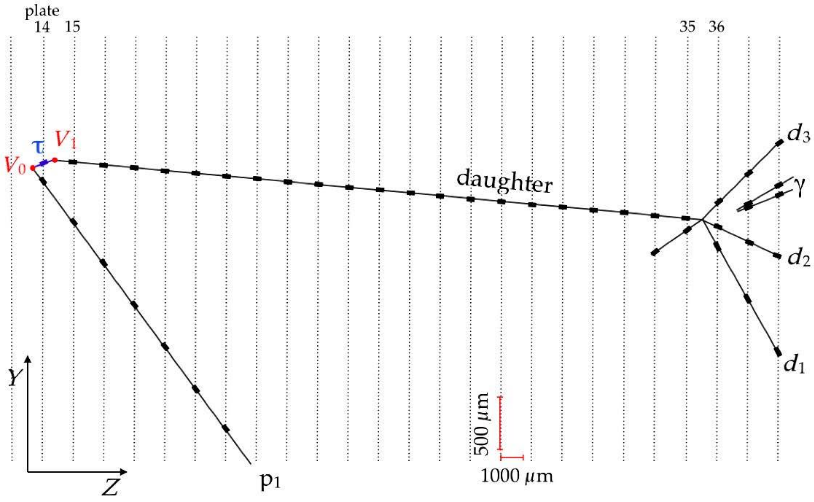
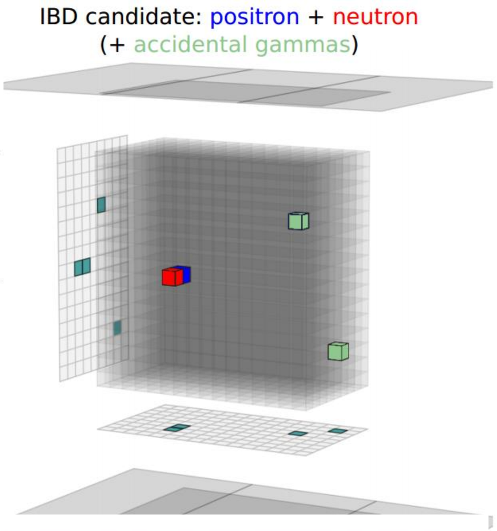
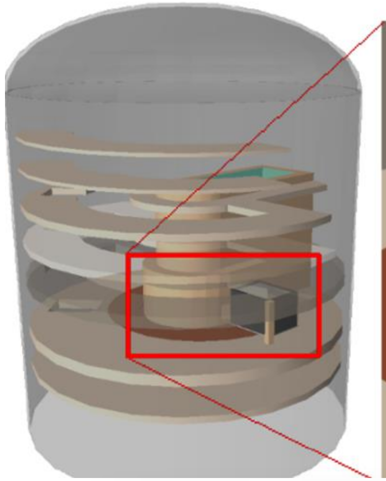
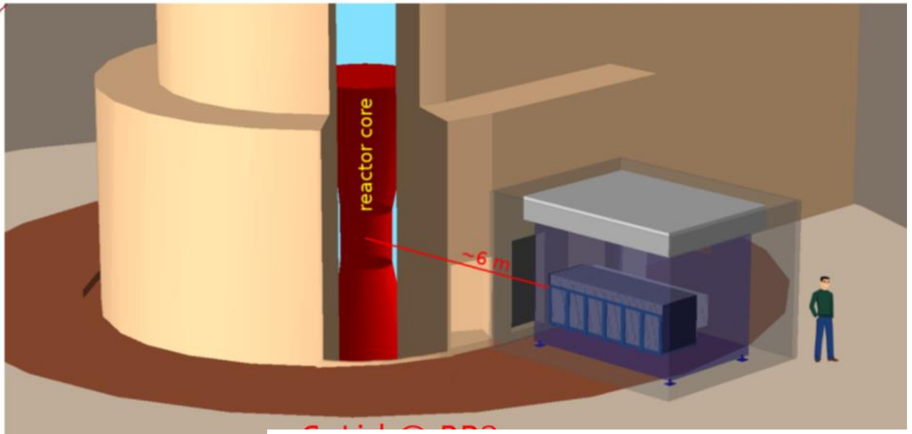
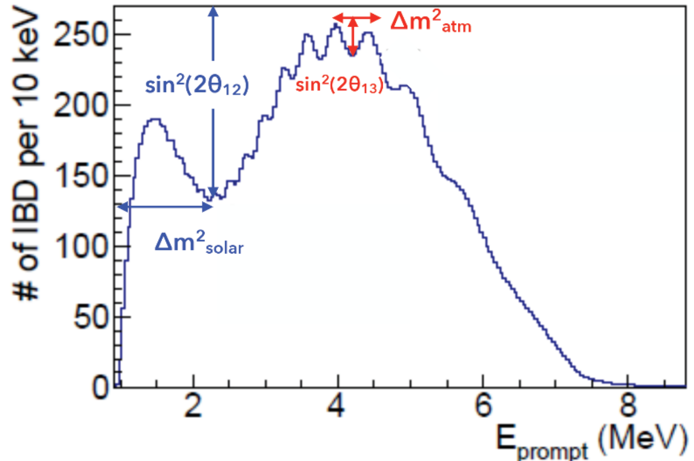
Neutrino Physics in Belgium











