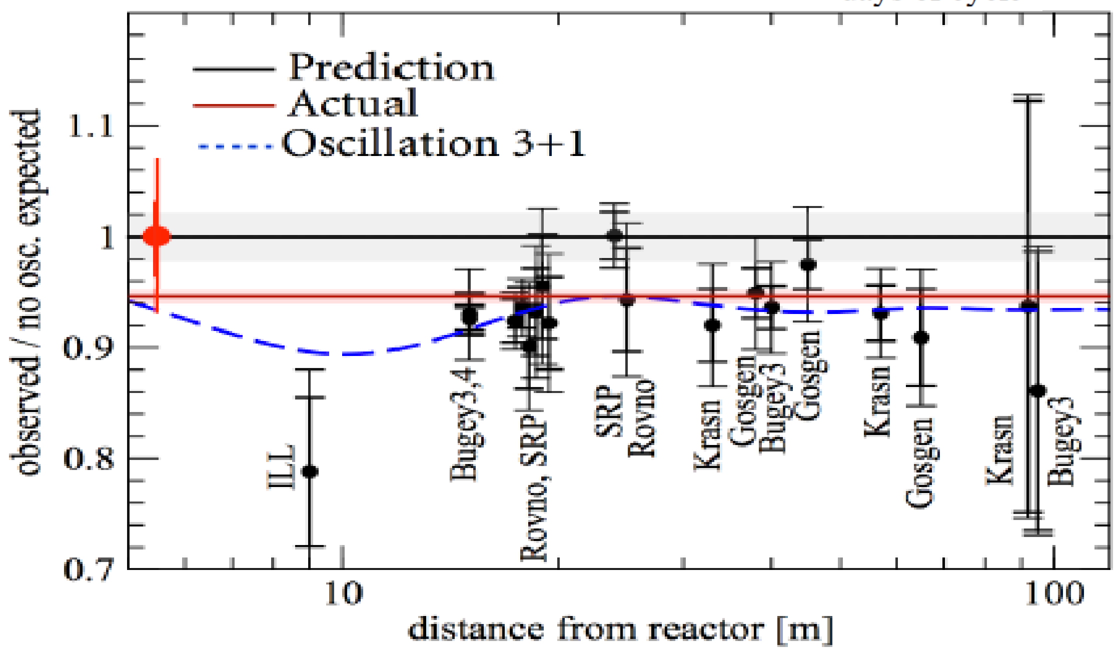




Physics potential of SM1

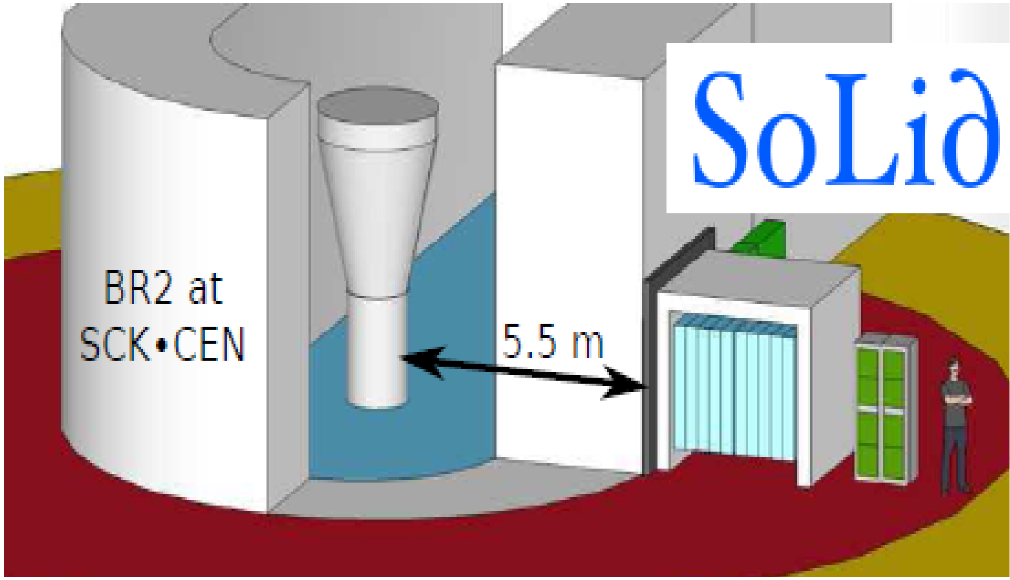
- First rate measurement at 5.5m from a reactor core
  - Demonstrate technology is mature
  - <5% statistical accuracy
- Measure IBD efficiency and reconstruct energy spectrum
- First insight into reactor anomaly at this distance
- Aim at 6-8% total uncertainty





