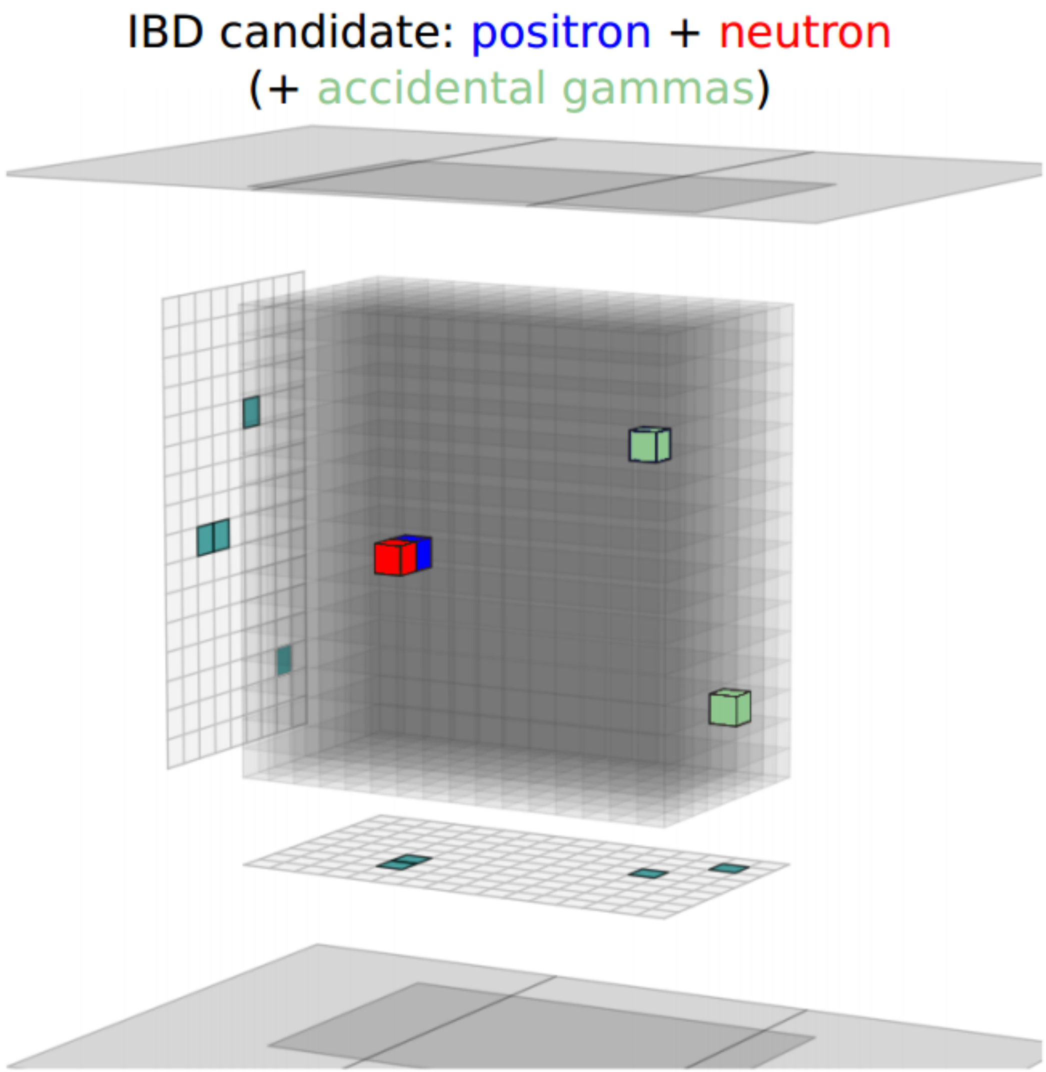
SoLid: a new short baseline neutrino experiment



Frederic Yermia

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Neutrino Oscillations

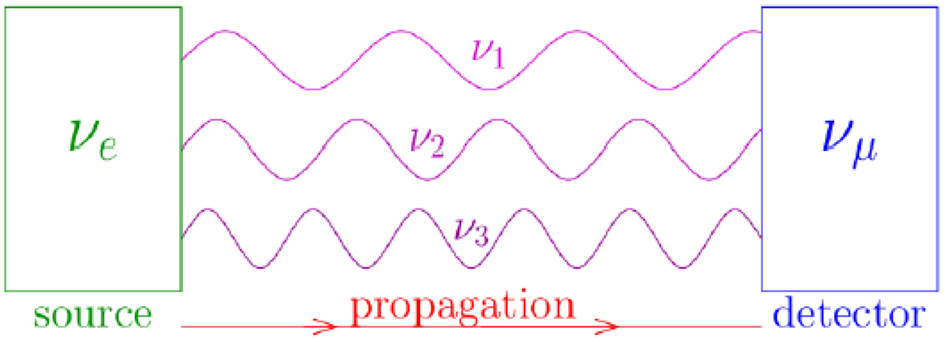
- 1957: B. Pontecorvo proposed Neutrino oscillations in analogy with $K^0 \leftrightarrows \overline{K}^0$ oscillations (Gell-Mann and Pais, 1955)

- Flavor Neutrinos ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos ν_1, ν_2, ν_3 propagate from source to Detector

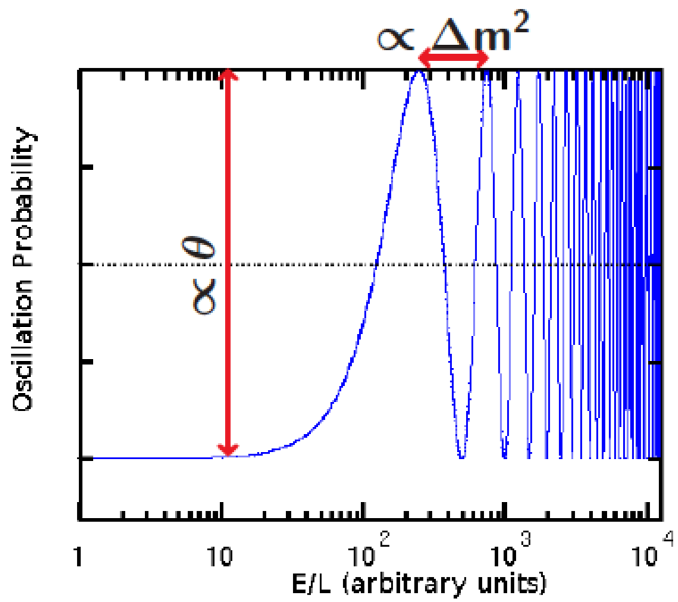
- A Flavor Neutrino is a superposition of Massive Neutrinos

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \text{ (2 neutrinos approximation)}$$

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



Cartoon from C. Giunti (INFN, Torino)



Neutrino Oscillations

- Oscillations described by the PMNS matrix:

Atmospheric | Reactor | Solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}.e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}.e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\boldsymbol{\theta_{23}}$: $P(\nu_\mu \to \nu_\mu)$: Atmospheric ν and Beam

$\boldsymbol{\theta_{13}}$: $P(\nu_e \to \nu_e)$: Reactor ν
$\boldsymbol{\theta_{13}}$ & $\boldsymbol{\delta}$: $P(\nu_\mu \to \nu_e)$: Beam

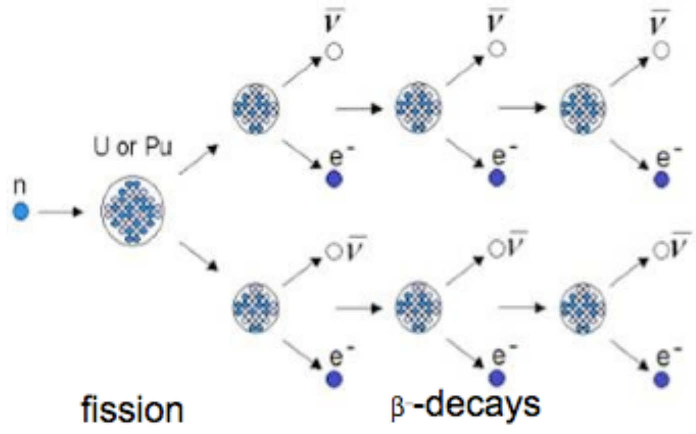
$\boldsymbol{\theta_{12}}$: $P(\nu_e \to \nu_e)$: Solar ν and Reactor ν

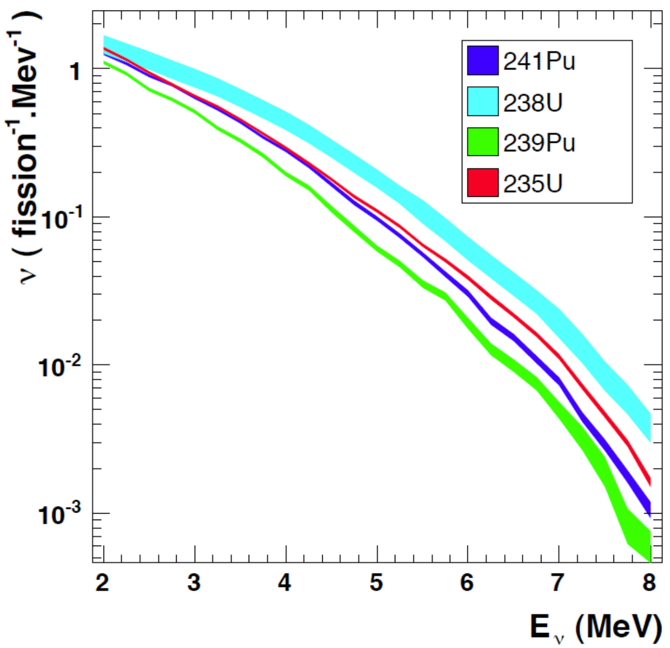
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and 1 phase (δ) to be measured

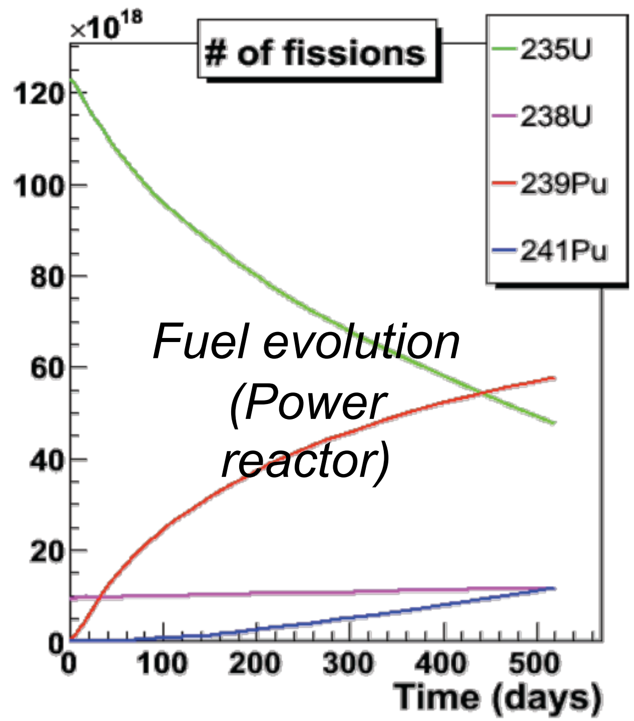
- Demonstrated by Super-Kamiokande and SNO experiments (Nobel Prize this year)
  Phys.Lett.B433, 9 (1998) and Phys.Rev.Lett.89, 011301 (2002)

Reactor antineutrinos

- Reactors are copious sources of $\overline{\nu}_e$
  - Beta decays of fission fragments
  - Low energy antineutrinos
  - isotropic flux
  - An 1 GW_{th} power reactor emits 2 10^{20} $\overline{\nu}_e.s^{-1}$







Example: Double Chooz Experiment

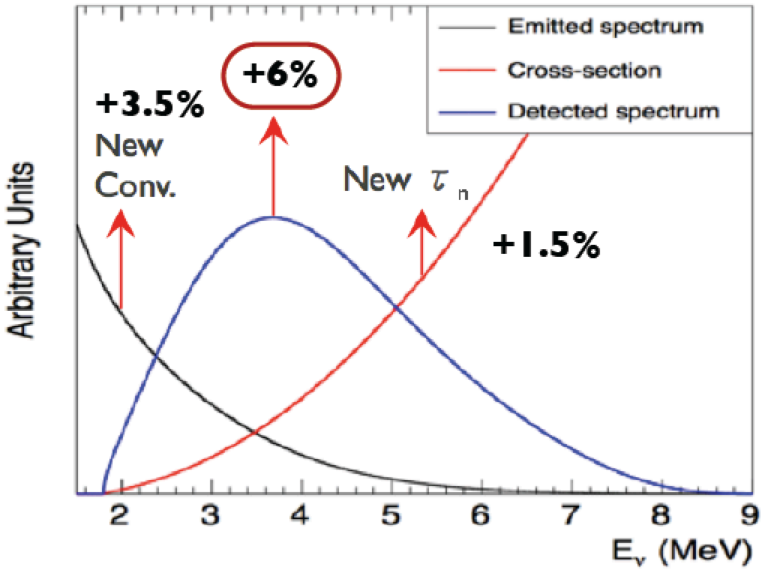
reactor experiment ➔ disappearance experiment

2012 : Reactor Anomaly

Revised reactor neutrino spectra

2011 re-evalatation of reactor antineutrino flux and update on cross-section parameters (Mueller et al. PhysRevC83054615)

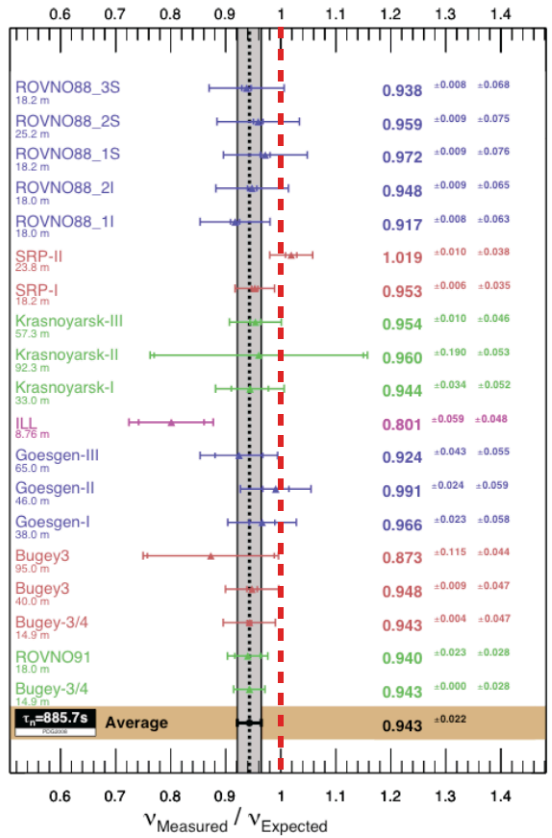
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



- **3.5% new conversion of ILL beta spectra**
- **1.5% off-equilibrium**
- **1.5% neutron lifetime τn**

➔ Significant increase of the prediction by 6.5%

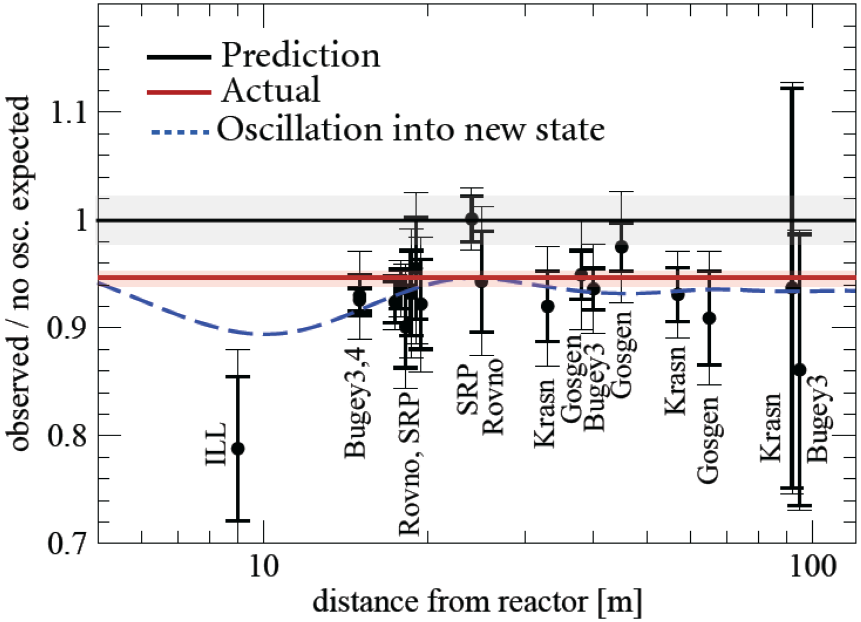
Reanalysis of reactor SBL experiments
G. Mention et al., Phys. Rev. D83, 073006 (2011)



μ = 0.927 ± 0.023,
(updated in White Paper on sterile neutrinos:
[2012 result]
[hep-ph:1204.5379]

↔ Rate deficit 6.5%

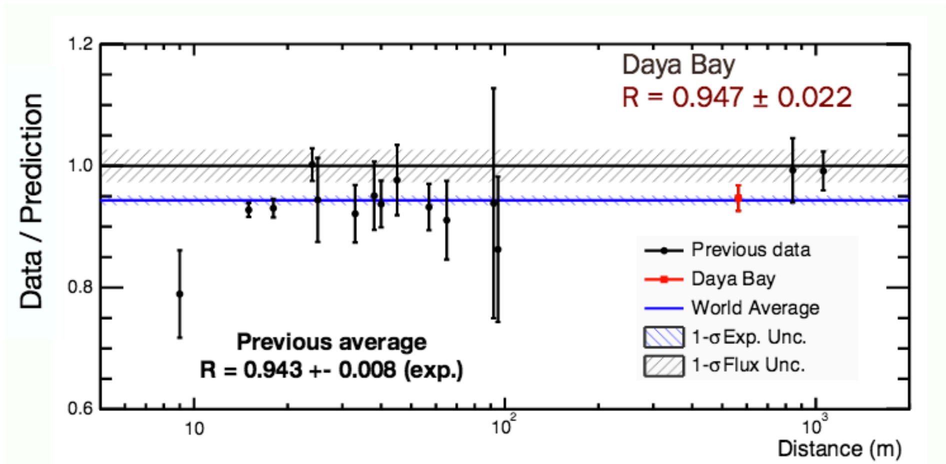
Reactor Anomaly + other anomalies in neutrino sector



↓ 2.7σ deficit

current rate anomaly due to unknown effect, to some prediction issues or to new physics ?