Nick van Remortel
University of Antwerp, Belgium

RECFA meeting
Brussels 21/4/2017

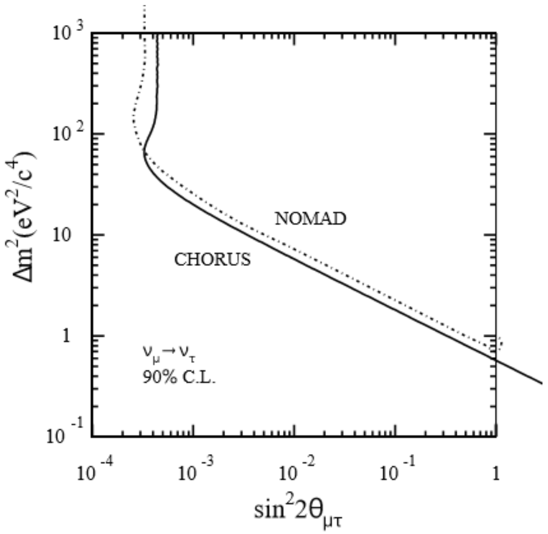
Fundamental Interactions .be
foundation of public utility
HERCULES STICHTING
Belgian Science Policy Office
belspo
fwo Research Foundation Flanders
Opening new horizons
fnrs
LA LIBERTÉ DE CHERCHER

Experimental facts and consequences

- Since 1998: unambiguous proof of neutrino oscillations → ν mass
  - Dirac (Majorana) $\nu's$: 3masses(m_1, m_2, m_3), 3 angles ($\theta_{12}, \theta_{13}, \theta_{23}$), 1 (3) CP-phase
  - <u>Oscillation experiments</u>:
    - Not sensitive to Dirac vs Majorana
    - Measure very small $\Delta m_{ij}^2 = m_i^2 - m_j^2$
      - Only 2 independent values: $\Delta m_{sol}^2 = \Delta m_{21}^2 = 7.37 \times 10^{-5} eV^2$
        $\Delta m_{atm}^2 = \left|\Delta m_{32}^2\right| = 2.50 \times 10^{-3} eV^2$
    - Measure very large $sin^2(\theta_{ij})$
    - CP-violating part: depending on signs of mixing, and on θ_{13}
    - Short baseline reactor & long baseline accelerator → measure Dirac CP phase
    - Long baseline accelerator & matter effect, and long baseline reactor neutrino → measure sign of Δm_{32}^2 (JUNO)
  - <u>Other measurements</u>:
    - Asolute mass scale and confront with cosmology
    - Dirac or Majorana
    - See-Saw?
    - More than 3 ? (SoLid)