Towards the next phase of SoLid

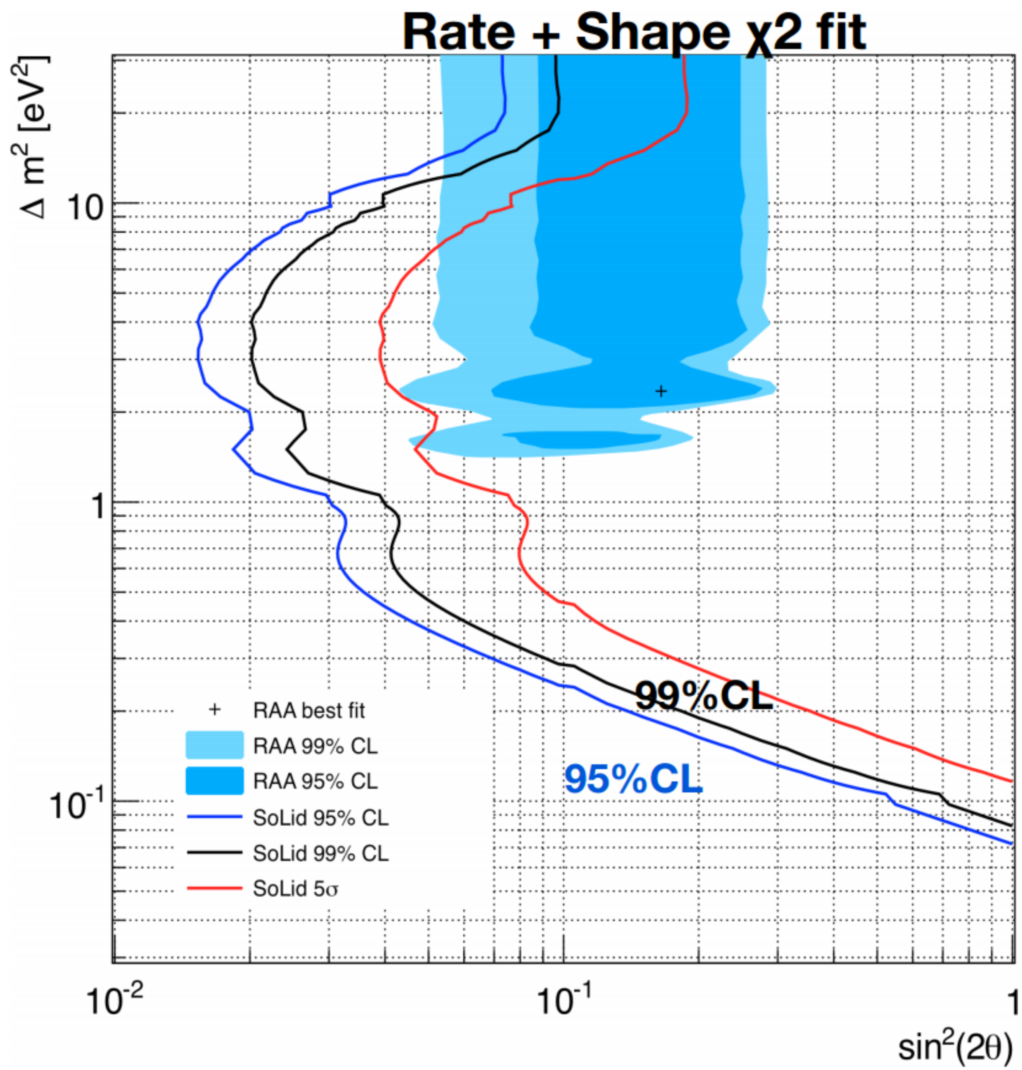
- BR2 down until Spring 2016
- Funding for 0.9 tonne detector
  → for Spring/Summer 2016
- Secure more funding to increase the mass (detector is easily extensible with more planes if design is kept)