Daya Bay's reactor flux measurement is consistent with previous SBL experiments



arXiv:1508.04233

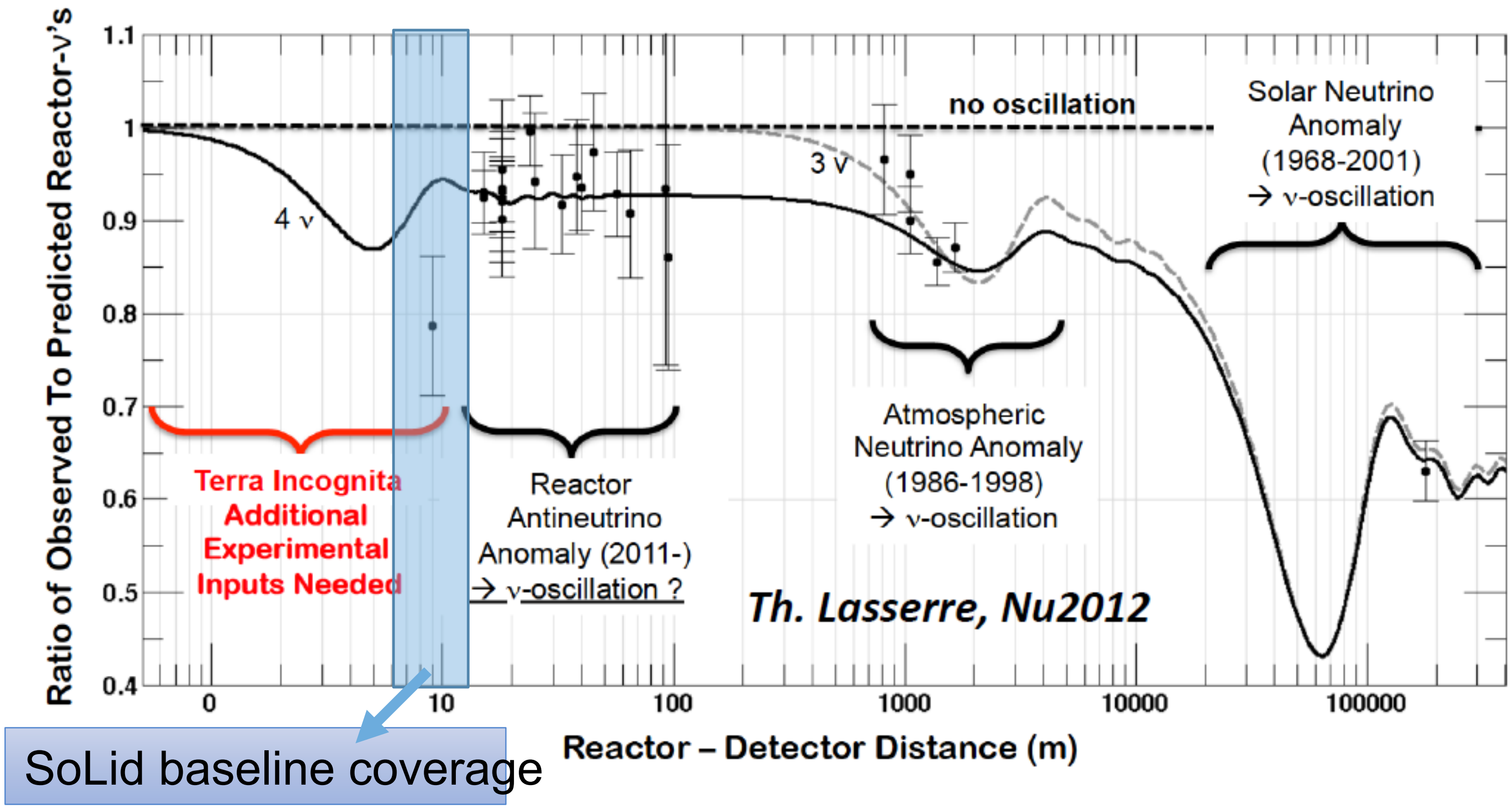
- LSND/MiniBoone :
  - LSND: [20-200 MeV] @ ~30m
  - MiniBoone: [475 MeV-3 GeV] @ ~ 550m

excess of events
~ 2-3 σ

- Galium :
  - GALLEX : ^{51}Cr (720 keV) @ ~ 1m
  - SAGE : ^{51}Cr (720 keV) ^{37}Ar (810 keV) @ ~1m

deficit of events
~ 2-3 σ

Terra incognita

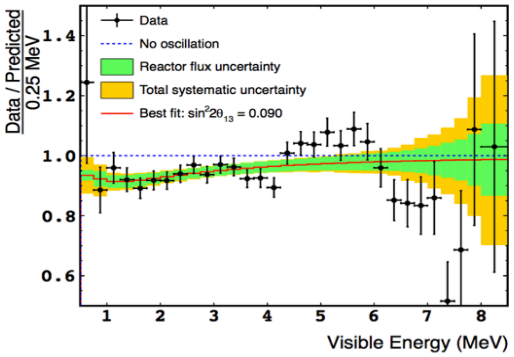


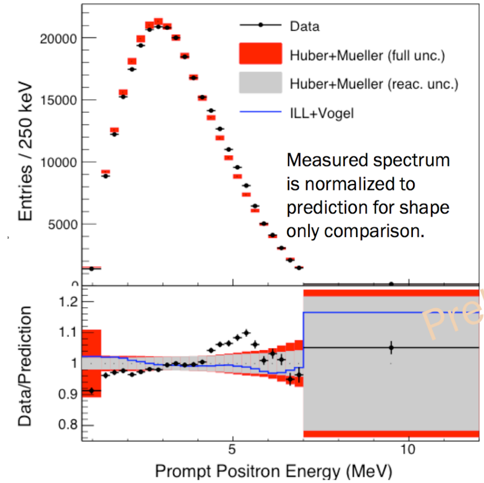
- Oscillations due to an (additional) sterile neutrino are not excluded from other data sets
  - Hints from other experiments in the same channel
  - Further input is needed ! Very short-baseline reactor experiment

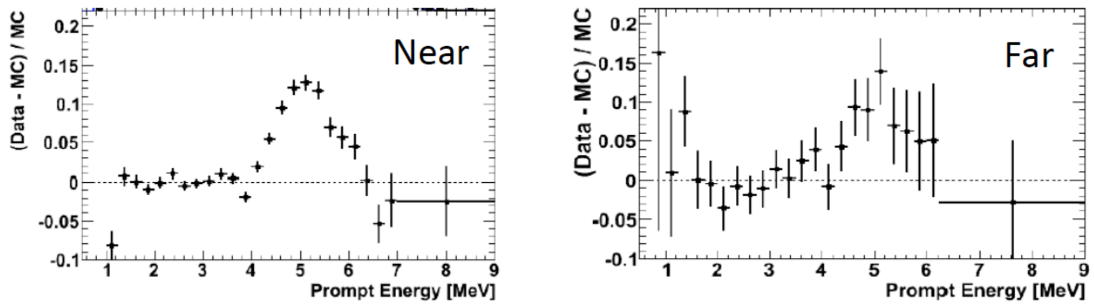
Recent reactor data

- Distortion in e+ spectrum observed / predicted at all three experiments (Double Chooz, Daya Bay, RENO)
  - 4**σ** local excess in [4,6] MeV window in Daya Bay data
  - no effect on θ_{13} **measurement and reactor anomaly**
  - **Origin of the excess to be understood: is it a physics effect or a bias in the predictions?**

Ratio data/non oscillation predictions

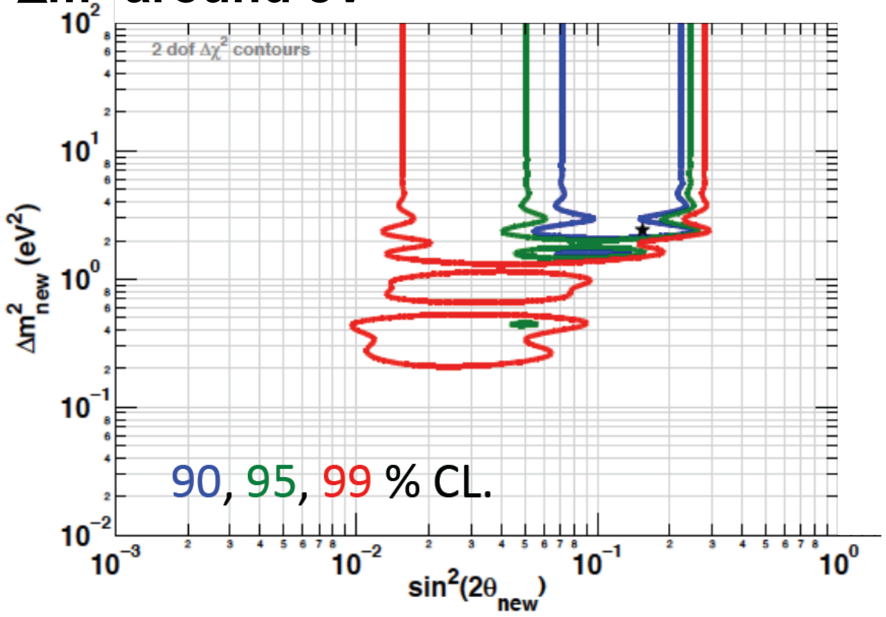




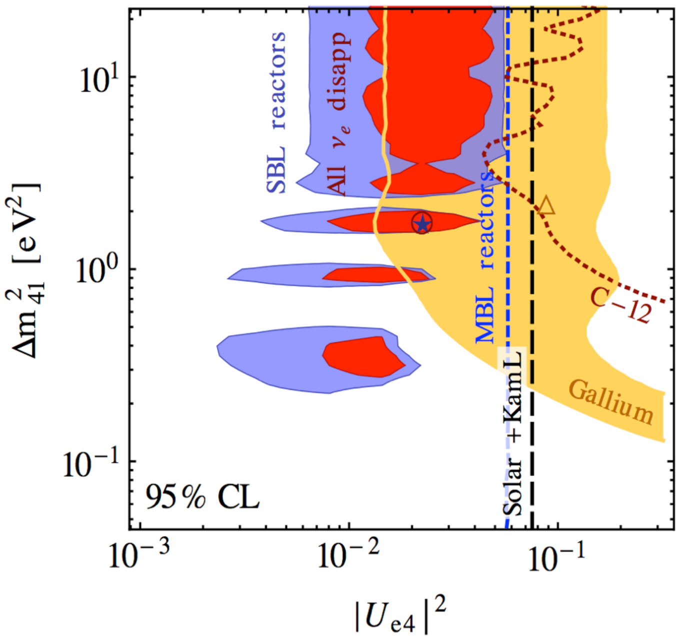


Sterile Neutrinos

The measured anomalies can be explained by a sterile neutrino state with Δm^2 around eV^2



Sterile neutrino white paper arXiv:1204.5379



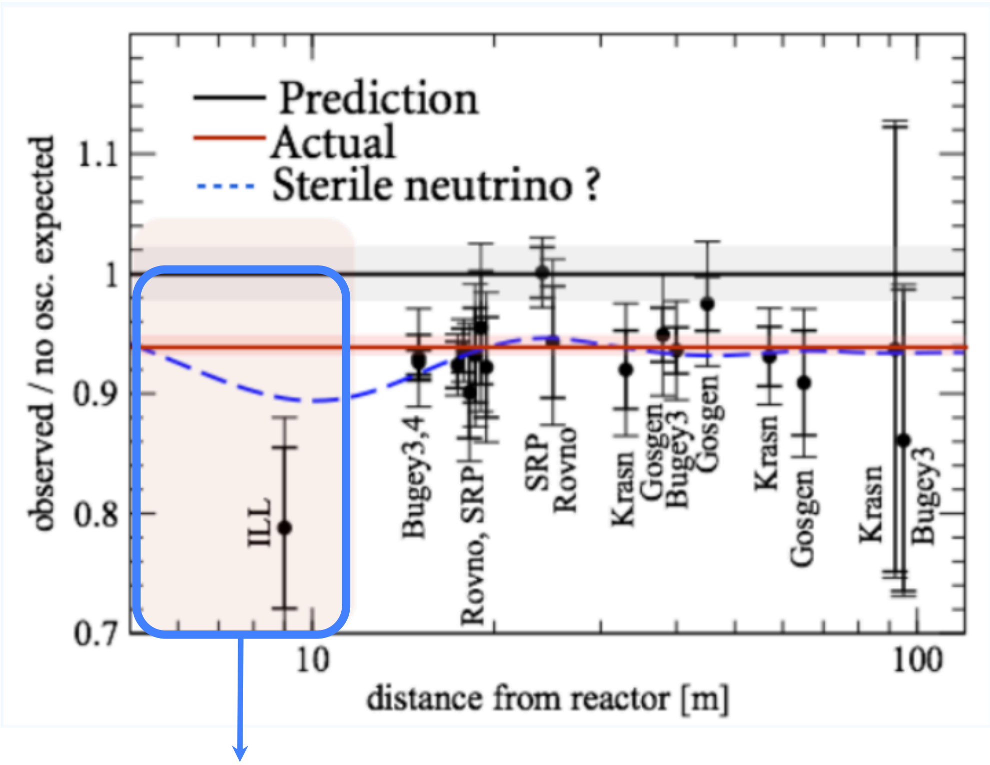
J. Kopp et al., hep/ph: 1303.3011

Combined no oscillation disfavored at more than 99.9% C.L. (3.3σ)

Two techniques in ν_e disappearance to address this on a short timescale:

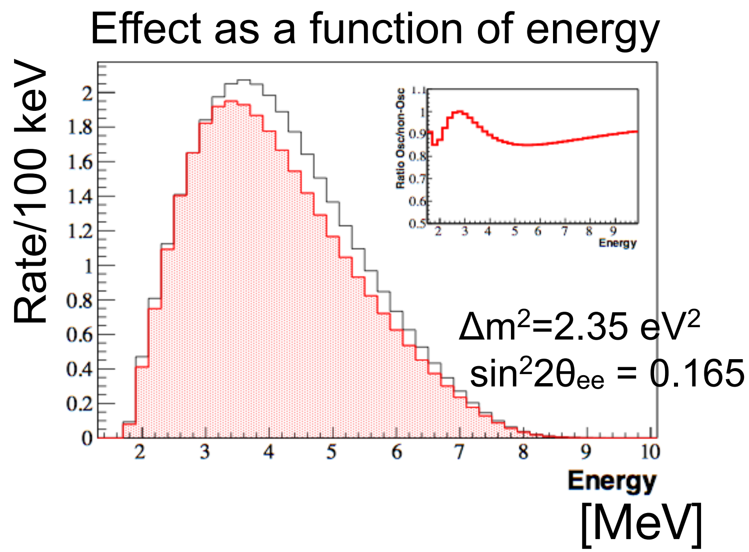
1. **Large source, large detector experiments**
2. **very short baseline [5-20] m reactor experiments**

Look for rate and energy variations



Data scarce at short distance :

Need better experiments and other data points !

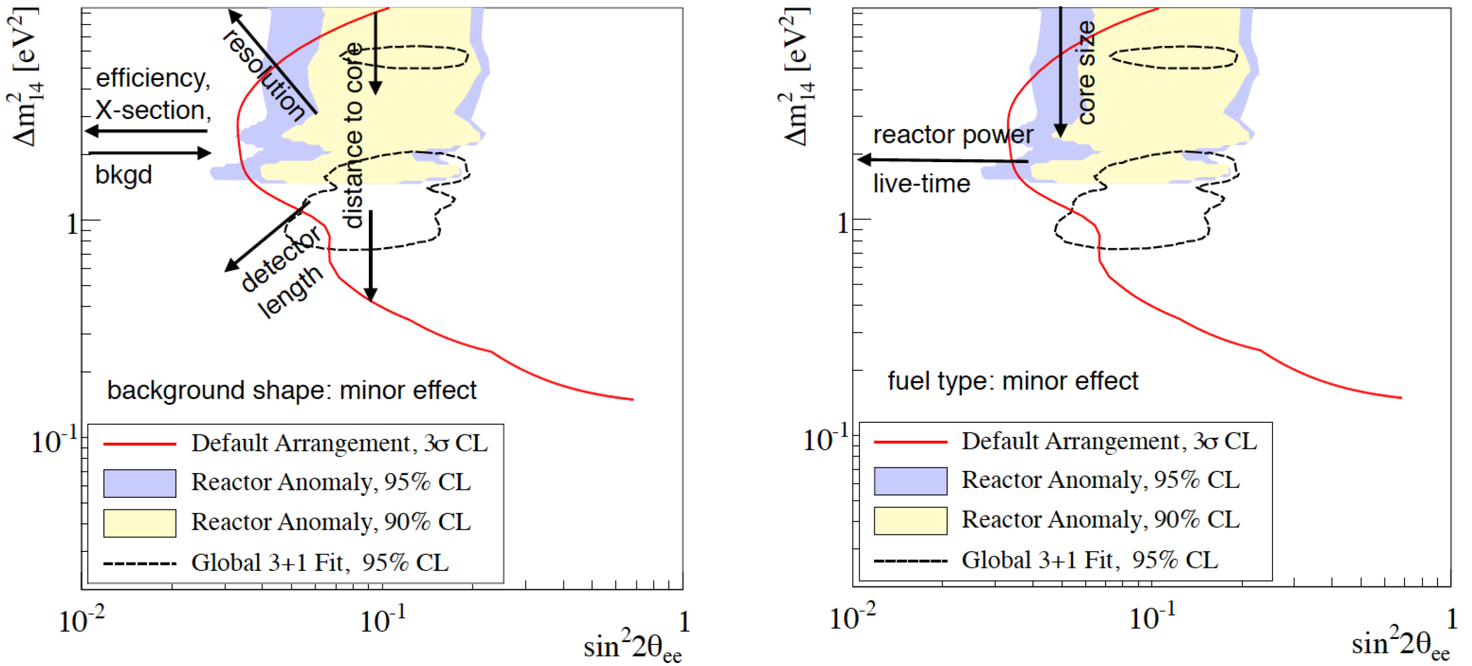


- Good energy resolution experiment
- Good position resolution

- Control of background is key for best sensitivity

Key Experimental Parameters

Reactor and detector parameters relevant for covering the suggested parameter space.
K.M. Heeger et al., arXiv:1212.2182v1



Total Statistics: Highest possible power and a detector with the highest possible efficiency

Detector length: A large detector length increases an experiment's ability to resolve oscillations with position in addition to spectral distortions in energy.

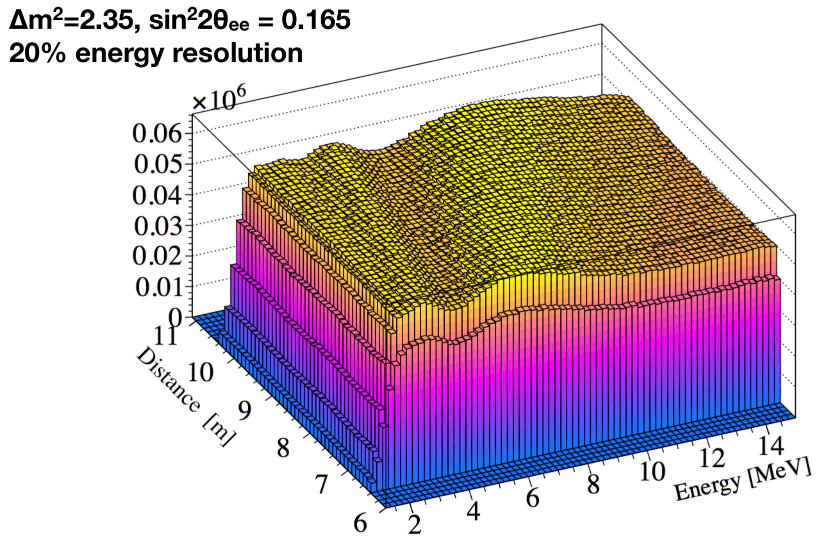
Detector-reactor distance: The closest reactor-detector distance r_{min} determines the Δm^2 range of highest sensitivity.

Detector resolution: Oscillations at higher Δm^2 are only visible if resolutions and bin sizing are smaller than the oscillation itself.

Background: The S:B ratio is crucial for the success of the experiment. Small S:B ratios make it difficult to resolve oscillation effects above statistical background fluctuations and uncorrelated background uncertainties

Keys to a Short-Baseline Reactor Experiment

1. Sensitivity to the higher **Δ**m^2 range (2 eV^2 and above) requires a compact reactor core, good energy resolution and position.



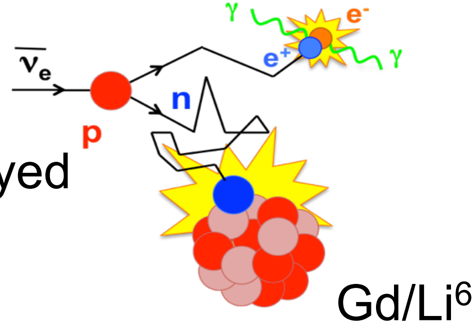
2. Use ratio of spectra at various distances
   - cover similar solid angle
   - no assumption on shape of spectrum
   - flexible baseline
3. Small oscillation effect (5-15% relative effect)
4. Detector should be portable, cannot use tons of shielding material
5. Detector should be able to work on the surface with very small overburden and close a reactor core.
6. Background is important, needs to be characterized and under control

Detection principle and Backgrounds

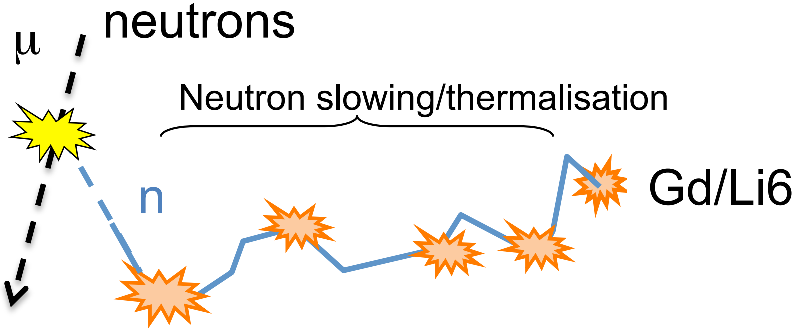
- Inverse beta decay detection
- Low overburden
  - Large muon induced background (FN), difficult to shield
  - Pass E and ΔT ν cuts!
- Close to the reactor core
  - High reactor neutron and gamma accidental background
  - difference reactor ON/OFF data not enough
  - Reactor background conditions can change over the data taking at research reactors
    - need high background rejection power, Control of background is key !
  - limit passive shielding to low Z to avoid regeneration of background