Totally different from quark mixings

Legacy experiments



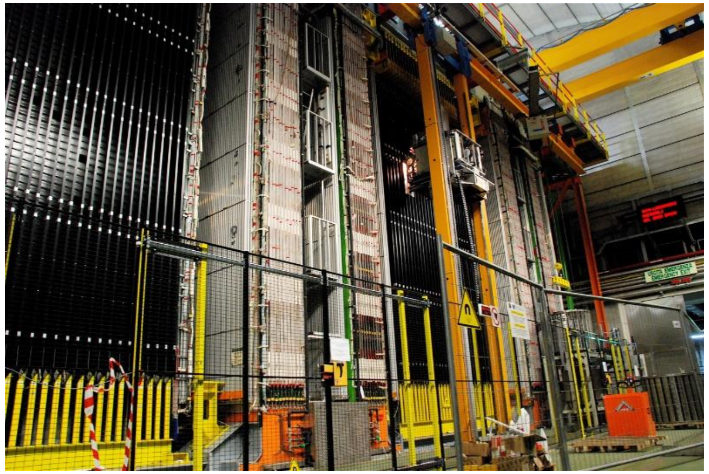
- Involvement of ULB, VUB, UCL in neutrino beam experiments, searching for $\nu_\mu \to \nu_\tau$ in appearance mode

CHORUS: L/Eν≃0.6km/27GeV

datataking stopped in 1997: latest papers in 2011

(IIHE-ULB) P. Vilain, G. Wilquet,

(UCL) D. Favart, T. Delbar, G. Grégoire



OPERA: L/Eν≃ 730km/17GeV

(IIHE-ULB) P. Vilain, G. Wilquet,

data taking 2008-2012:

Latest update on $\nu_\mu \to \nu_\tau$ in 2015

Interpretation of data in terms of steriles (2015)

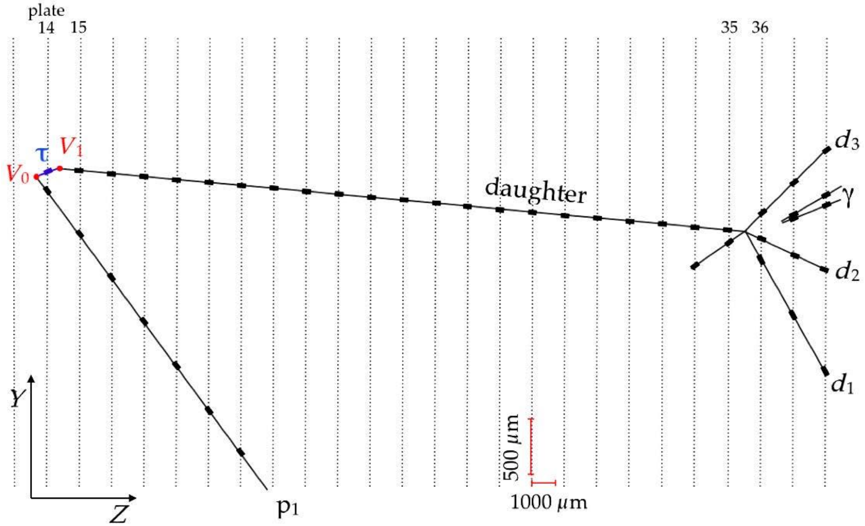
More coming ..

OPERA

- Belgian responsibilities: G. Wilquet, P. Vilain
  - Scintillator strip Target Tracker
  - Design&Simulations
  - Chair Collab. board
  - Chair Editorial board
- Scientific output since 2010:
  - 15 Peer Reviewed papers (2 in 2015, 1 in 2016)
  - 4 more in writing

Phys. Rev. Lett. 115, 121802 (2015)

$\Delta m_{23}^2 = 3.3 \times 10^{-3}\, eV^2$



5th CC interaction candidate in OPERA

5 ν_τ Candidates out of 5408 scanned interactions

Confirmation of atmospheric ν oscillations due to $\nu_\mu \leftrightarrow \nu_\tau$