- 5 years of running
- Measure or rule out short baseline oscillations (near/far)
- Compare measured and calculated flux and spectrum
- Fuel composition measurements
  → detector useful for reactor monitoring (non-proliferation treaty)?

Expected sensitivity of SoLid

- Event rate 416 $\bar{\nu}_e$/day/tonne (assuming an IBD event efficiency of 41%)
- 2.88 tonne detector mass
- Energy resolution of 17% at 1MeV
- 300 days running (140 days/year)
- Positron threshold of 0.6MeV
- S:B of 6:1 assumed
- Systematics:
  - Spectrum normalization: 1.8%
  - Spectrum shape: 0.7 – 4%
  - Thermal power: 3%
  - Detection efficiency: 2%



Conclusions: a lot of action, first results from NEMENIX and SM1 expected by Summer

- Currently optimizing particle identification (muons, positrons, gammas, neutrons)
  - Also developing simulation for cross-checks
- Measuring:
  - Particle rates
  - Hit efficiency of cubes and muon veto planes
  - Light yield
- Calibration of the energy with radioactive sources and muons
- Optimisation of the selection of inverse beta decay events
- Reactor flux calculation, including spatial distribution

→ *stay tuned for the first results in a couple of months*

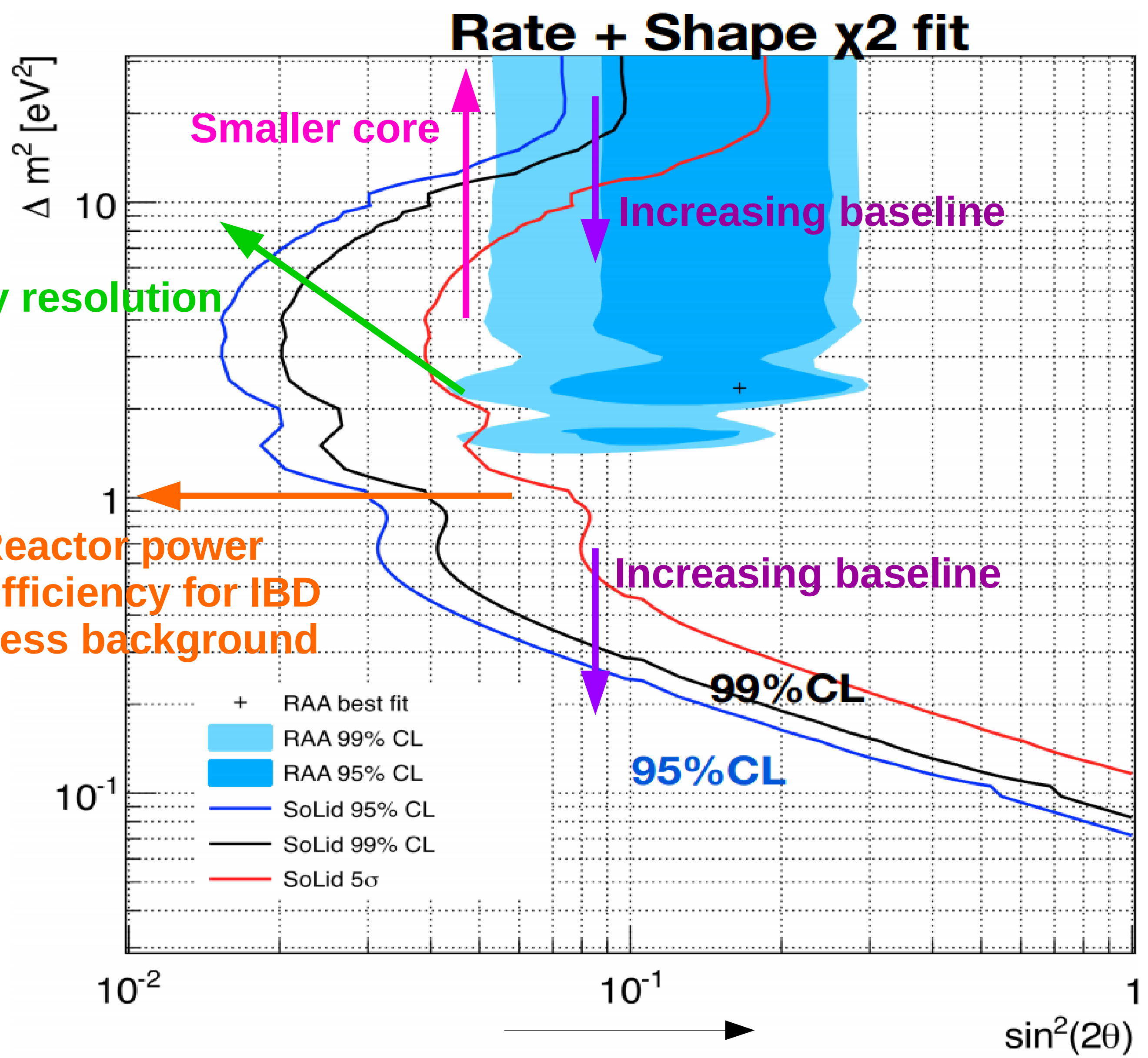
- In parallel to SM1 activities:
  - Results for NEMENIX being finalized
  - Design and construction of phase 2 detector