Detection principle: Inverse Beta Decay $\bar{\nu}_e + p \rightarrow e^+ + n$

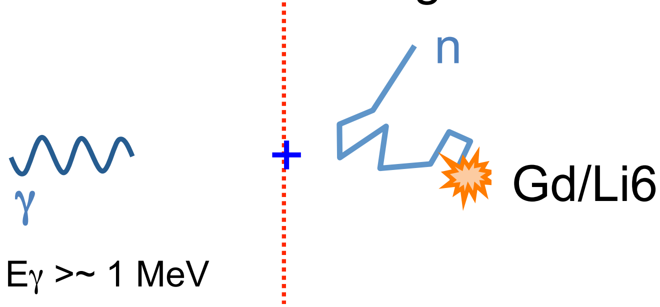
Coincidence prompt-delayed event



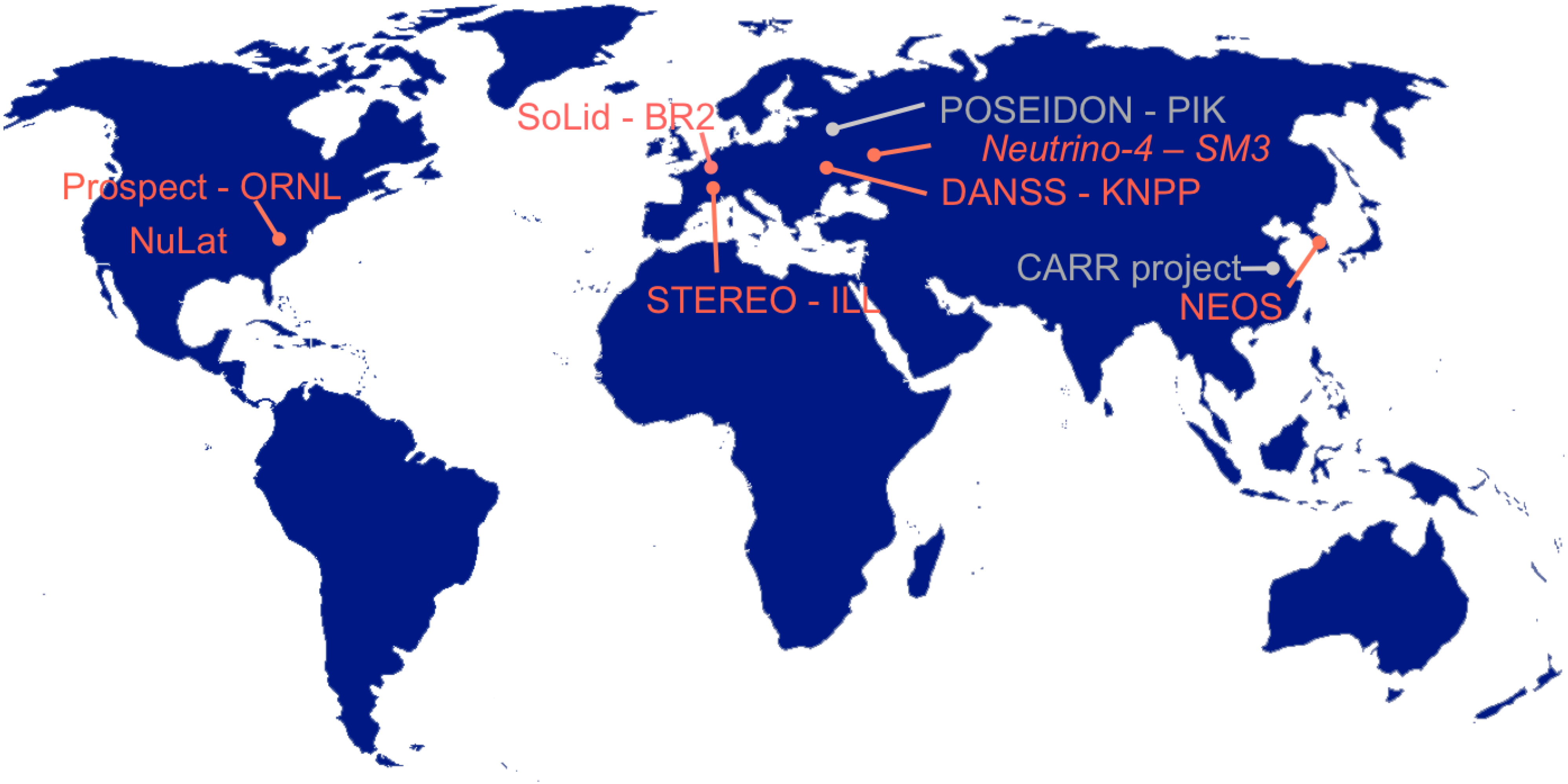
Correlated background from fast neutrons



Accidental background



SBL Reactor experiments



Detection principle:
Inverse Beta Decay

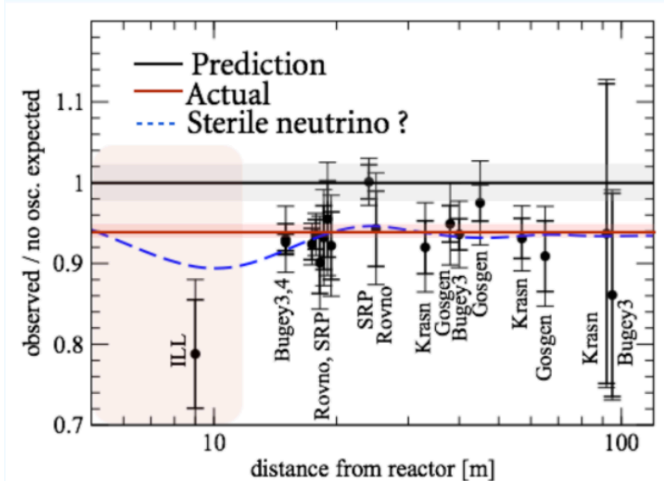
Neutron capture:Gd/Li^6

Site: research reactor or power reactor

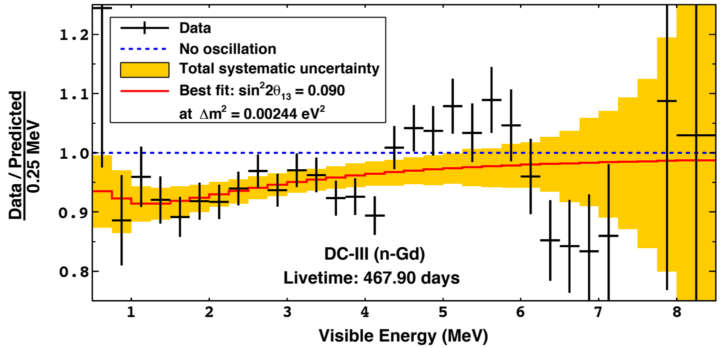
Universiteit Antwerpen
LPC Caen
Universiteit Gent
Merton College Oxford
University of Oxford
SCK•CEN
Subatech
Vrije Universiteit Brussel
Laboratoire de l'Accélérateur Linéaire
Virginia Tech
Imperial College London

Physics motivation

✓ Search for short base-line oscillation and test the sterile neutrino hypothesis ($\Delta m^2 \sim eV^2$)

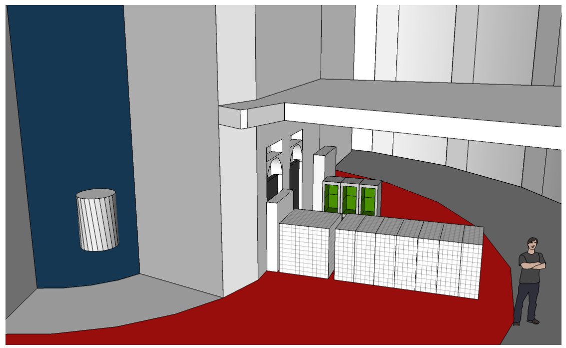


✓ Precise measurement of the 235U anti-ν_e spectrum



JHEP 10 (2014) 086 [Erratum ibid. 02 (2015) 074]

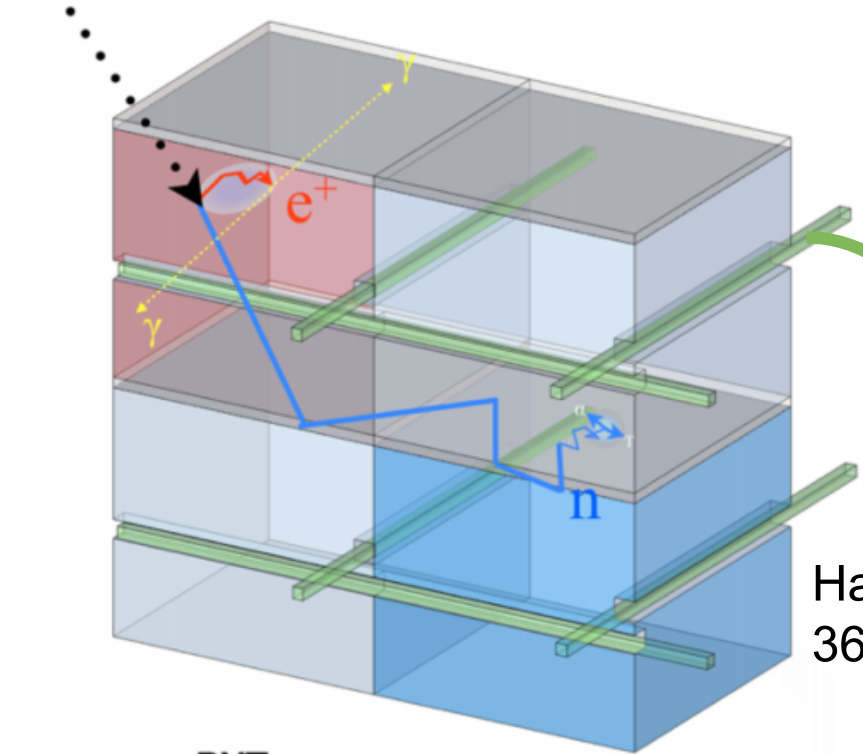
✓ Full detector for challenging measurement (~ 6.8 m from the HEU research reactor BR2 core @ SCK-CEN at Mol, Belgium)

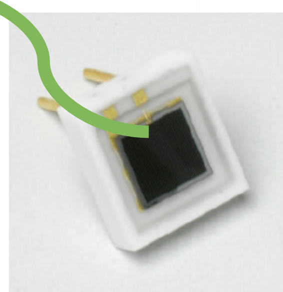


SoLid detector technology

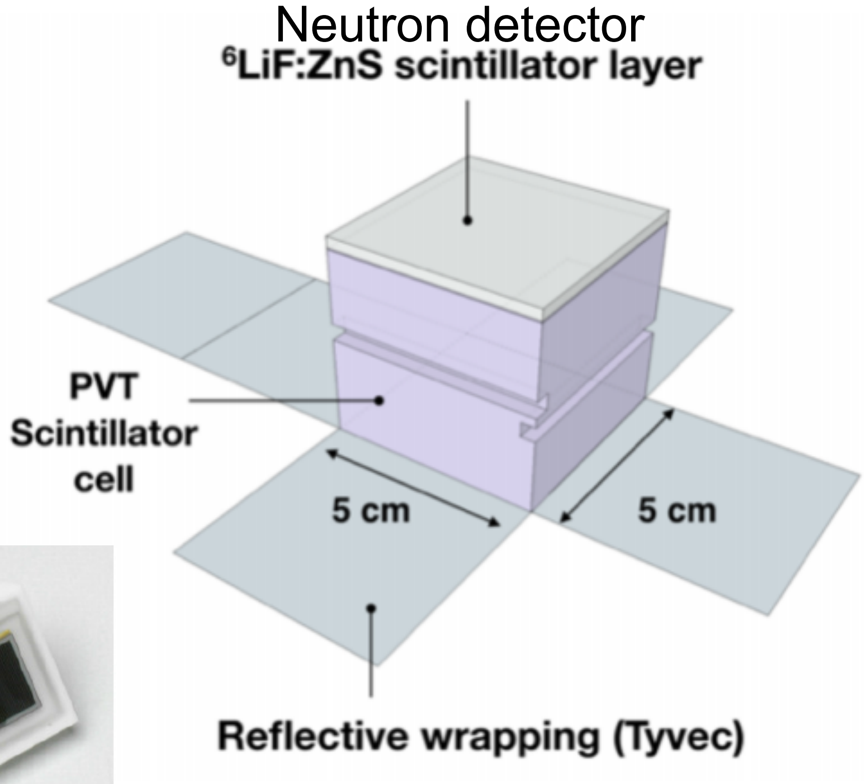
Key detection mechanism: IBD

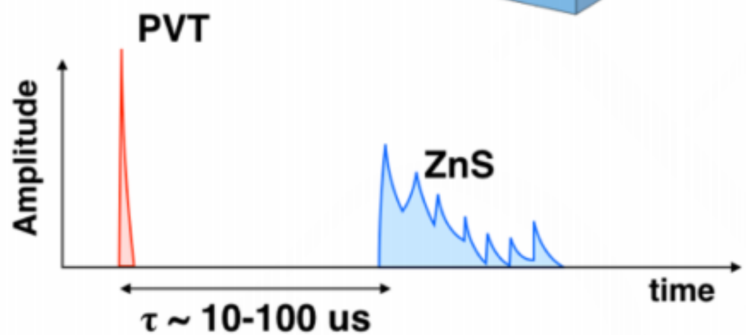
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



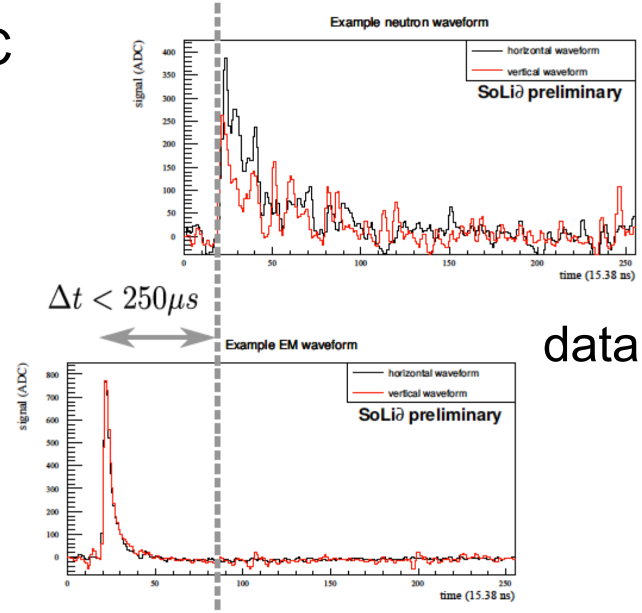


Hamamatsu MPPC
3600 pixels



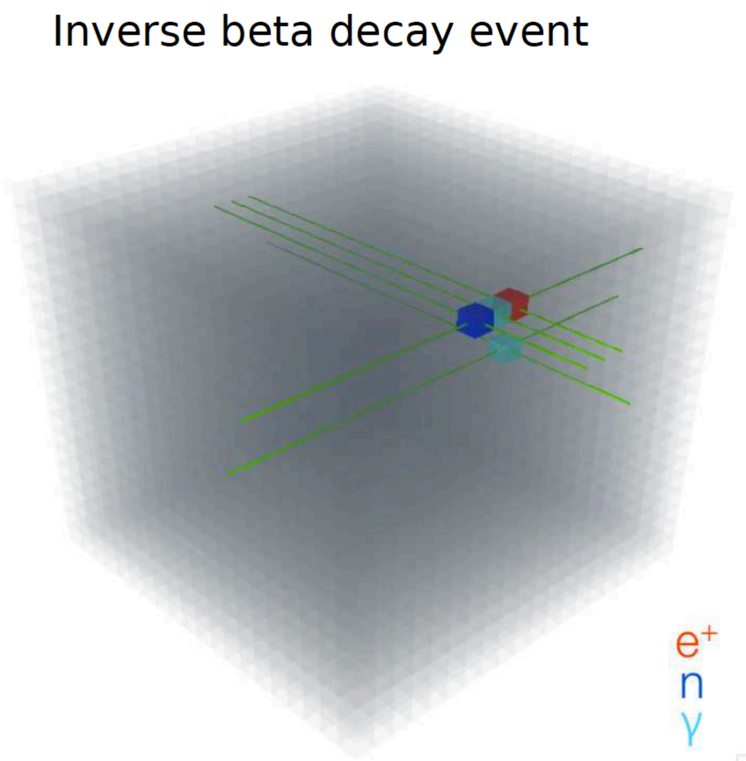


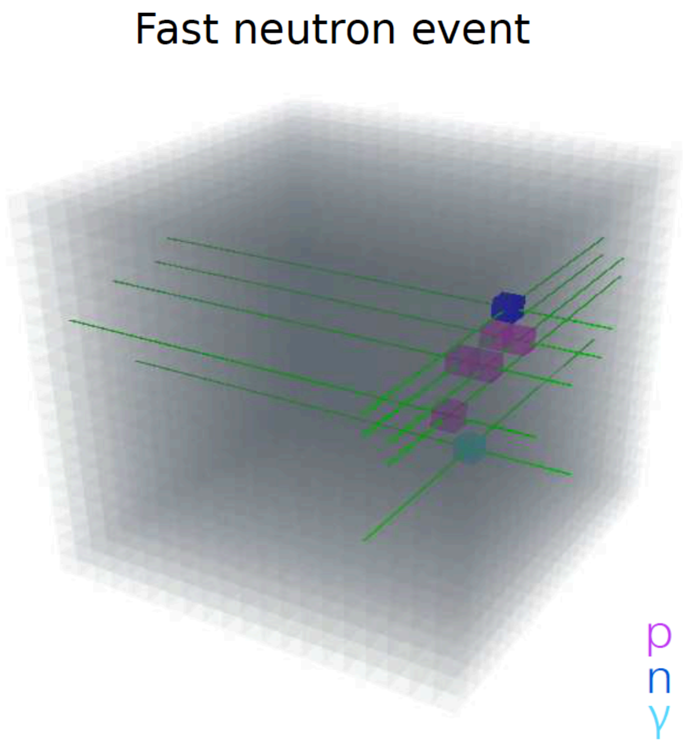
$$^6_3Li + n \rightarrow {}^4_2He(2.05\ MeV) + {}^3_1T(2.75\ MeV)$$



data

Event topology in SoLid



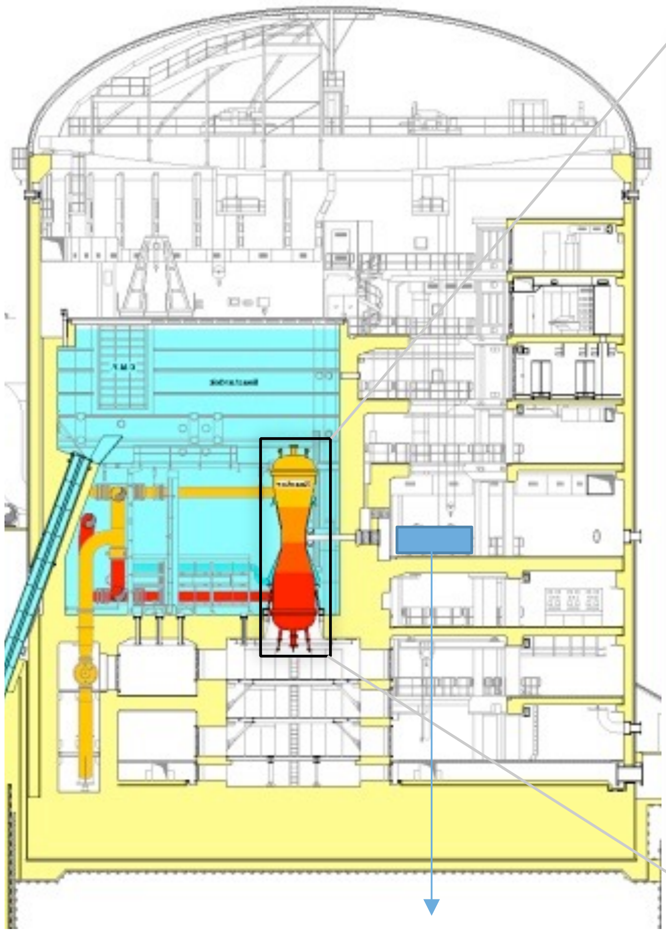


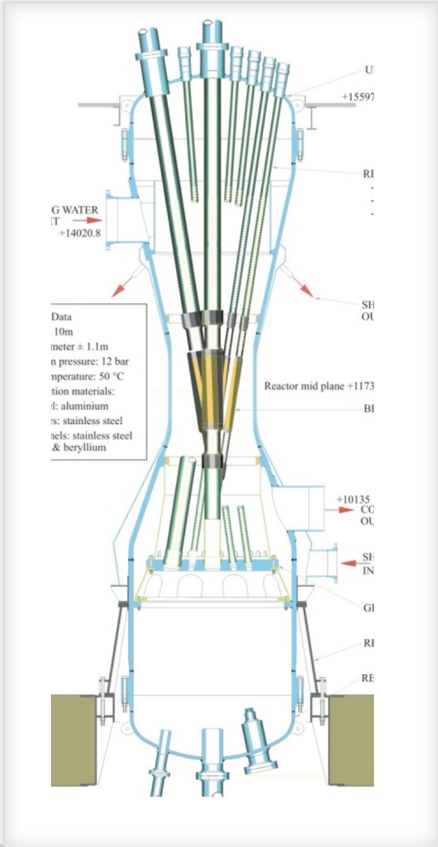
- High granularity allows for signal localization and thus enhances significantly the background rejection
- Possible fast neutron rejection through event topology