BELGIUM

Universiteit Antwerpen
Universiteit Gent
Vrije Universiteit Brussel
SCK•CEN

FRANCE

LPC Caen
LAL Laboratoire de l'Accélérateur Linéaire
Subatech
LPC

UK

University of Bristol
Imperial College London
University of Oxford

USA

Virginia Tech
Invent the Future

SoLi∂ at BR2

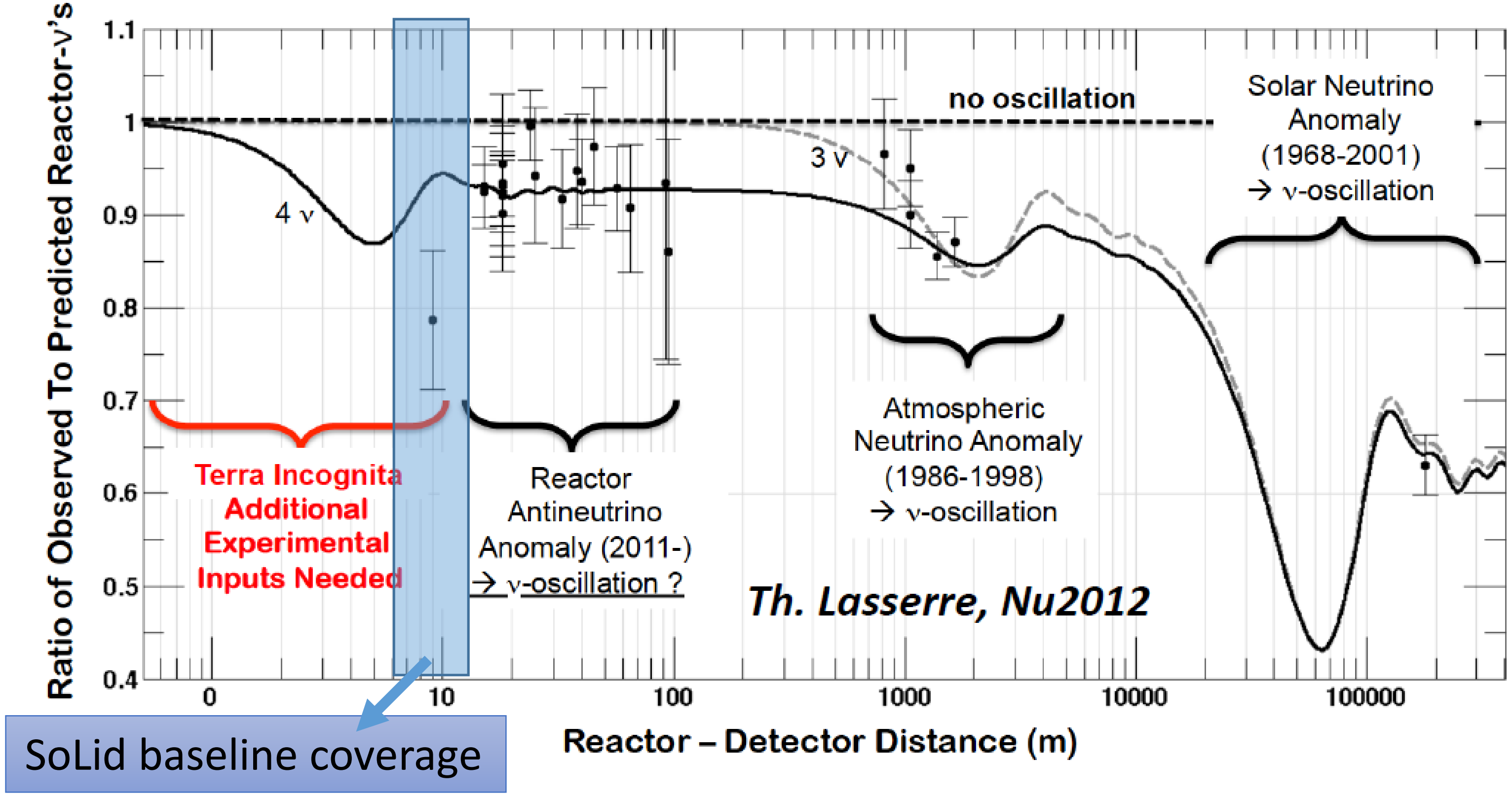
Belgium @ SoLid

- Relatively small experiment: 12 institutes, ~50 collaborators
- Belgian participation since 2013, via:
  - UGent:
    - 5 FTE: D. RyckBosch (IB Chair), M. Labare, C. Moortgat (SCK), I Michiels, Ph. Van Auwegem, P. Sennesael, Ch. Schuerens
    - Construction, Simulation, Analysis
  - VUB:
    - 2 FTE: J. D’Hondt, P. Van Mulders (convener), L. Kalousis (convener), S. Vercaemer
    - Construction, Simulation, Analysis
  - UAntwerpen:
    - 5FTE: N. van Remortel (tech Coordinator), I Pinera (convener), Y. Abreu, W. Beaumont, M. Verstraeten, S. Vercaemer, A. De Roeck (Pub comm. Chair)