Additional material

Effect of reactor and detector choices on sensitivity

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Smaller oscillation length

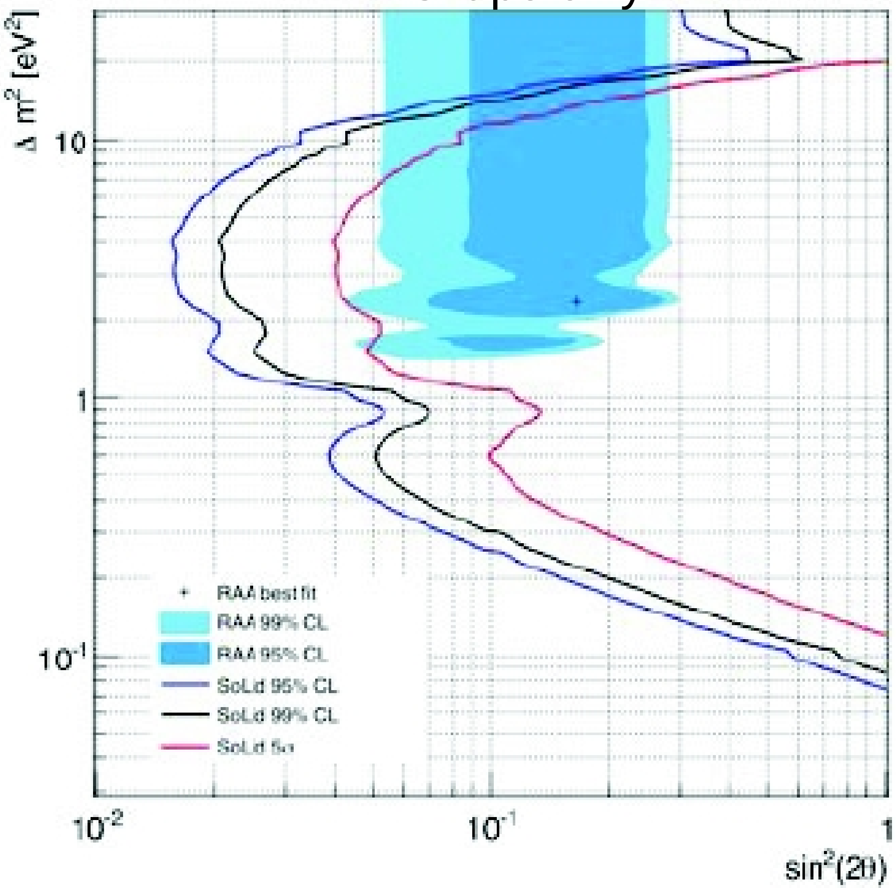


oscillation

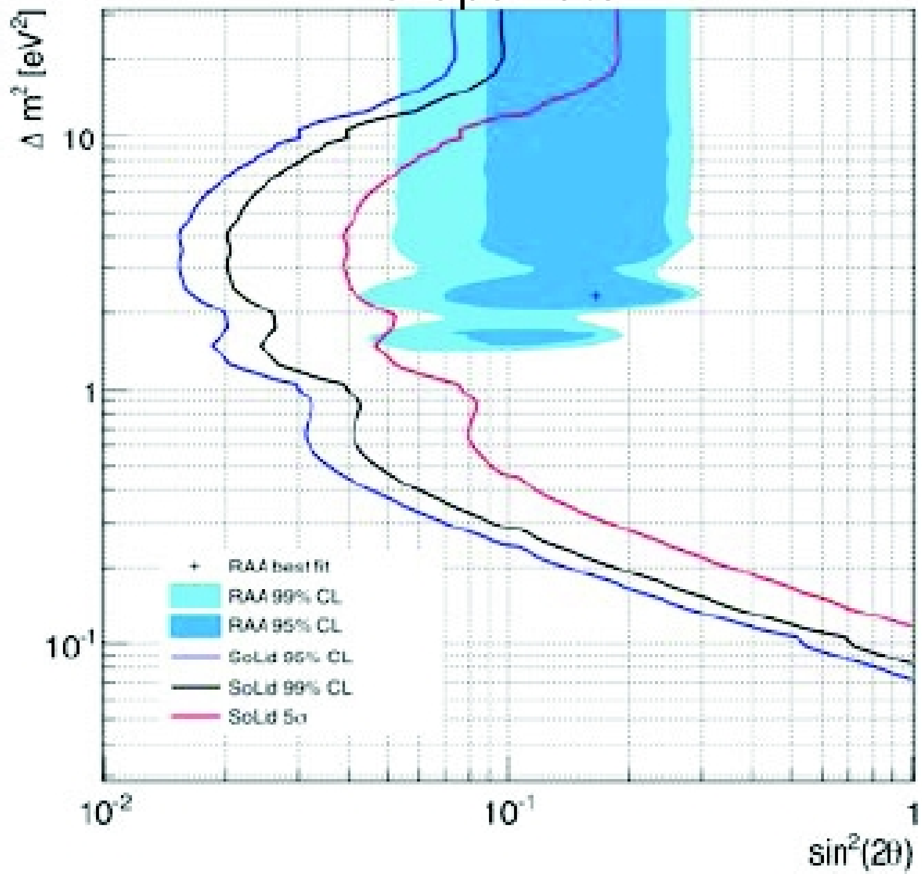
Minor effects:
- **Fuel type**
- **Background shape**