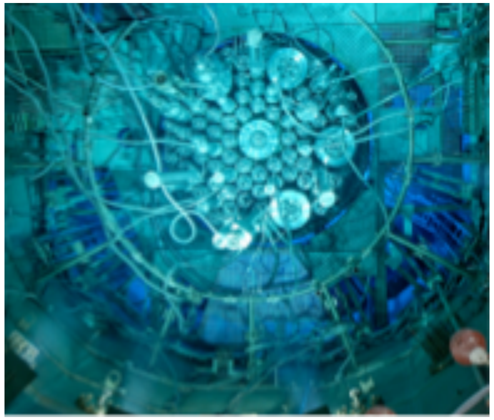
Belgian Reactor 2 (BR2)@ SCK•CEN

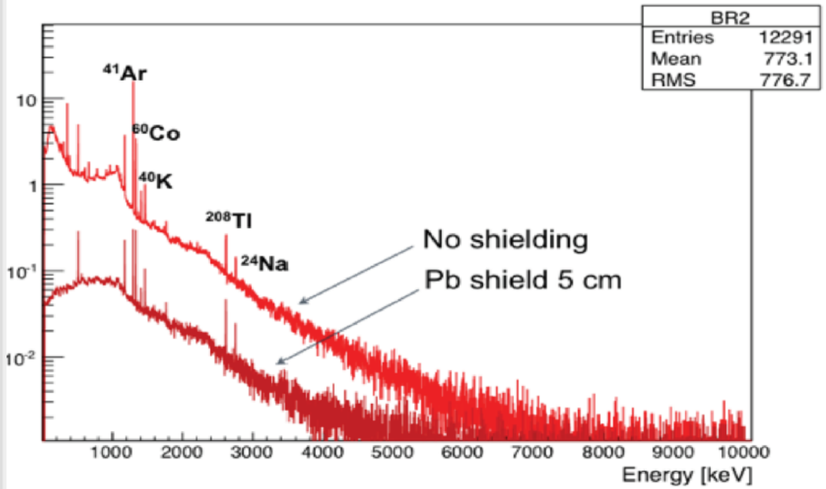
BR2 Confinement building

Aluminum pressure Vessel
Twisted core









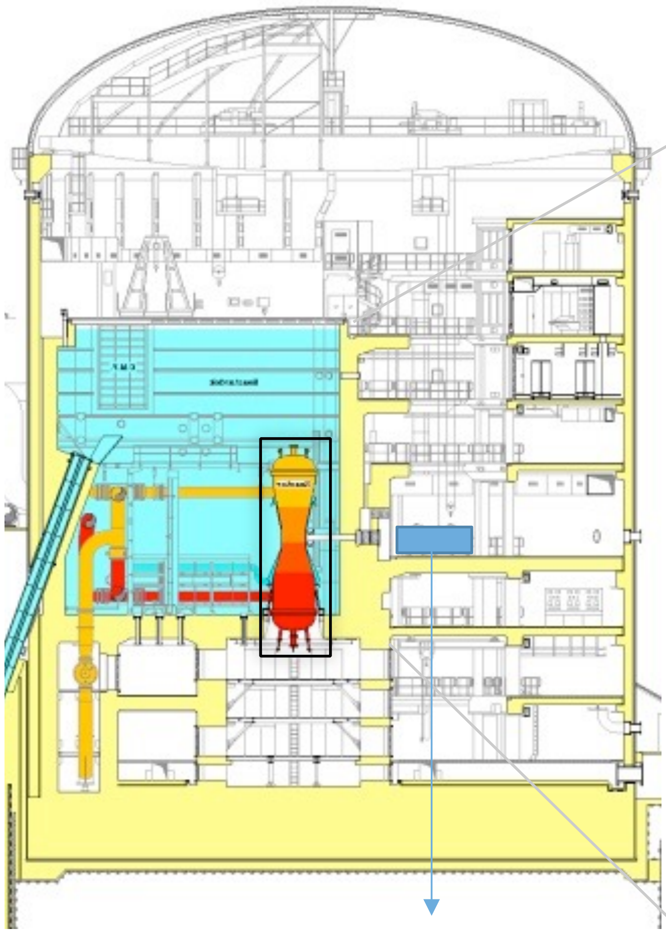
SoLid $\bar{\nu}_e$ detector:

- 1.5 T fiducial
- Baseline: 5.5 – 10m
- On-axis with reactor core

- 95% Enriched 235U
- Effective core diameter d=0.5m
- Peak power: 70-80 MW_{th}
- Duty cycle: ~ 150 days/year
- Low accidental background

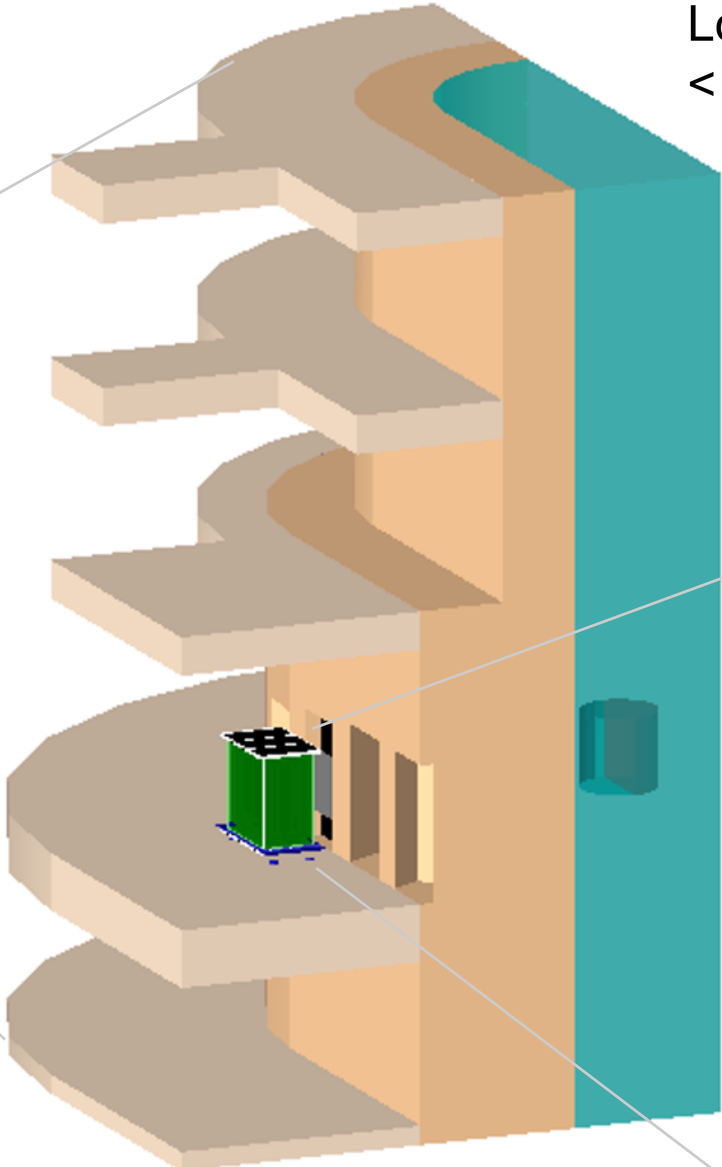
Belgian Reactor 2 (BR2)@ SCK•CEN

BR2 Confinement building



SoLid $\bar{\nu}_e$ detector:

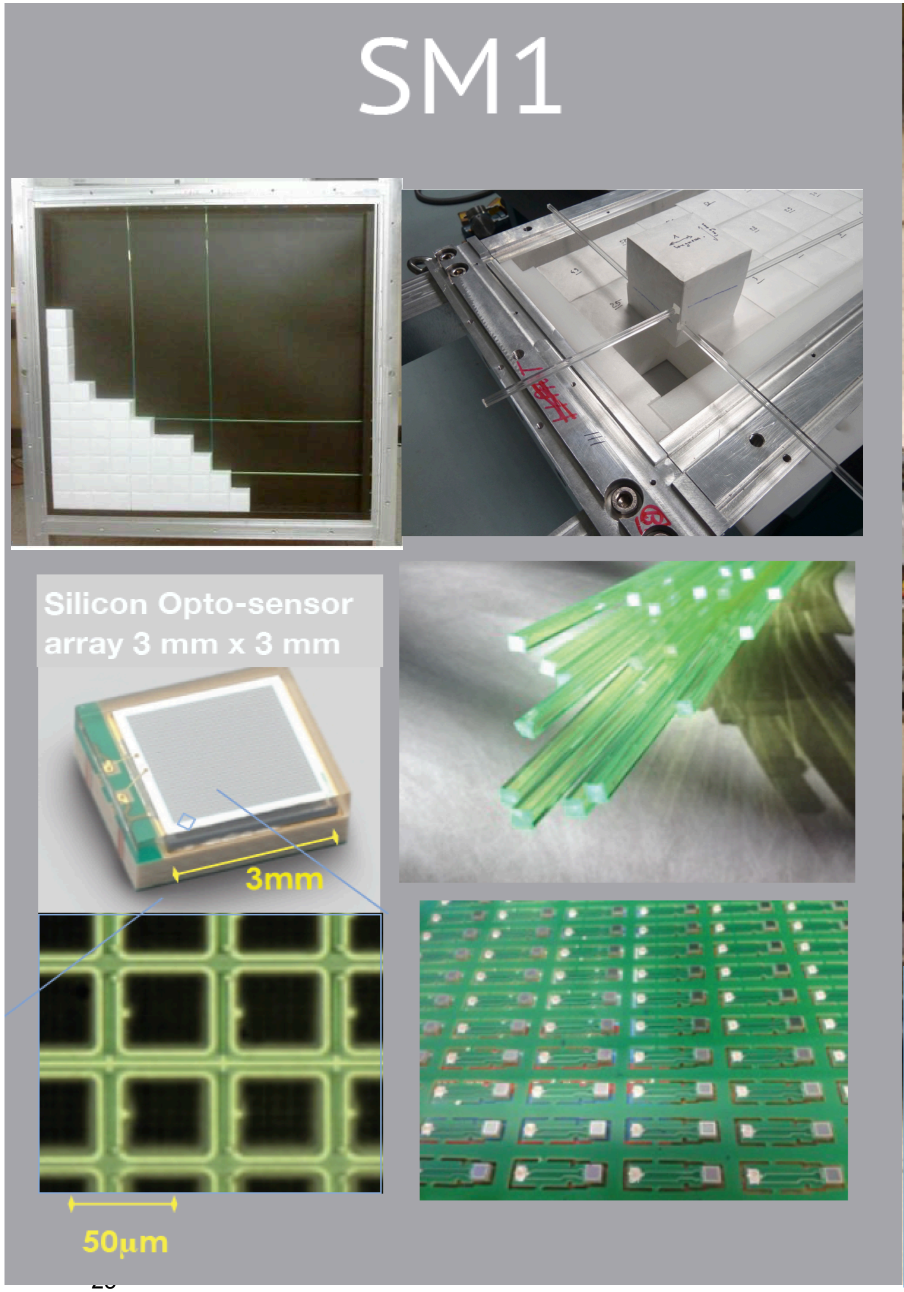
- 1.5 T fiducial
- Baseline: 5.5 – 12m
- On-axis with reactor core



Low vertical overburden
< 10m WE

<u>SM1:</u>
Full scale module
300 kg
2300 voxels

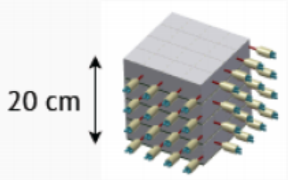
SoLid Module 1 (designed by Subatech)



- Detector split into vertical planes
- Optically isolated scintillator cubes wrapped in Tivek sheets
- 16 vertical and 16 horizontal 3 x 3 mm square WLS fibres + MPPC

Detector construction and operation
…a staged approach

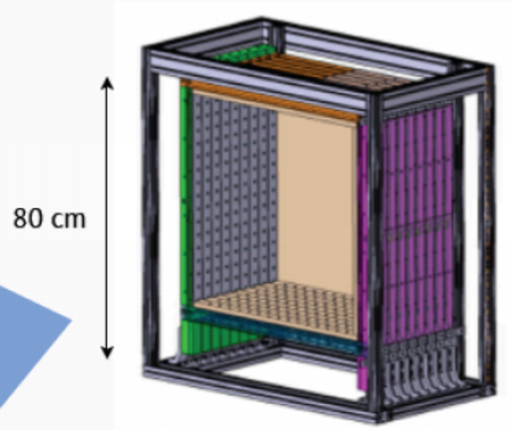
2013



NEMENIX **8kg**
64 voxels, 32 chan.

20x

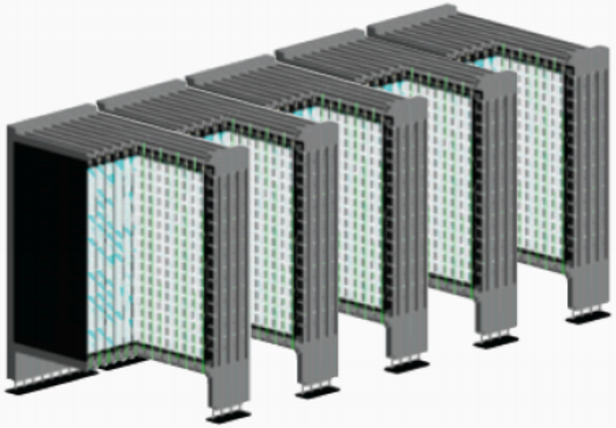
2014-2015



- SoLid Module 1 (SM1)
288kg
9 Detector planes
2304 voxels, 288 chan.

5x

2016



- 5x modules **1.440 tonnes**
11520 voxels, 1920 chan.
needs 2-3 tonnes for SoLid

Proof of Concept

1. Demonstrate neutron PID
2. Measure Backgrounds
3. Measure Coincidence Rate

Real Scale Systems Test

1. Demonstrate scalability
2. Test Production (schedule & procedures)
3. Demonstrate Power of Segmentation

Physics Scale Detector

1. Implement Neutron Trigger
2. Optimize Production
3. Optimize Performance
4. Do Initial Oscillation Search

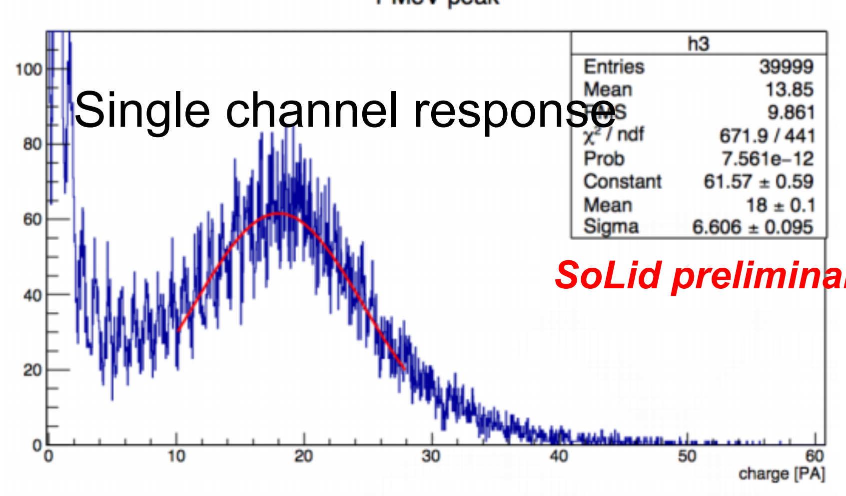
EM Energy response

Energy Scale& resolution

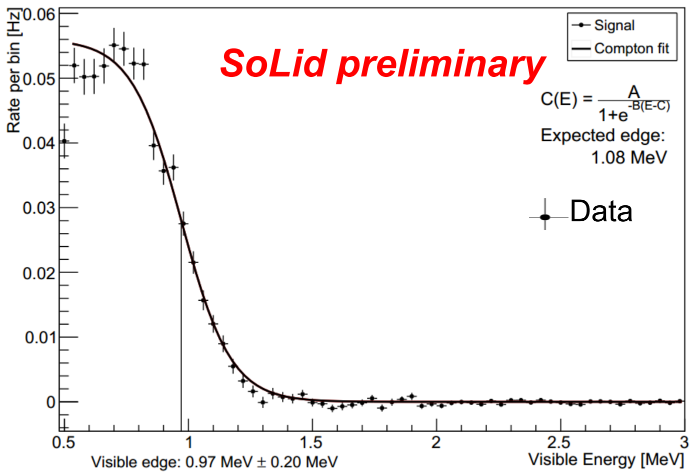
Laboratory test bench

Using 1MeV conversion electron

From ^{207}Bi

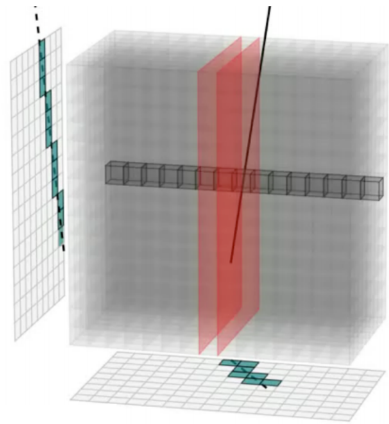


In situ: ^{60}Co-spectrum in a cube



With 4-channel readout/cube ≥40 PA/MeV

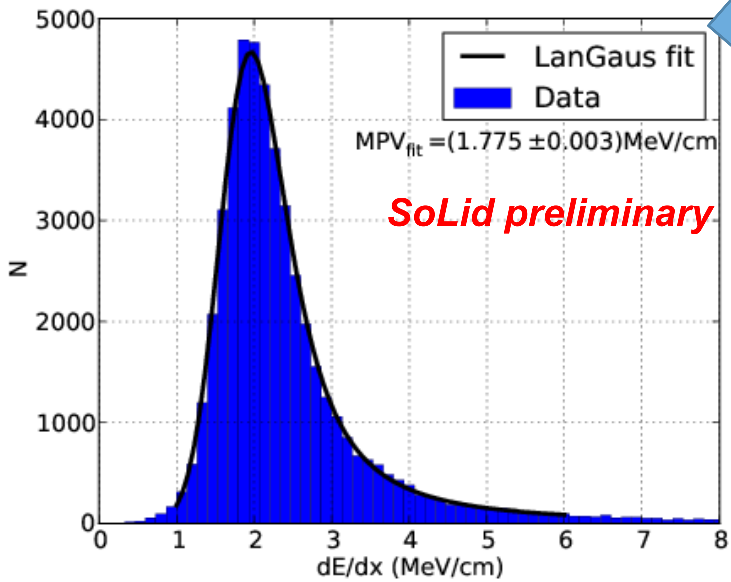
$15\%/\sqrt{E}$ at 1MeV Achievable !



Crossing muon event

Inter-channel calibration

Using reconstructed muon tracks

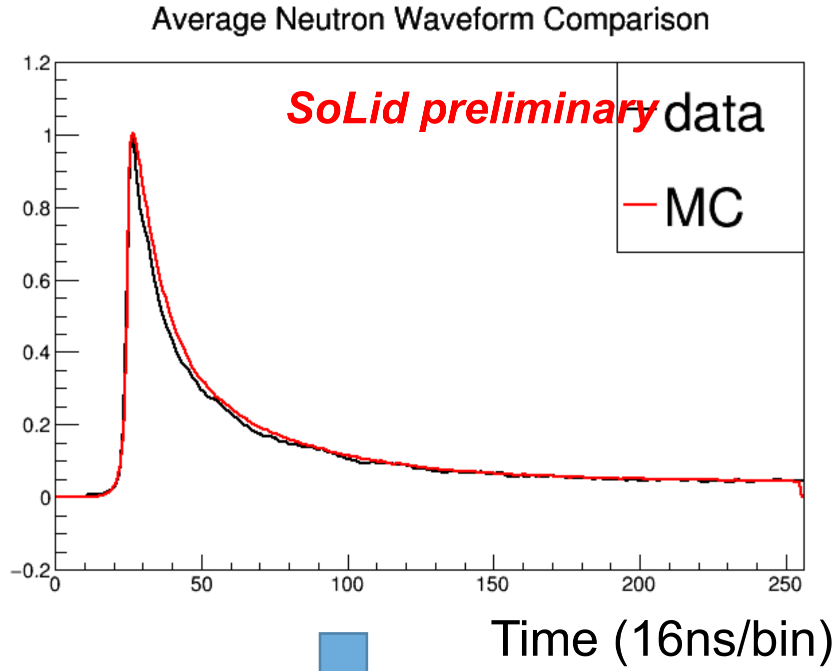


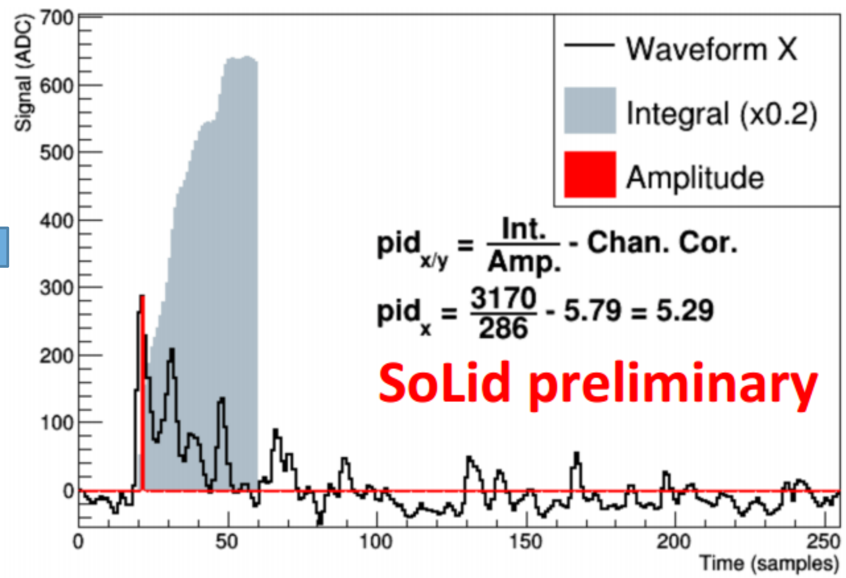
Neutron reconstruction

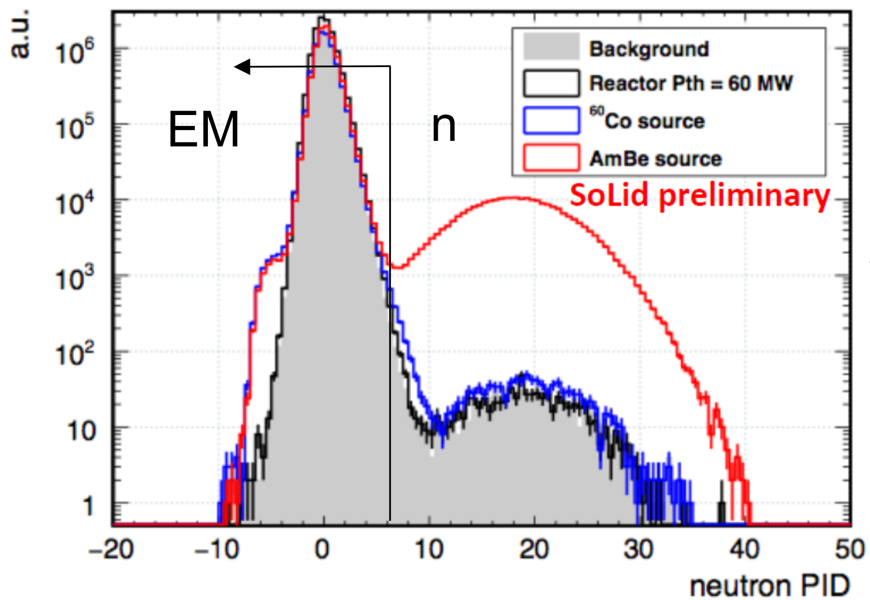
- Capture on ^{6}Li and excitation of ZnS(Ag) scintillator

$$^6_3Li + n \rightarrow \, ^4_2He(2.05\ MeV) + \, ^3_1T(2.75\ MeV)$$

- Capture efficiency for IBD neutrons using single (double) ^{6}LiFZnS per cell: 65% (80%)
- Distinct pulse shape allows separation from EM signals
- Validated with ^{60}Co and AmBe sources

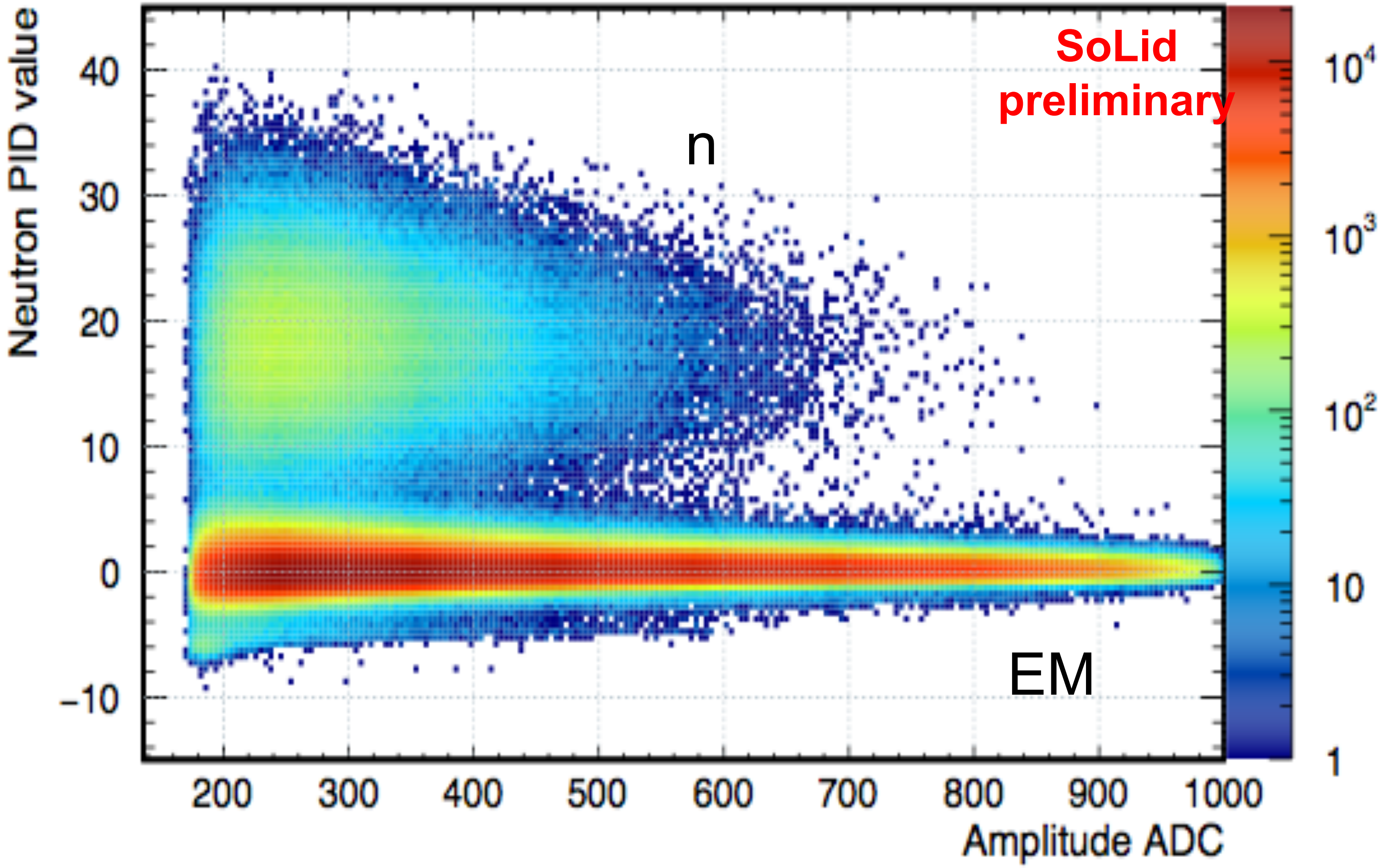






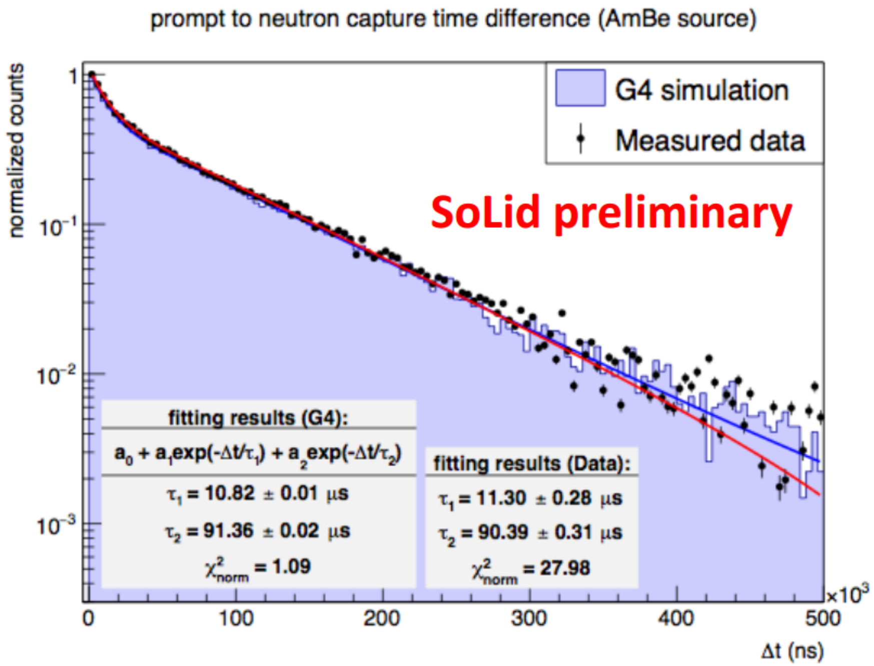
Neutron identification

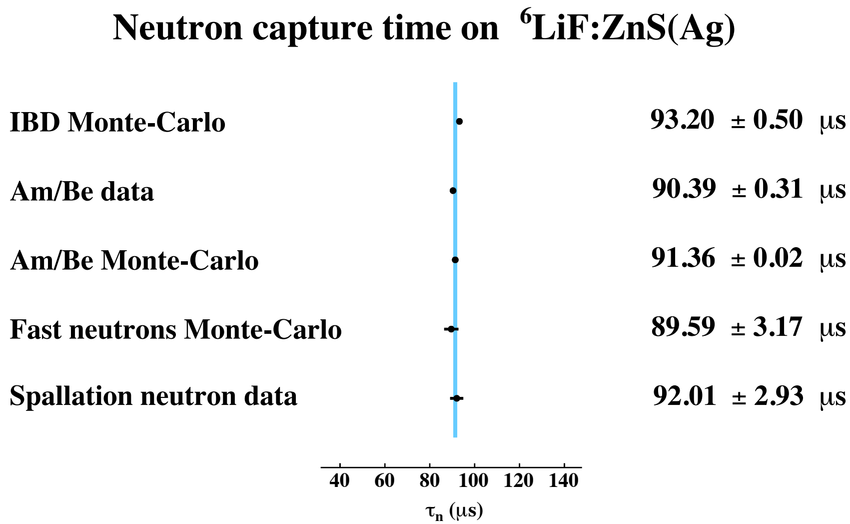
AmBe data



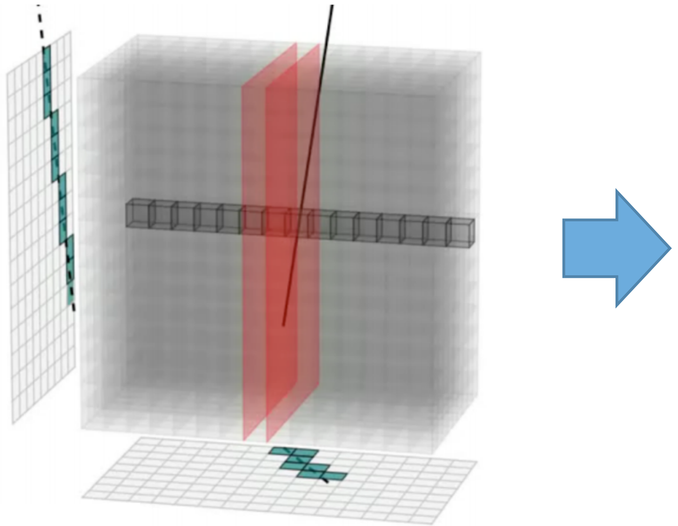
Neutron reconstruction

- Neutrons thermalize over distance of < 10cm: → Confined topology of IBD events
- prompt-neutron time difference determines IBD search window
- Simulation validated with Calibration sources (AmBe)

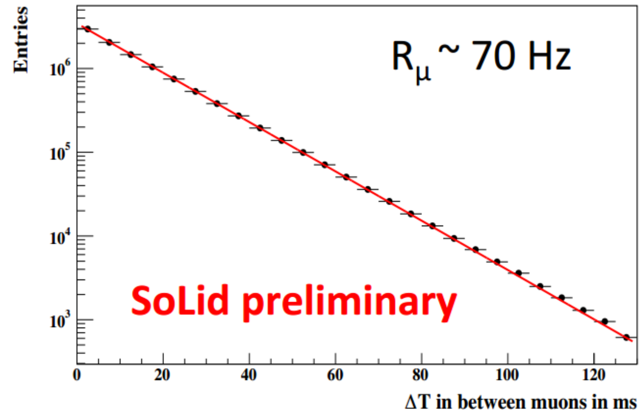


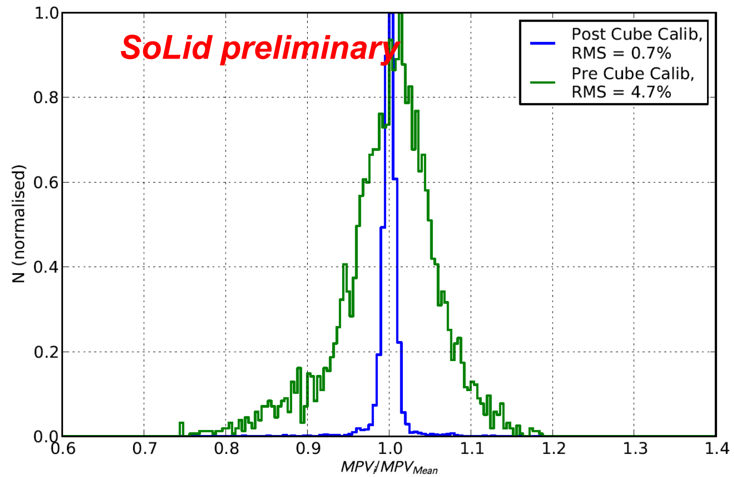


Muons

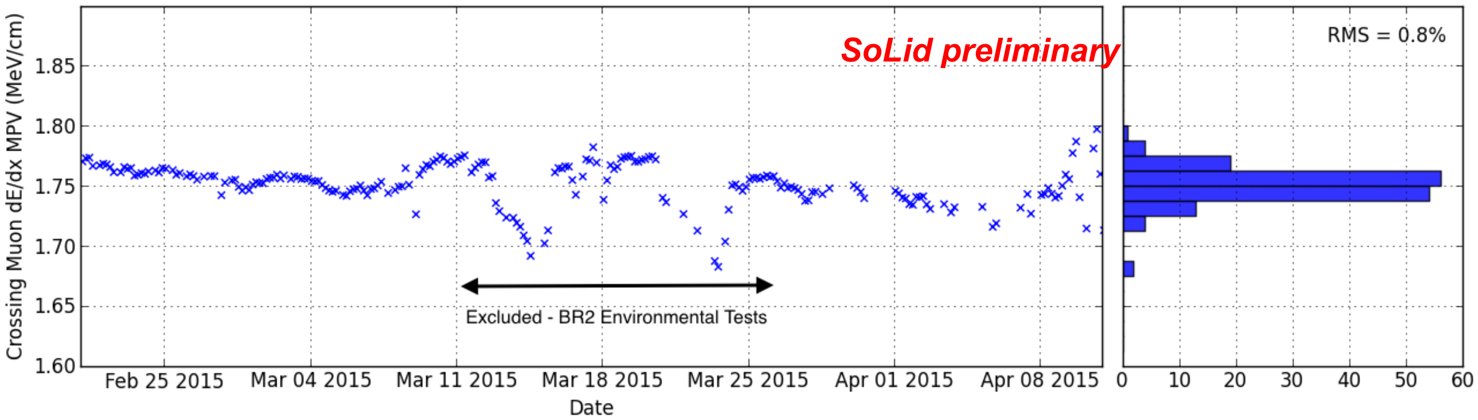


Crossing muon event





- SoLid is excellent Muon tracker
- dE/dx exploited for
  - Energy scale and inter-channel calibration
  - Tagging and veto of muons by outer shell !
- Monitor detector stability over time: ~1%

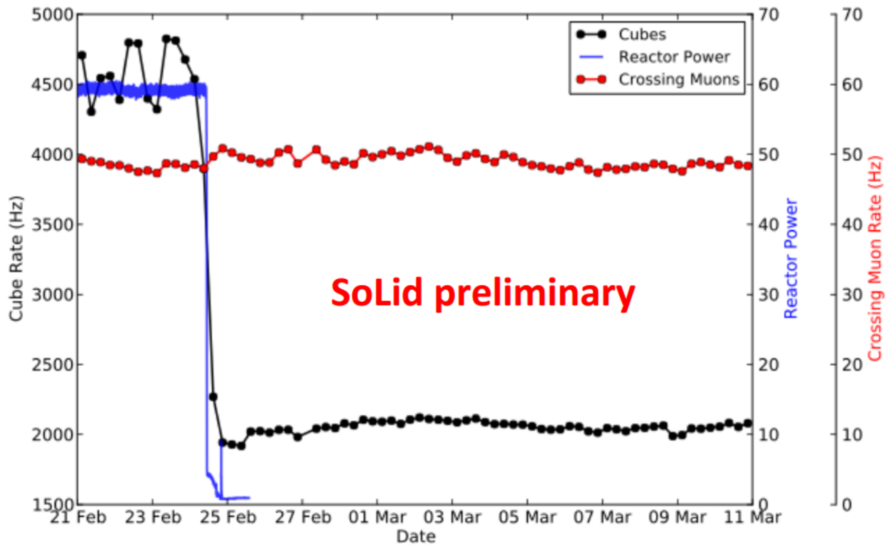


SM1 data taking & operational stability

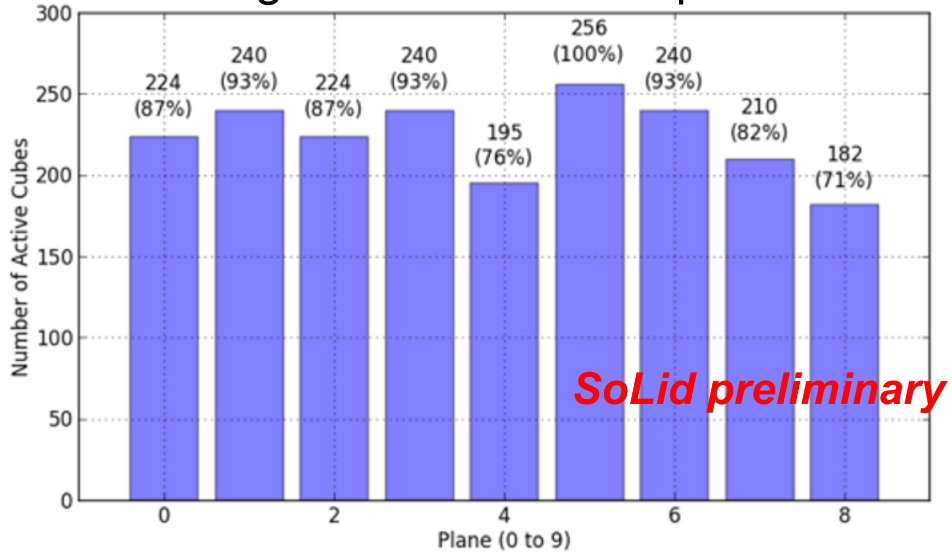
	Period	Exposure Time
Reactor On	00:00 21 Feb → 08:00 24 Feb	50.9 hours
Reactor Off	00:00 01 Mar → 00:00 13 Mar and 00:00 01 Apr → 12:00 11 Apr	428.8 hours

+ Dedicated calibration campaigns with sources: 60Co, AmBe, 252Cf

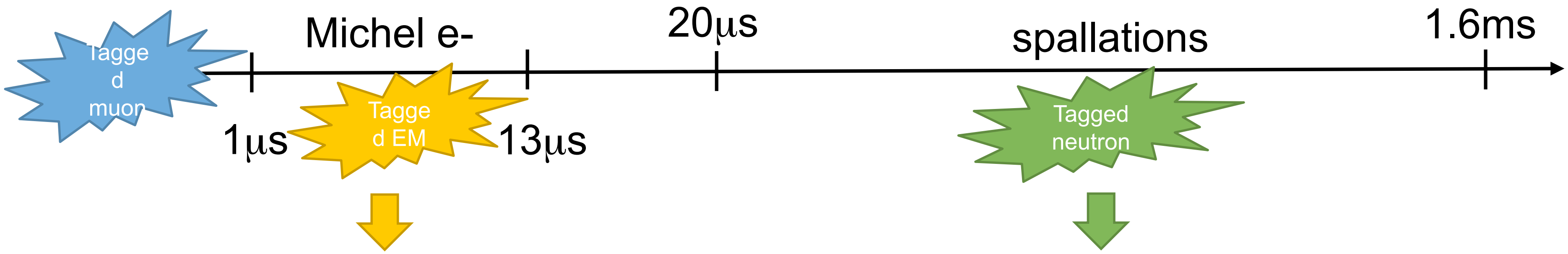
Stable rates of EM signals



87% good/stable cube operation

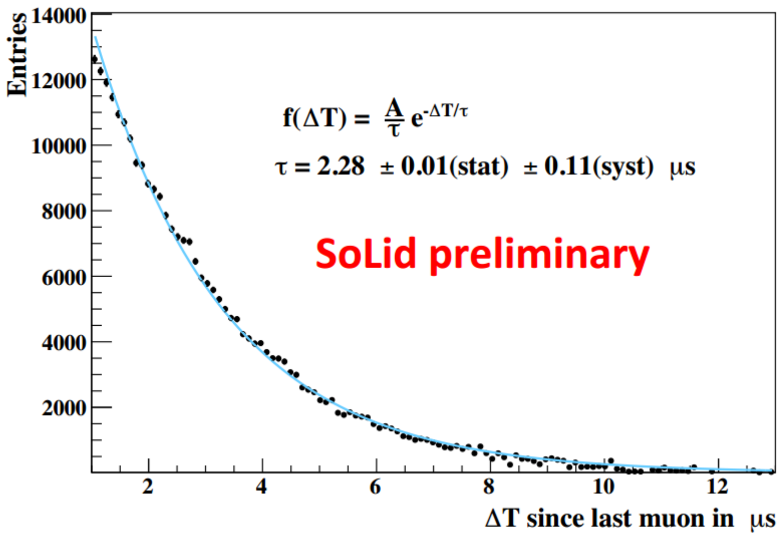


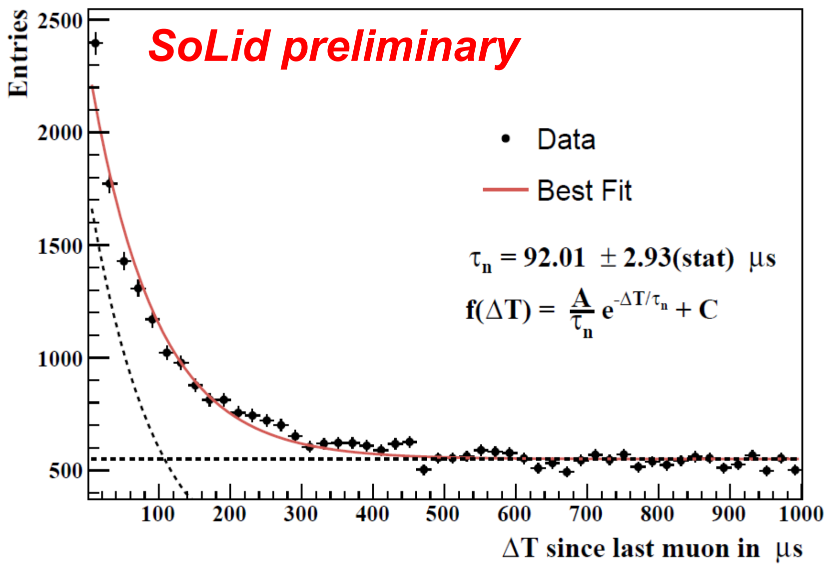
Time correlated signals: Muon Tagged



$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

$$\mu + N \rightarrow \mu + N^* + n$$





- Validation of Muon tagging
- Timing crosscheck
- Neutron contamination of EM signals: < 0.01% of Michel electrons tagged as neutrons