Sensitivity using shape only

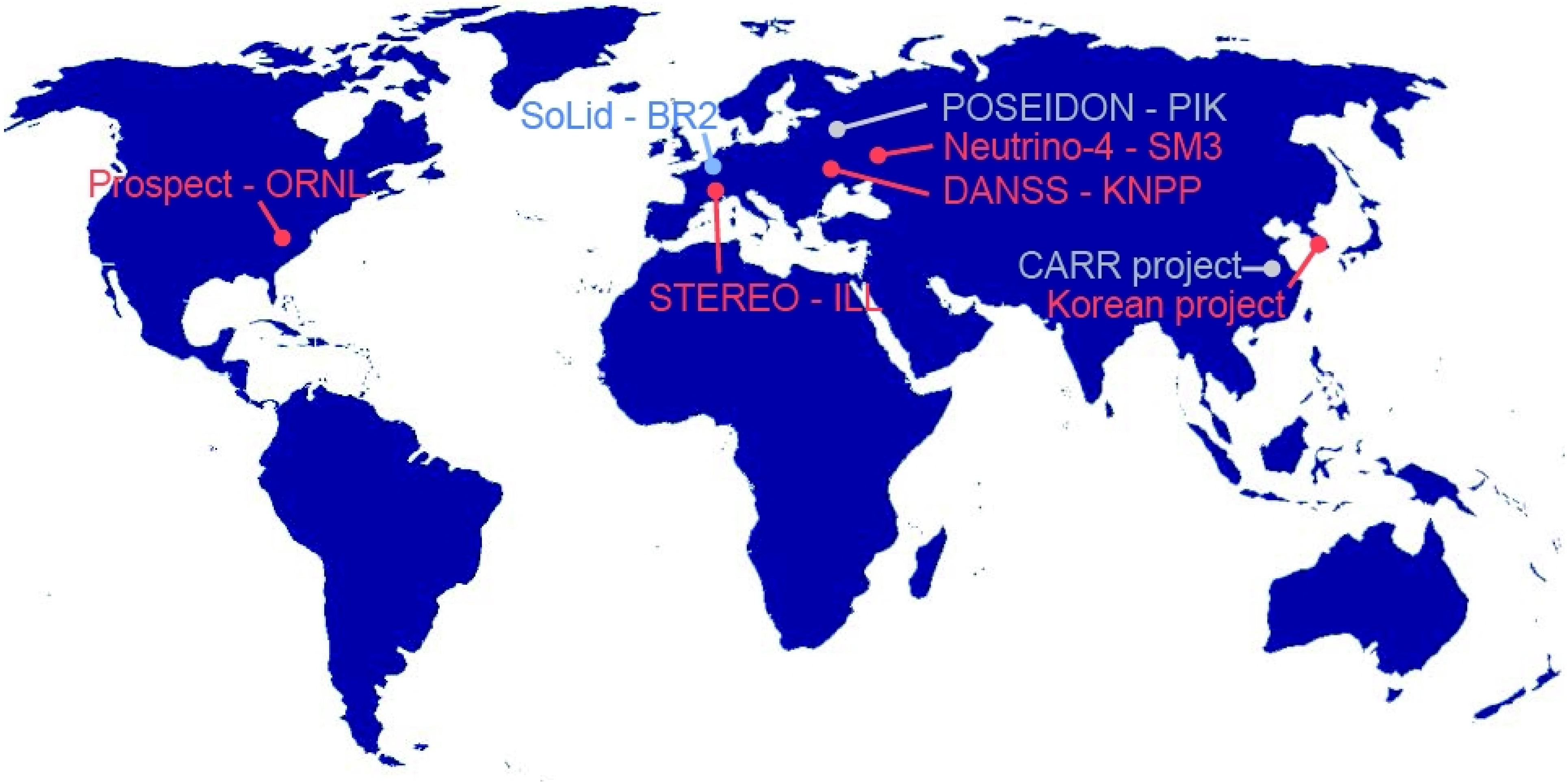
shape only



shape+rate



New reactor experiments



New reactor experiments

	Tech	Reactor	P [MW]	L (m)	M (tonnes)
Nucifer (Fr)	LS+Gd	OSIRIS	70	7	0.8
POSEIDON	LS+Gd	PIK	100	5-8	~3
STEREO (Fr)	LS+Gd	ILL	57	8.8-11.2	1.75
Neutrino-4 (Ru)	LS+Gd	SM3	100	6-12	1.5
PROSPECT (US)	LS + Gd/^{6}Li	ORNL HFIR	85	7-18	1 & 10
SoLid (UK/B/Fr)	PVT + ^{6}LiF:ZnS	SCK•CEN BR2	45-80	5.5-11	1.44/2.88
DANSS (Ru)	PS + Gd	KNPP	3000	9.7-12.2	0.9
Hanaro (KO)	PS + Gd/^{6}Li	Hanaro/ Younggwang	30-2800	6-?	~1