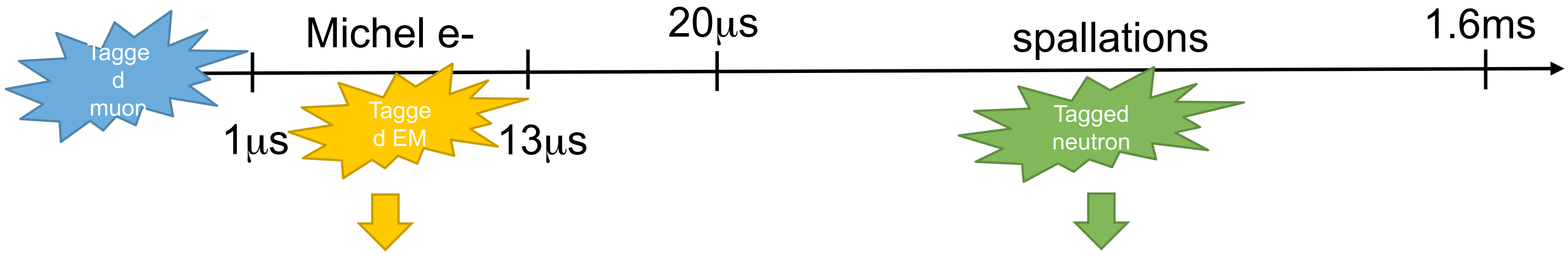
Capture time compatible with results from AmBe data and simulation

→ Muon induced spallation neutrons

→ Investigate directionality

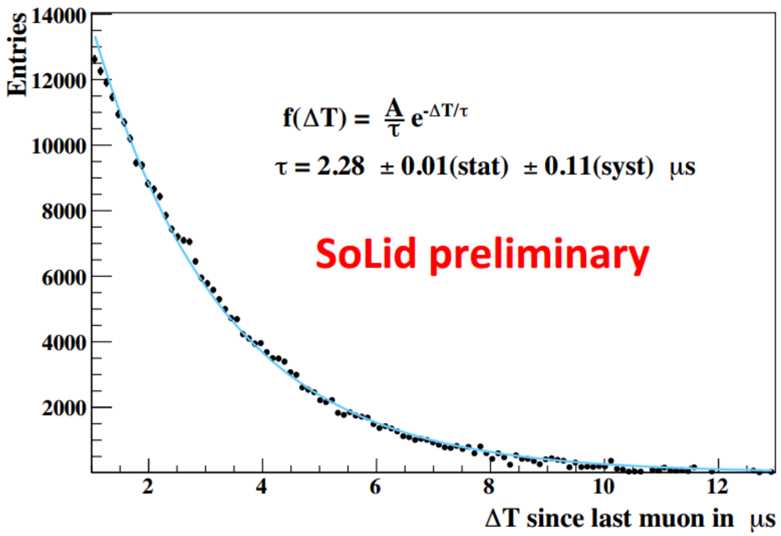
→ Neutron-like Control sample

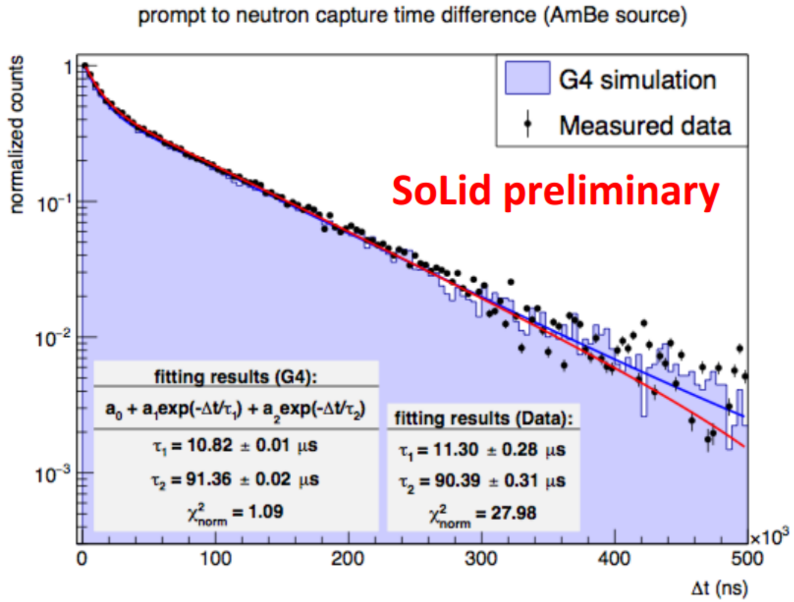
Time correlated signals: Muon Tagged



$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

$$\mu + N \rightarrow \ \mu + \ N^* + n$$





- Validation of Muon tagging
- Timing crosscheck
- Neutron contamination of EM signals: < 0.01% of Michel electrons tagged as neutrons

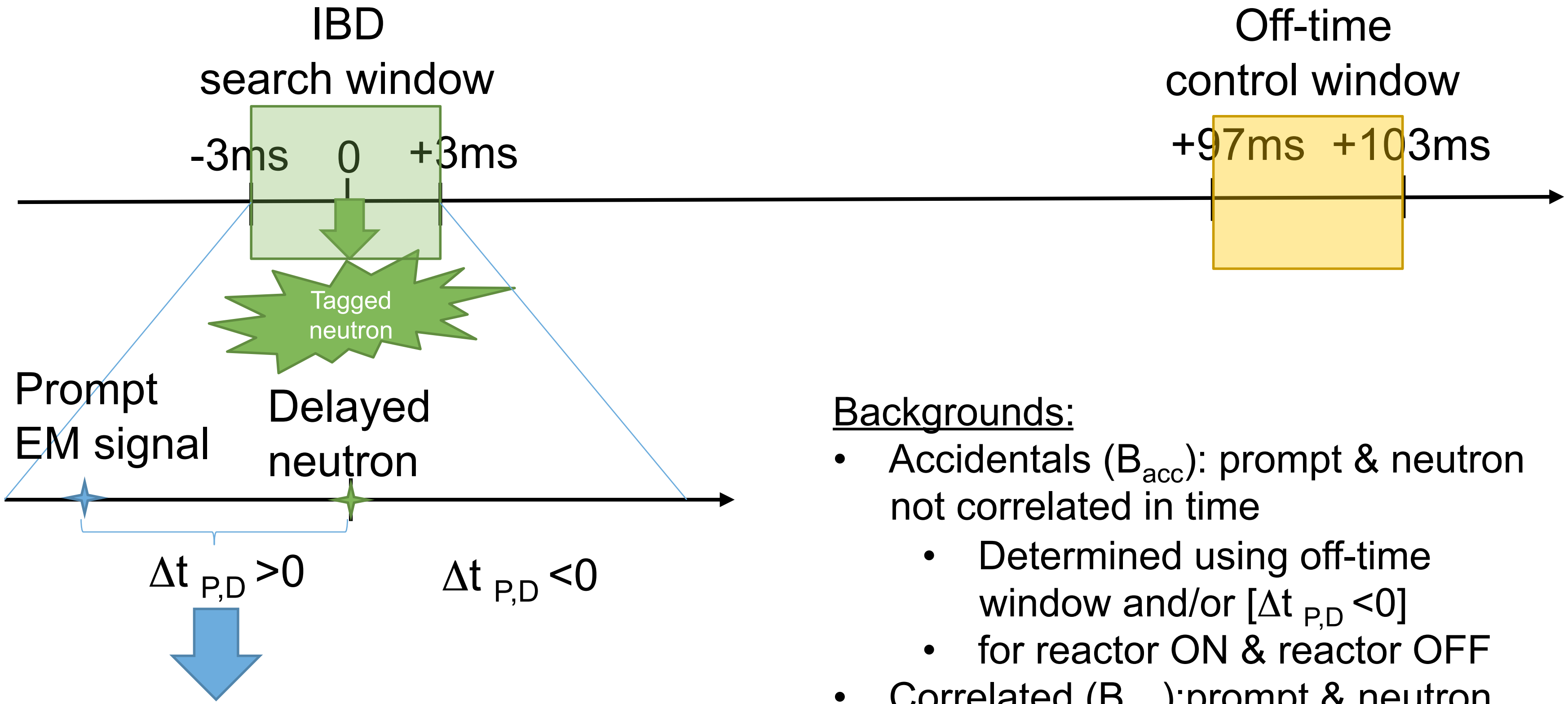
Capture time compatible with results from AmBe data and simulation

→ Muon induced spallation neutrons

→ Investigate directionality

→ Neutron-like Control sample

Time correlated signals: IBD-like



IBD signal region:

$0.1\ \mu s < \Delta t_{P,D} < 250\ \mu s$

Purified by:

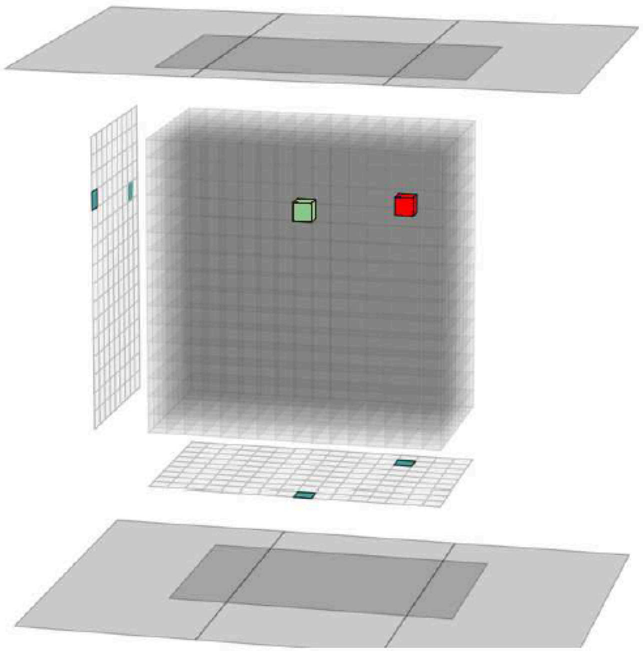
- Muon veto (fast n from μ)
- Energy thresholds (Gamma bg)
- Hit Multiplicity (fast n)
- Topological cuts (accidentals)

Backgrounds:

- Accidentals (B_{acc}): prompt & neutron not correlated in time
  - Determined using off-time window and/or [$\Delta t_{P,D} < 0$]
  - for reactor ON & reactor OFF
- Correlated (B_{cor}):prompt & neutron correlated in time
  - Determined using reactor OFF data in [$\Delta t_{P,D} > 0$] window

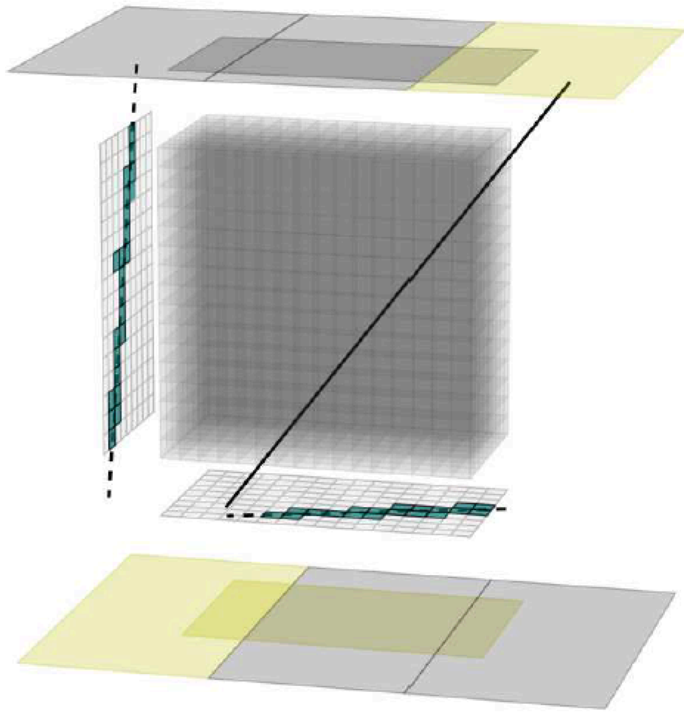
SM1– High Segmentation

ZnS + PVT



SoLid reactor off experimental data

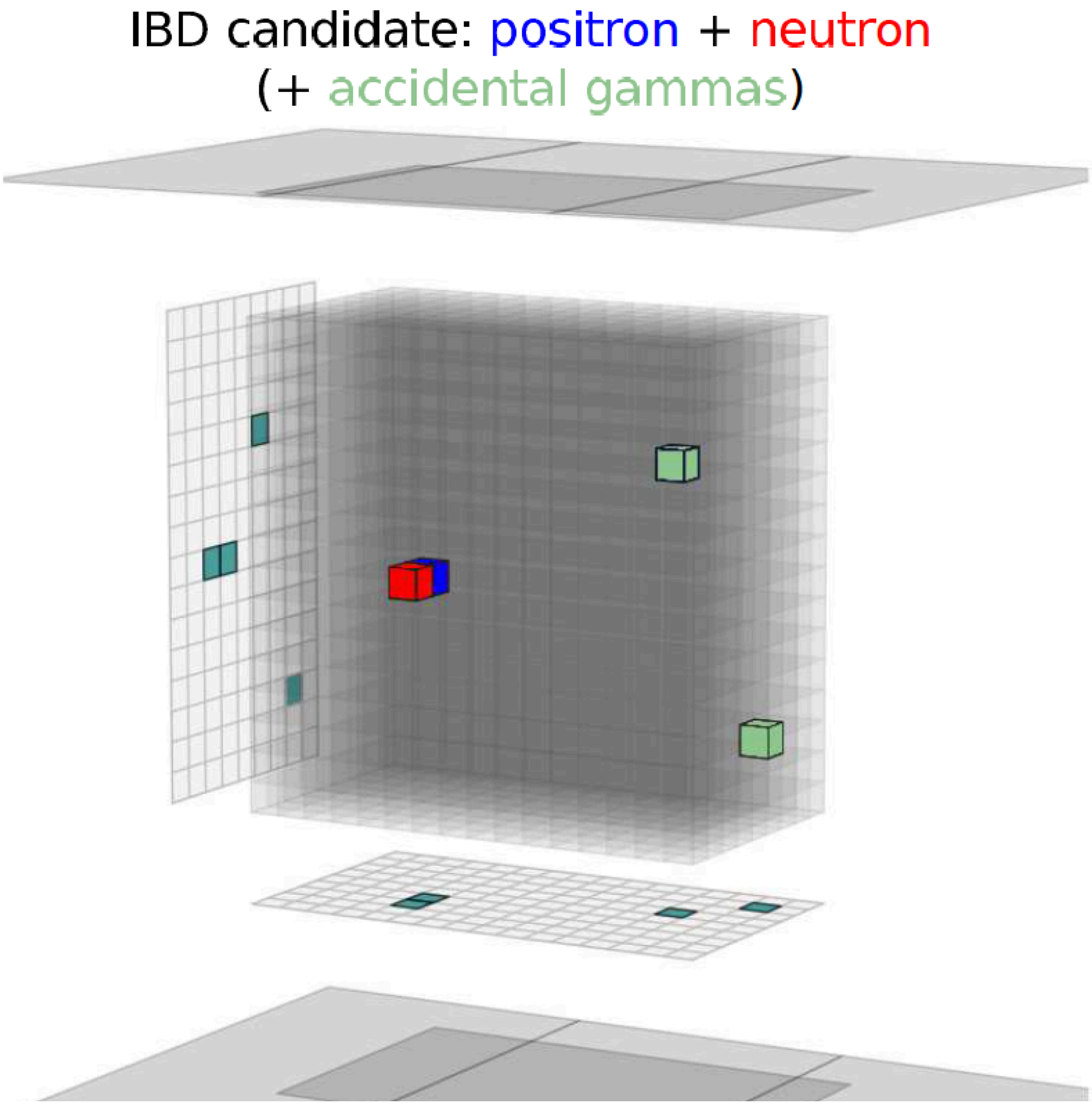
Cosmic muon track



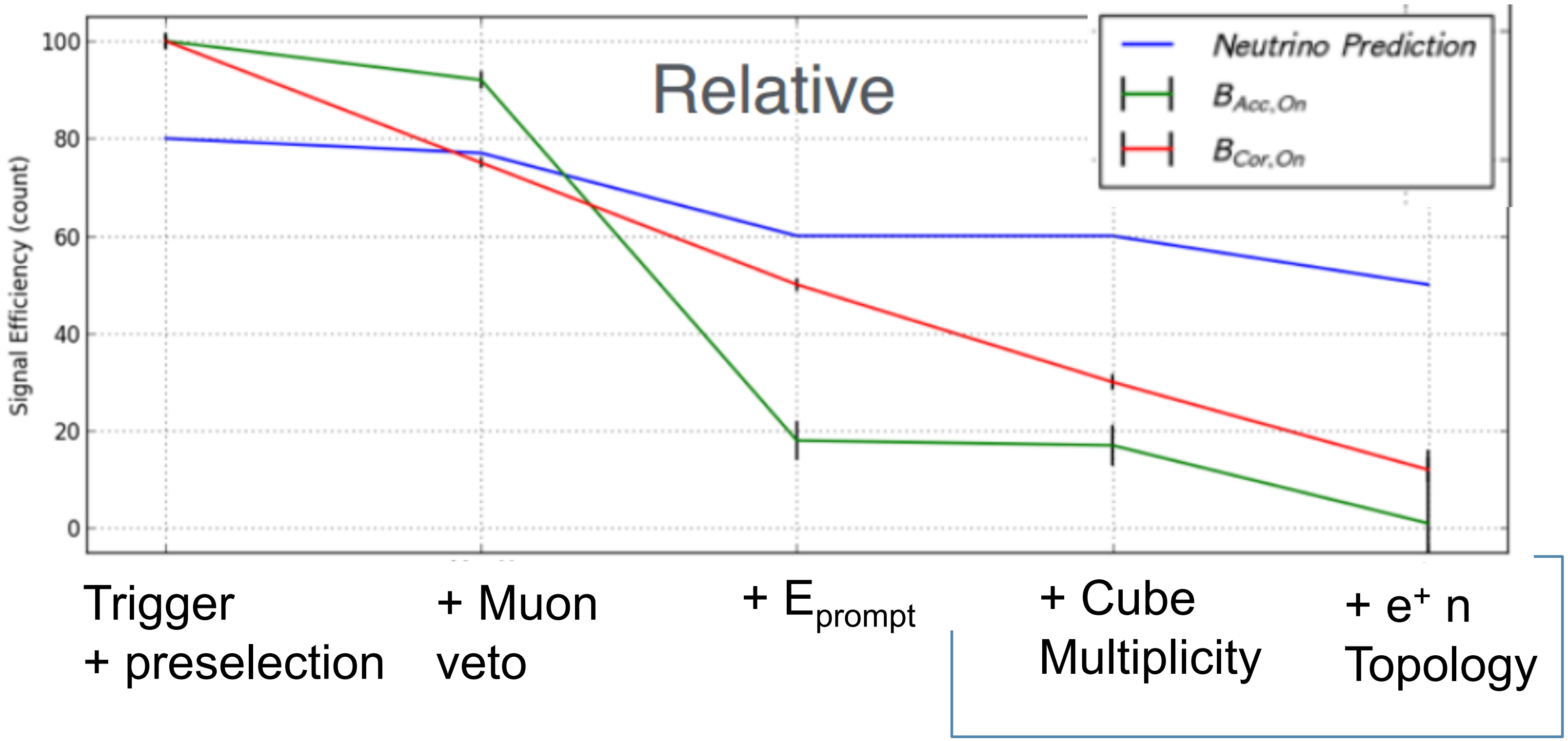
➔ **isolating events**

➔ **Muon tracker**

SM1 – IBD candidates



IBD Analysis performance

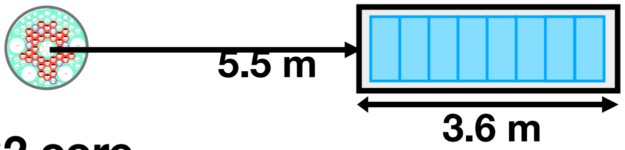


- Data-driven background determination
- Accidental background can be significantly reduced
- Time-correlated background reduced by 90% due to our unique segmentation feature
- High IBD efficiency achievable in future analyses