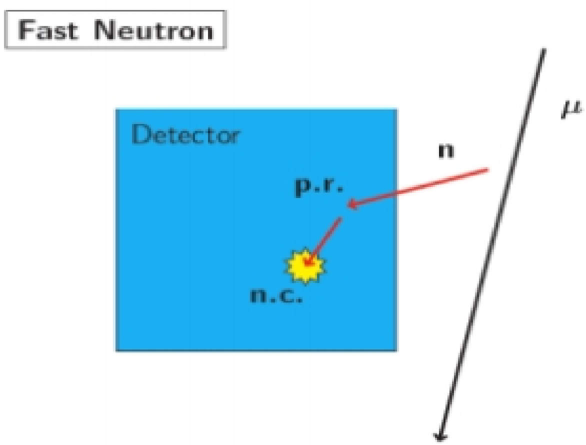
Very short baseline reactor experiments

- Hot topic in the field of neutrino physics

- Identify antineutrino interactions, but detector constraints:
  - Small – tonne scale
  - Reactor safety / limited access

- Control of the background is the key to reach the best sensitivity
  - Cosmics at ground level
    - High-energy neutrons
    - Cosmogenic decay
  - Fast neutrons
    - Nuclear recoil identified as e^+, thermalised neutron is captured
  - Reactor gammas
    - Increase accidental background
    - Impact on e^+ measurement
    - Can impact neutron detection

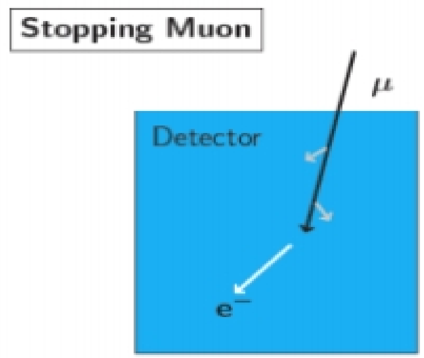
Background from cosmics



p.r. : proton recoil **n.c.** : neutron capture

Prompt event : Collision between a Fast Neutron and a nucleus

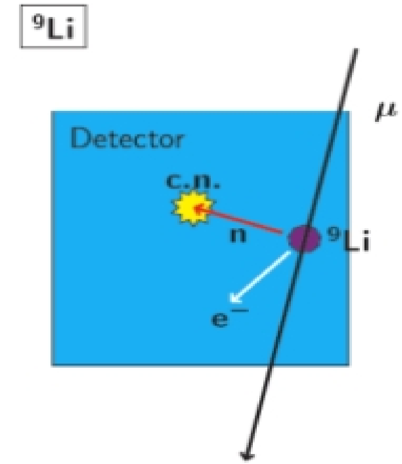
Delayed event : Fast Neutron capture



$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$ ($\tau \sim 2\ \mu$s)

Prompt event : (Short) track of a μ.

Delayed event : "Michel" e^- (from μ decay)



$^9\mathrm{Li} \rightarrow e^- + n + ^8\mathrm{Be}$ ($\tau \sim 200$ ms)

Prompt event : e^-

Delayed event : neutron

Expected efficiency for IBD events

IBD selection :