SoLi∂ : Experiment phases

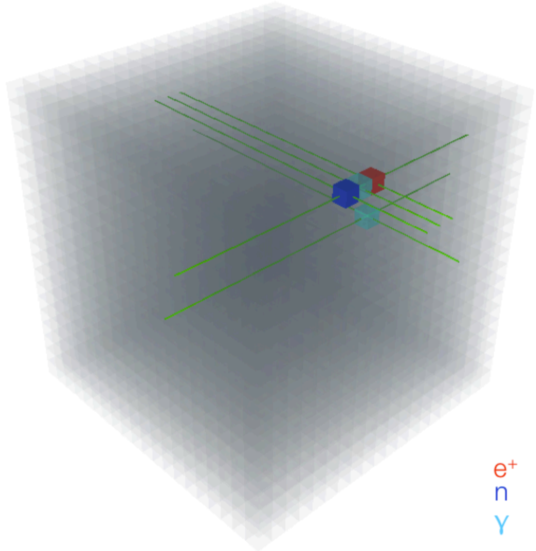
Phase I 2016-17

SoLid detectors

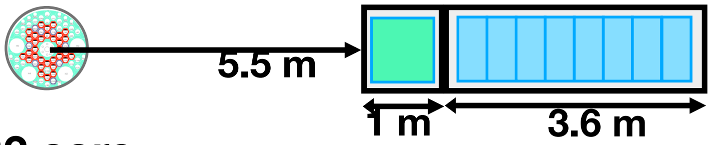


BR2 core

8x MARS modules
PVT cubes + WLS fibres
2 tonnes fiducial

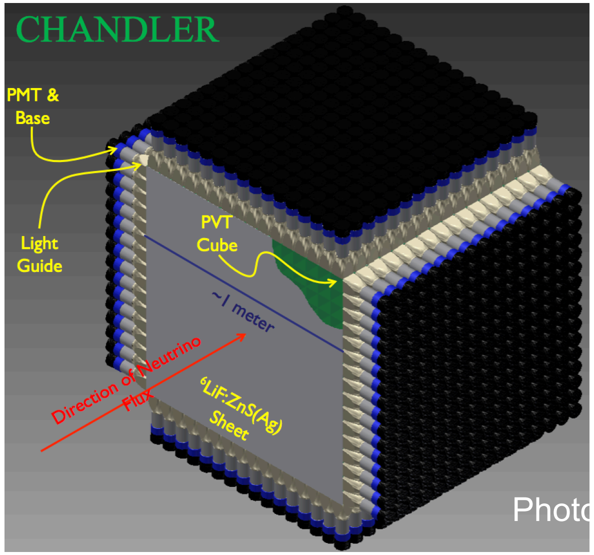


Phase II ~ 2018

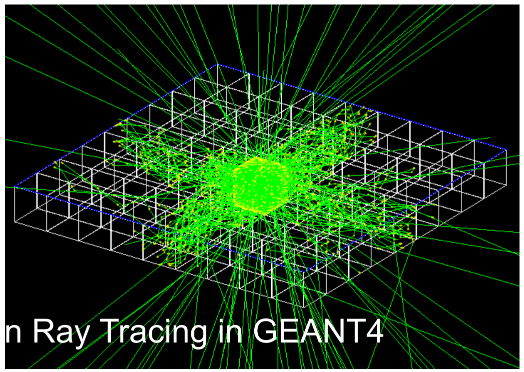


BR2 core

HiRes module
WLS PVT cubes + PMTs
1 tonne fiducial



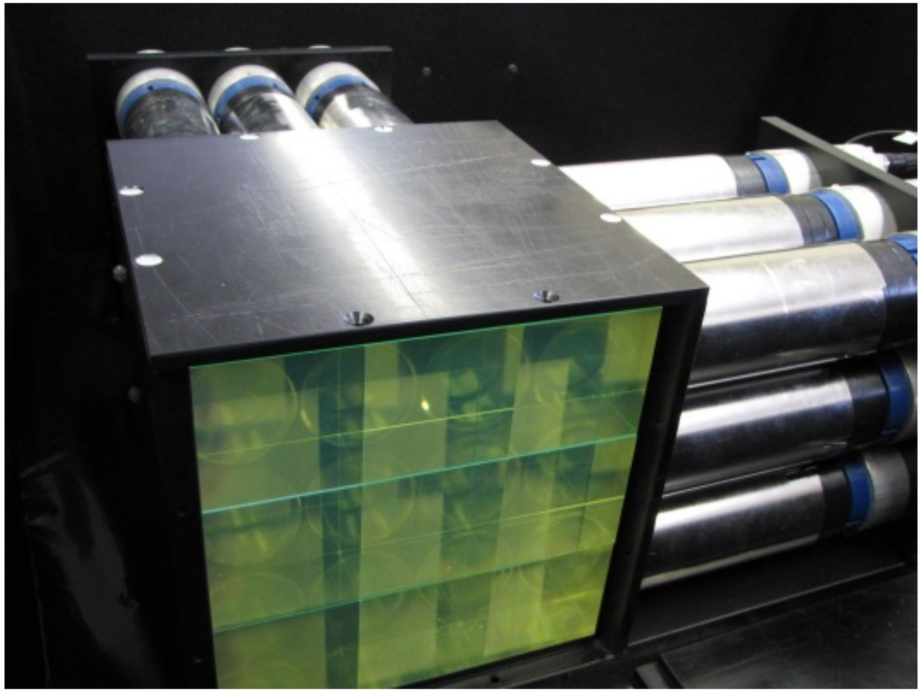
Light is transported by total-internal-reflection

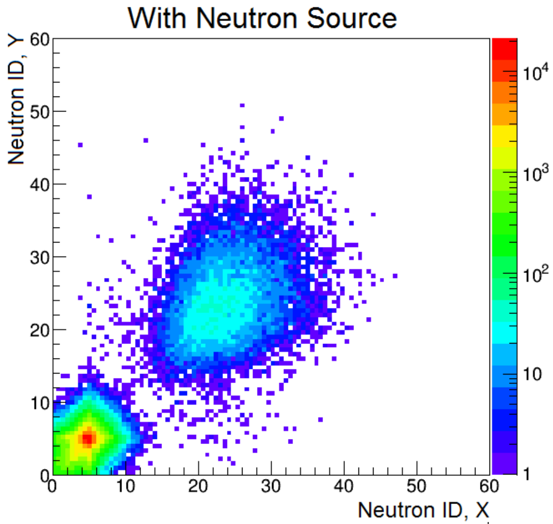


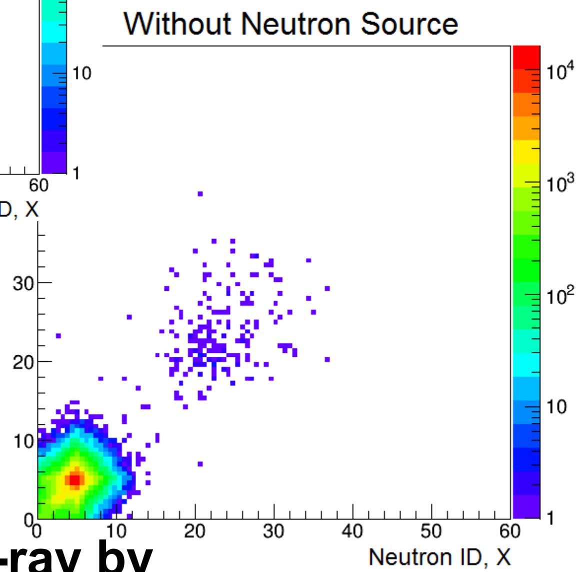
SoLi∂ : Neutron Capture in MicroCHANDLER

The 18-channel MicroCHANDLER prototype is idea for testing neutron tagging.

For each hit cell, we compute the neutron ID variable as the ratio of the integral of the pulse to the pulse peak value.



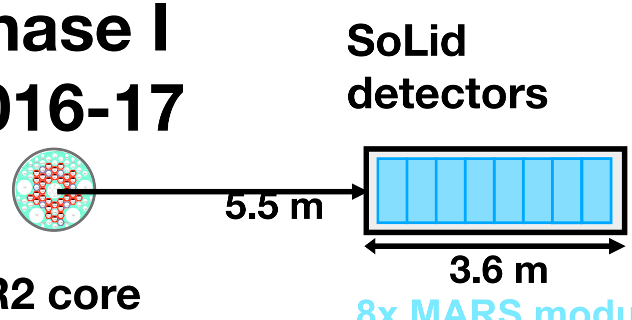




- **Very good discrimination Neutron / gamma-ray by pulse shape**

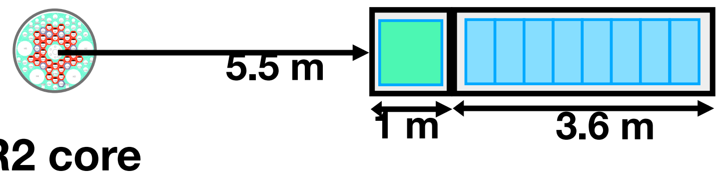
SoLi∂ : Sensibility

Phase I 2016-17

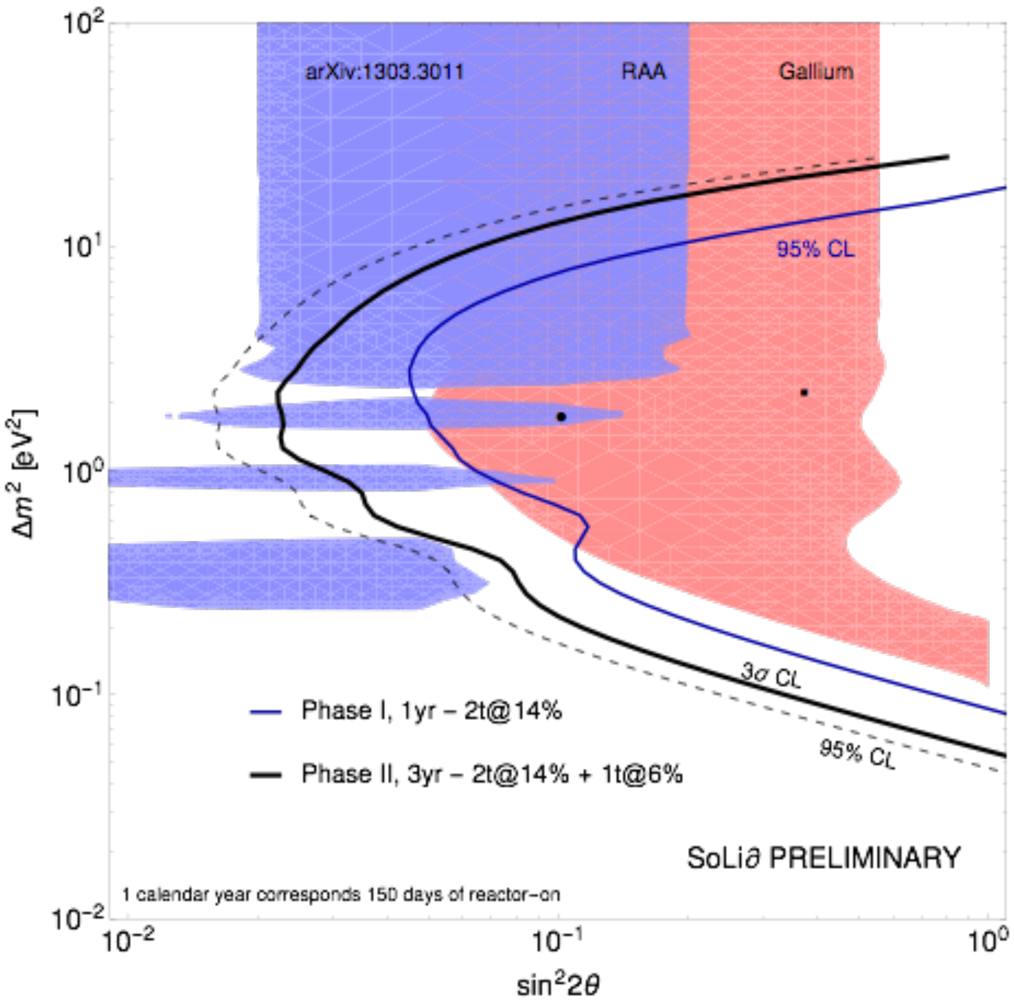


8x MARS modules
PVT cubes + WLS fibres
2 tonnes fiducial

Phase II ~ 2018

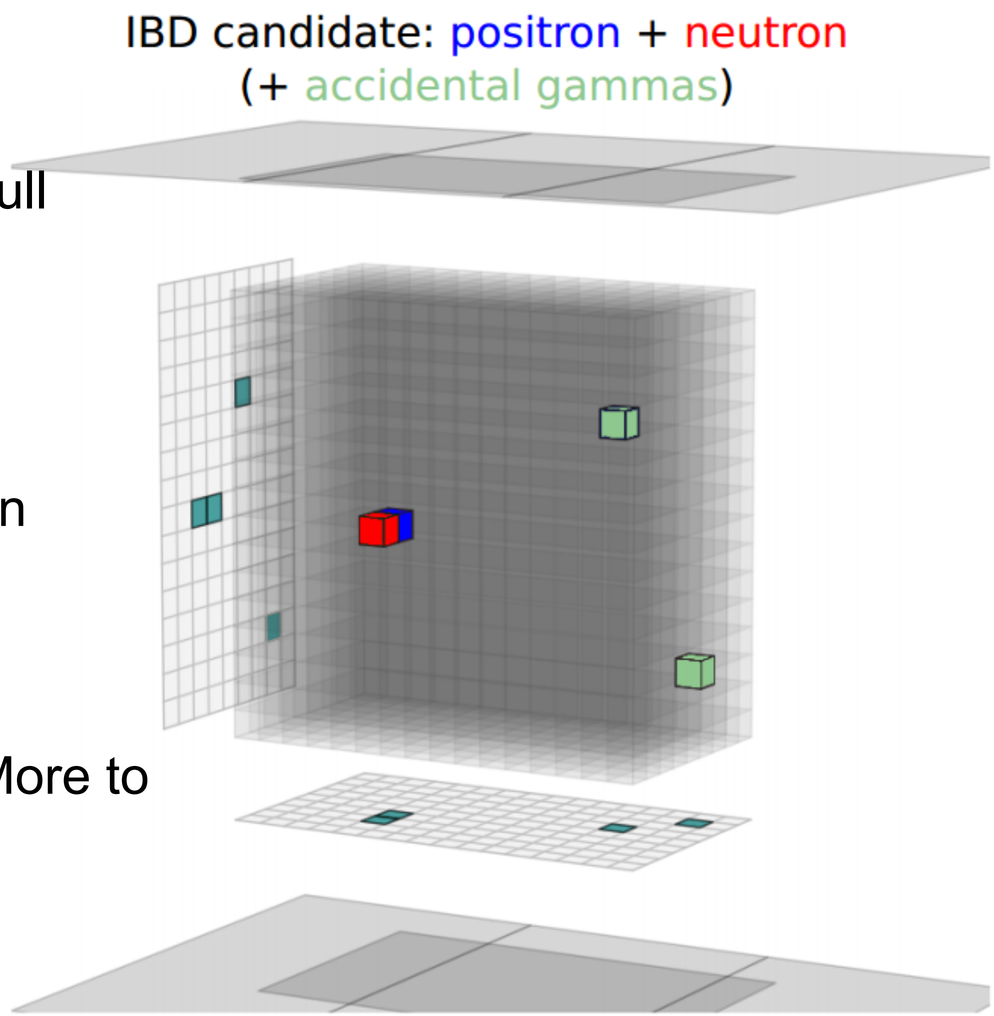


HiRes module
WLS PVT cubes + PMTs
1 tonne fiducial



➔2 phases to cover a large phase space
➔ best fit covered within the first year data taking

Conclusion

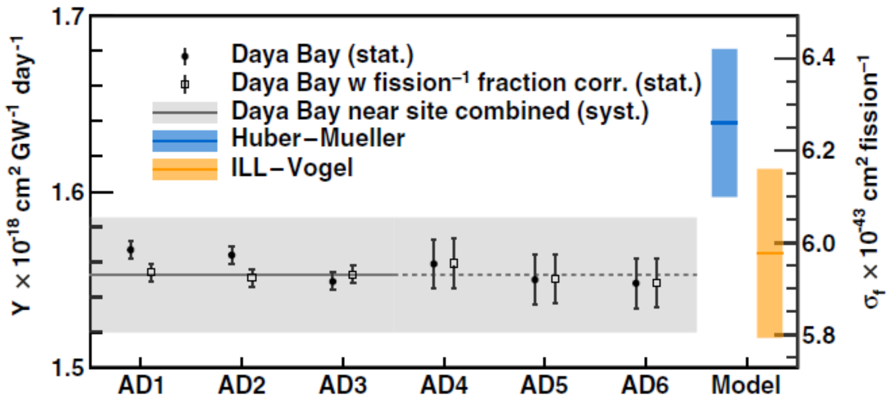


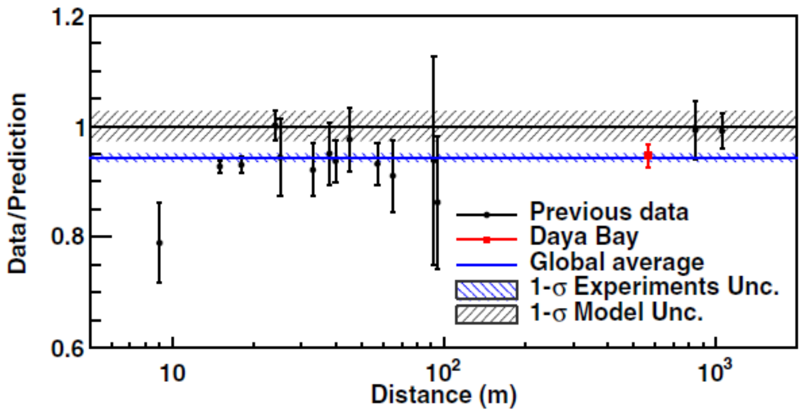
- Commissioned, operated and calibrated full scale detector module
- In realistic reactor conditions
- Very good stability over time
- Developed many analysis tools, including detailed detector + environment simulation
- Optimizing object reconstruction and identification
- Study of various backgrounds
- First hints of IBD candidates appearing: More to come
- Currently staging a scale-up to a 1.5 T experiment
- Data taking starting 2nd half 2016


Thank You!

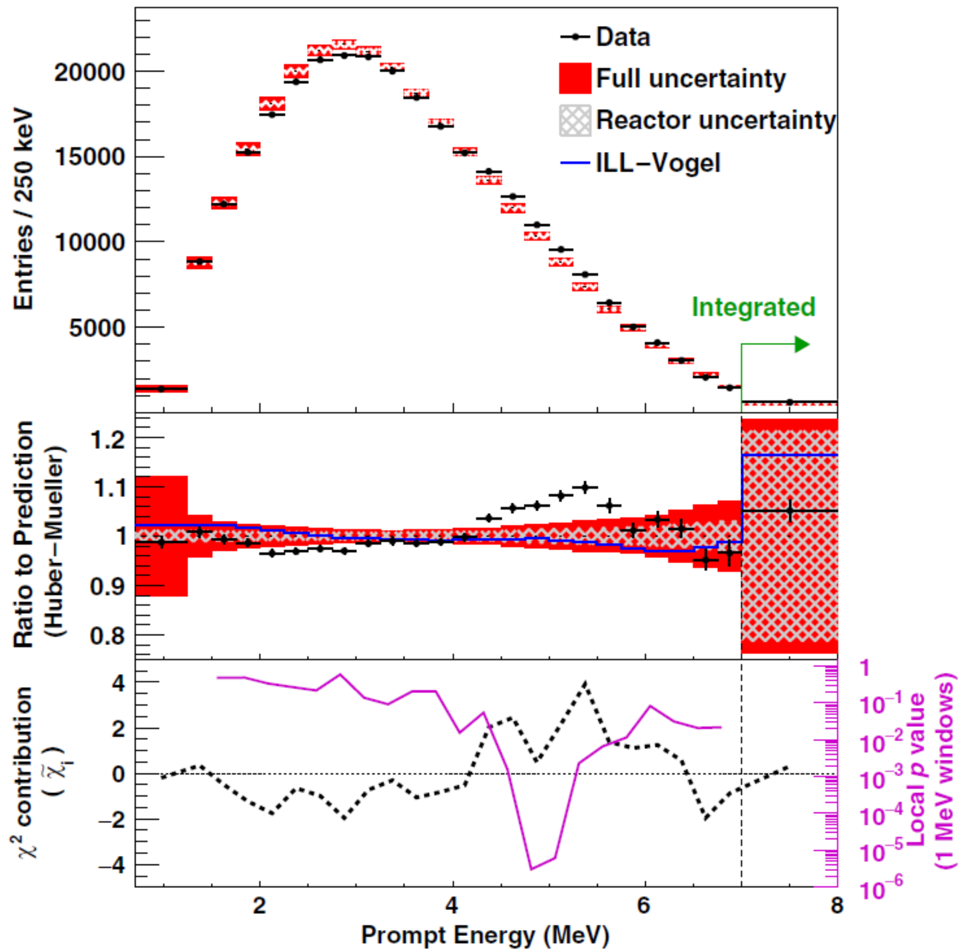
Backup

- Daya-Bay flux and spectrum measurements



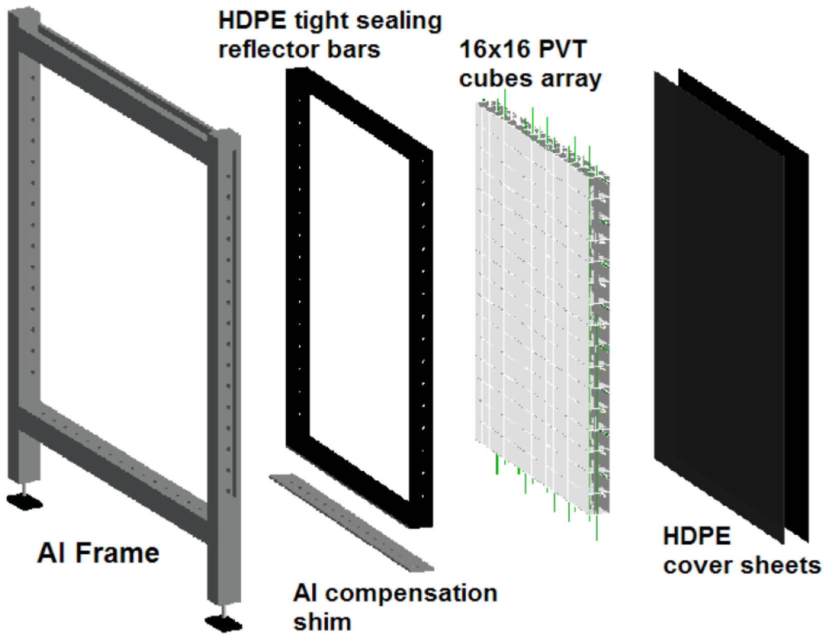


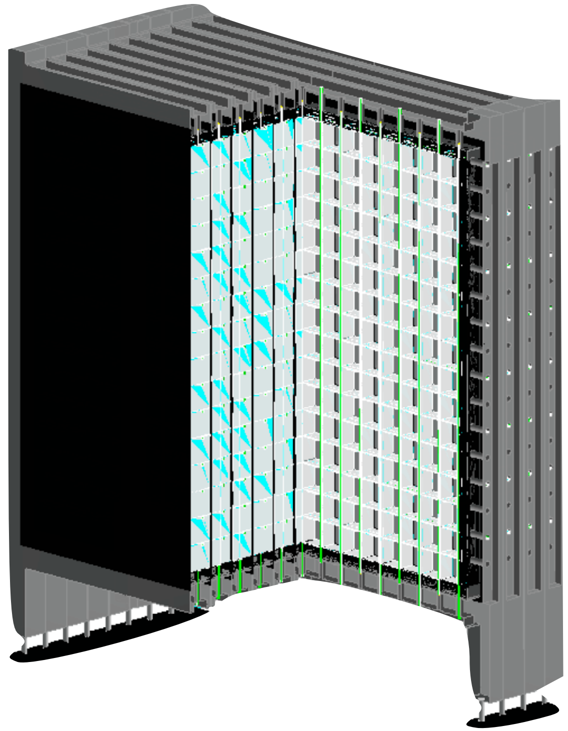
$$R_g = 0.943 \pm 0.008(\mathrm{expt}) \pm 0.025(\mathrm{model}).$$



- Very interesting to confirm the existence of the 5MeV bump for pure ^{235}U and at L=5meter !

SoLid Module 1 (SM1)

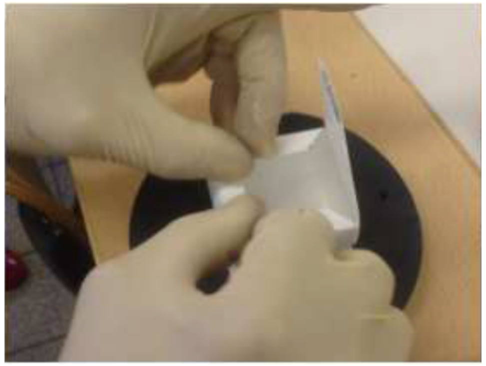


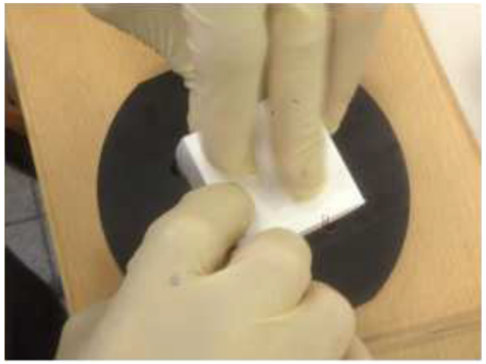


- 16 × 16 PVT cubes grouped together to form a single *detector* plane
  - Mechanical support with aluminum frame
  - HPDE to reduce neutron dissipation

9 planes totally, 288 kg
288 readout channels
80 × 80 × 45 cm

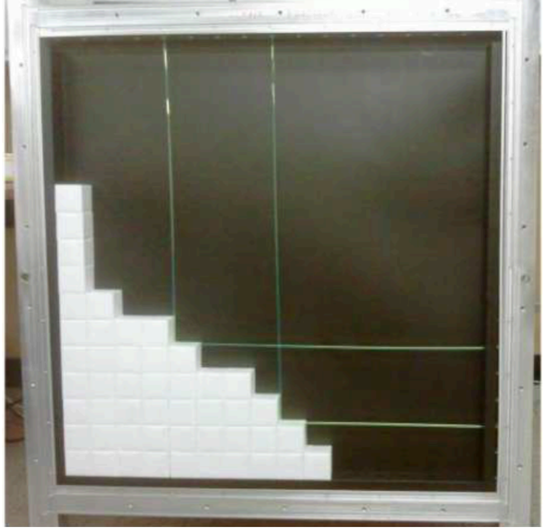
SM1 construction





- 300 cubes machined and assembled
  - Wrapped with tyvek and carefully weighted
  - Number of protons determined with better than 1 % accuracy

Single detector plane under construction



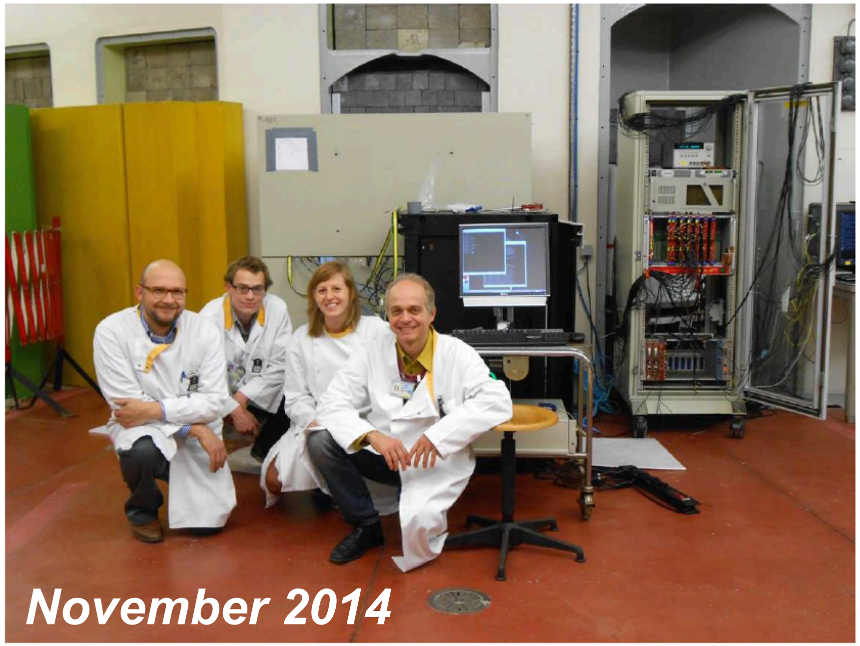
Assembled planes

Deployment at BR2

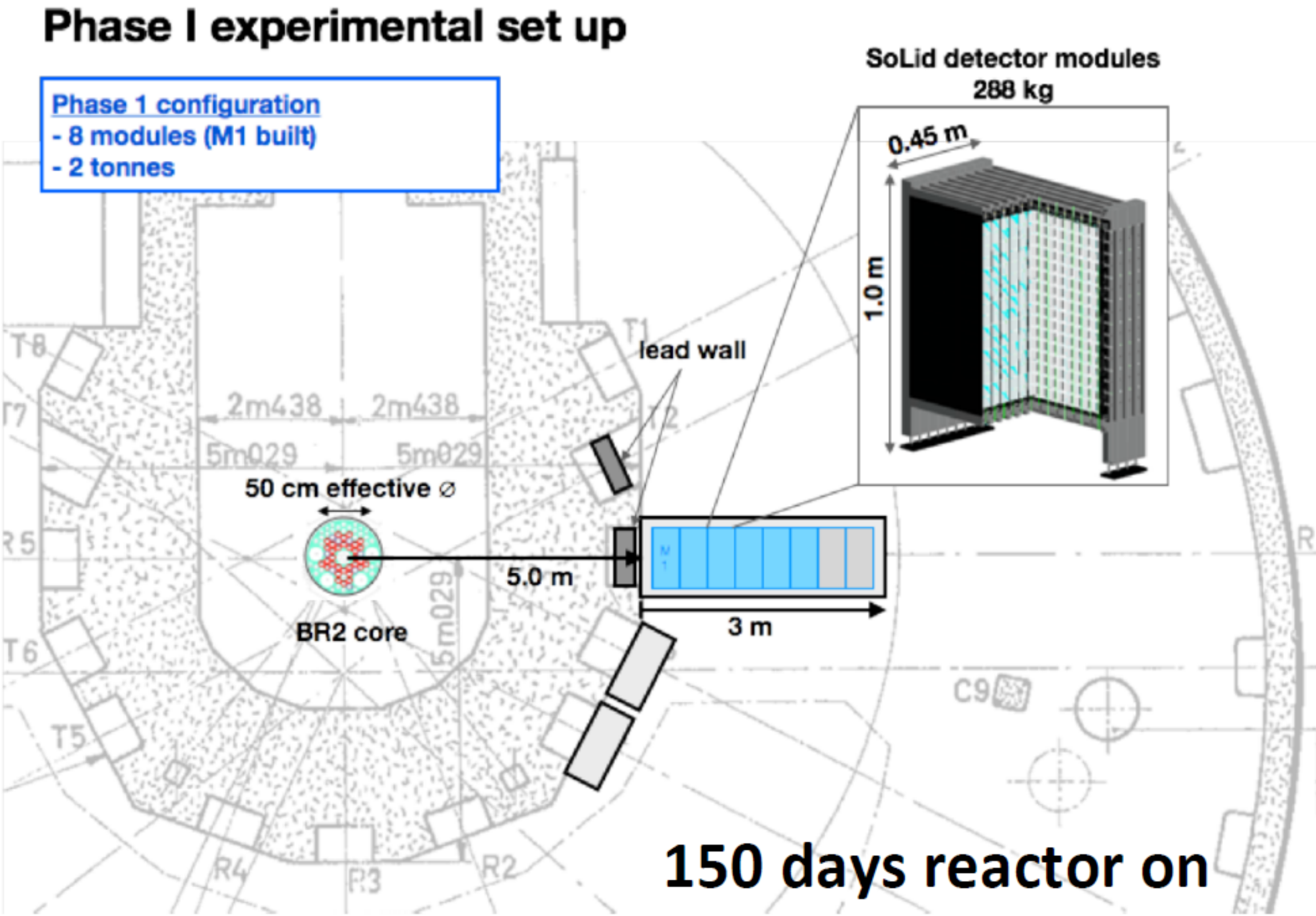

SM1 at Gent


Eppur si muove


Installation at BR2


November 2014

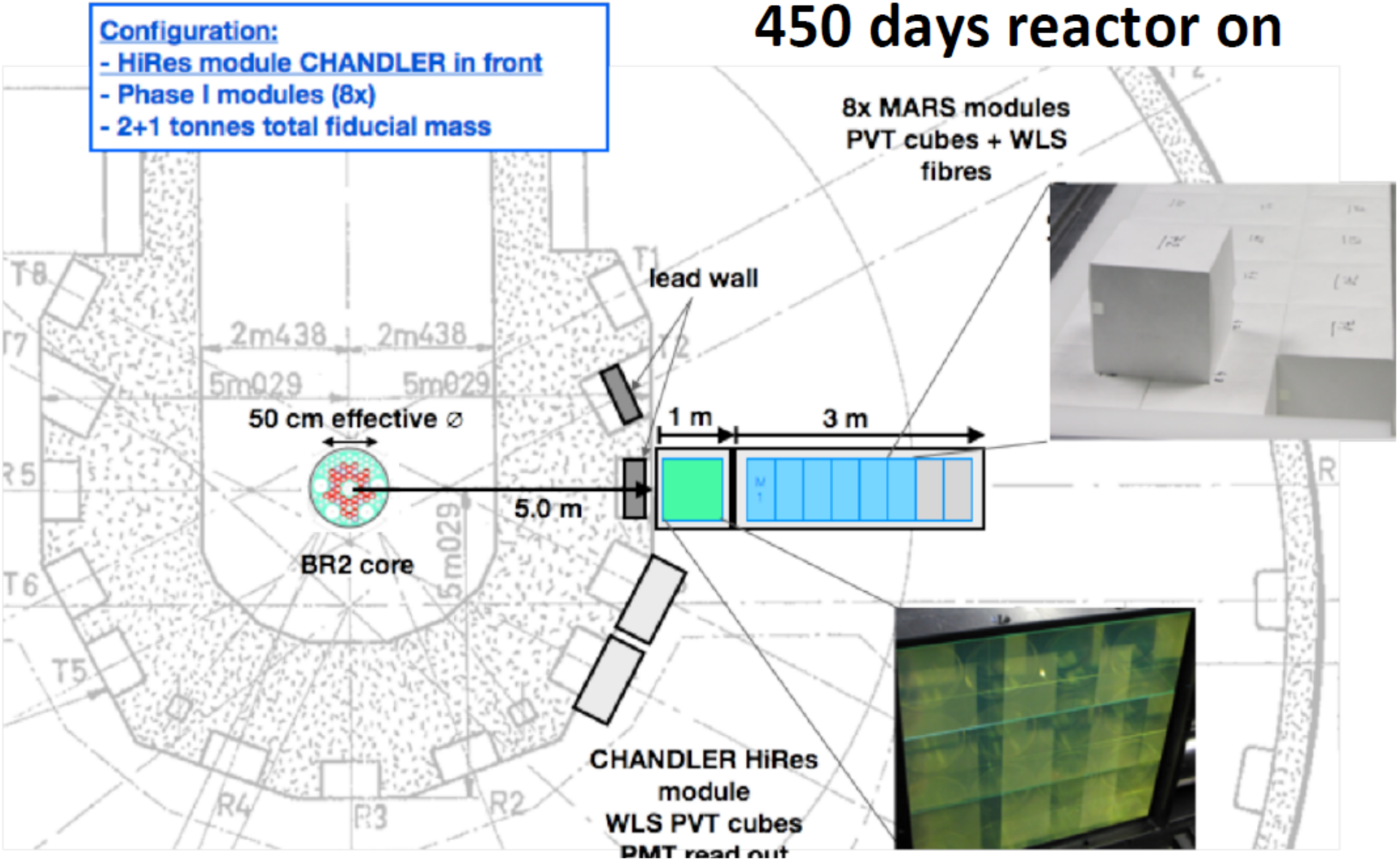
Phase 1 configuration



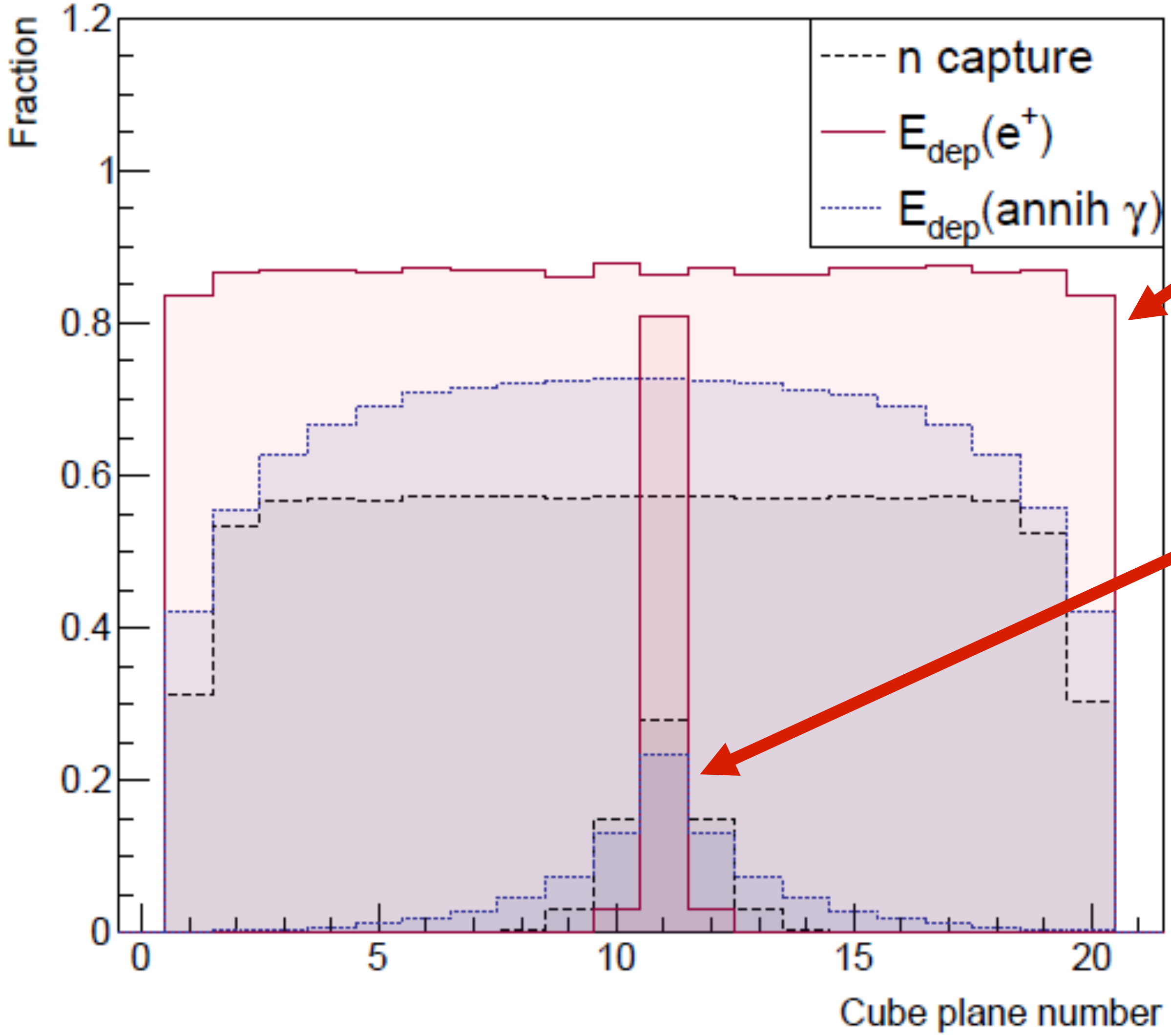
Phase 2 configuration

Phase II experimental set up

450 days reactor on



Neutron and EM energy containment



Averages over whole detector

Total efficiency

Generated in detector center

Containment of IBD event

Short term plans

- Implemented small design changes to:
  - Increase light yield: improve energy resolution and operate at lower tresholds
  - Improved front-end electronics and DAQ: lower noise levels and cope with increased trigger rate
  - Double amount of ^{6}Li based neutron screens
  - Dedicated neutron trigger
  - Supplementary passive shielding for cosmogenic bg
  - Possibility to add active muon veto
- Construction started in phased approach
- Start next data taking run second half of 2016
- Ready to undertake sensitive search for reactor antineutrino disappearance
- Provide precise measurement of ^{235}U $\bar{\nu}_e$ spectrum

Long term plans

- Complement SoLid with 1m3 HiRES (6% σ_E/E) CHANDLER near-detector module
- 8x8x5 voxel module currently under construction
- See eg. J. Link at Aspen 2016

https://indico.cern.ch/event/473000/session/2/contribution/10/attachments/1213996/1771830/Aspen_2016.pdf