Look for a neutron trigger

apply time cut 300 ns < Δt < 100,000 ns

Select MPPC pair E > ~600 keV around trigger

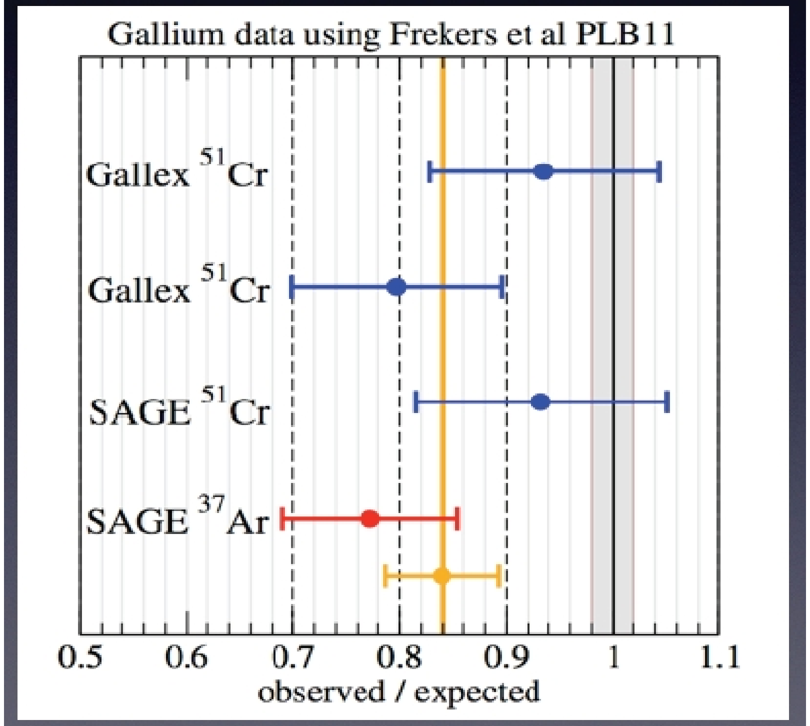
apply position cut (2 cubes max around trigger)

cut	Efficiency
n trigger	0.71
coincidence	0.58
Energy cut (20PE/600keV)	0.48
spatial cut	0.47
multiplicity cut	0.41

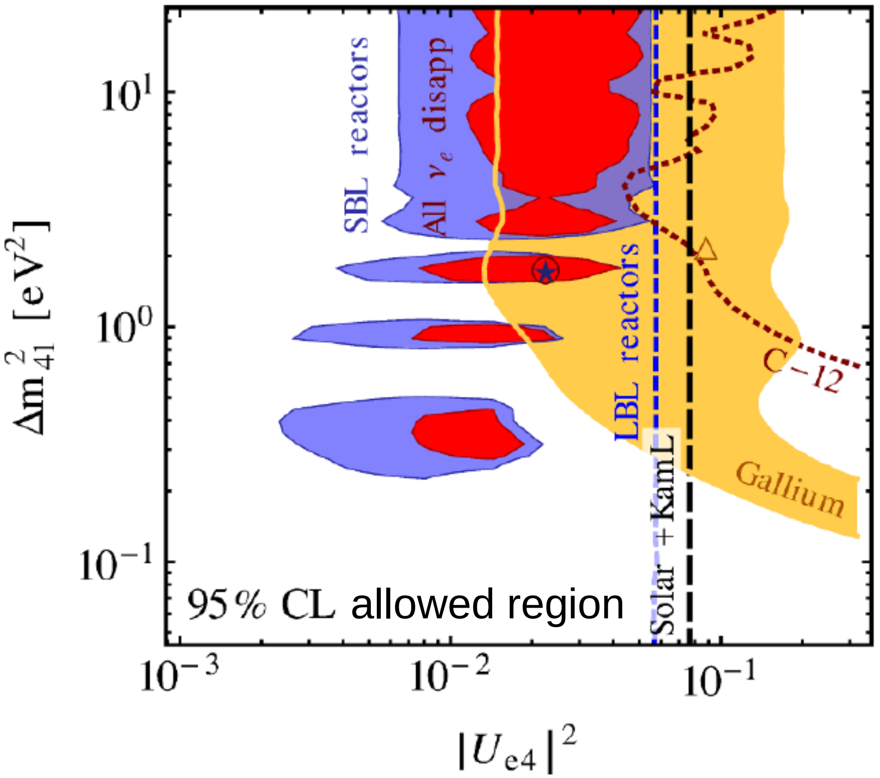
The gallium anomaly (solar neutrinos)

- GALLEX and SAGE experiments
  - Counting conversion rate of Gallium to Germanium by solar neutrino capture
  - Deficit of observed neutrino interactions compared to the expected number

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$



J. Kopp et al., hep/ph:1303.3011



- No oscillation hypothesis disfavoured at more than 99.9% CL
- Significance of best fit ~3.3σ