    - Electronics, Construction, Simulation, Analysis
  - SCK-CEN:
    - 3 FTE: E. Koonen, B. Coupé, L. Ghys (convener) , S. Kalcheva, J. Mermans, G. Van Den Branden, S. Van Dyck
    - Reactor flux, spectrum, Construction, Analysis

- Total construction (material) cost: 1.2 MEur
- SoLid construction constrained by Spending profile
- Belgian Funding:
  - Vlaamse Hercules Stichting: 450 KEur
  - FWO: 2 projects (mostly PhD/postdoc grants)
    - 530 + 600 kEur for 2015-2020, covering:
      - 4 FYE Gent
      - 8 FYE Antwerpen
      - 8 FYE Brussels
      - 80k service&operation SCK

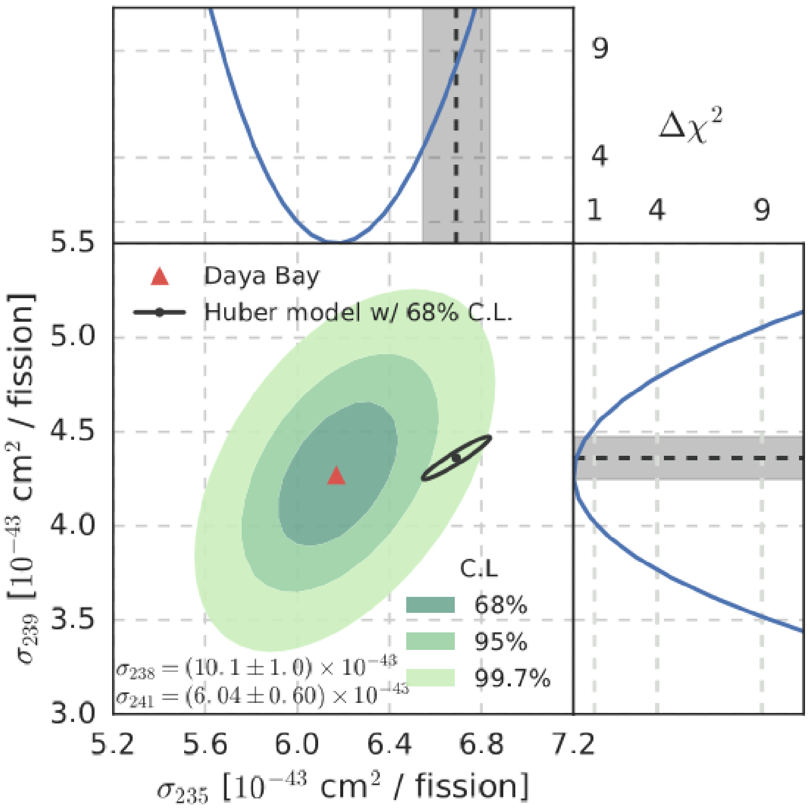
SoLid physics goals

- Challenge some long-standing neutrino anomalies: Radiochemical, Reactor, LSND-Miniboone
- Measure reference $\bar{\nu}_e$ spectrum of pure ^{235}U
- Demonstrate compact, cheap, highly segmented $\bar{\nu}_e$ detector technology: Reactor monitoring



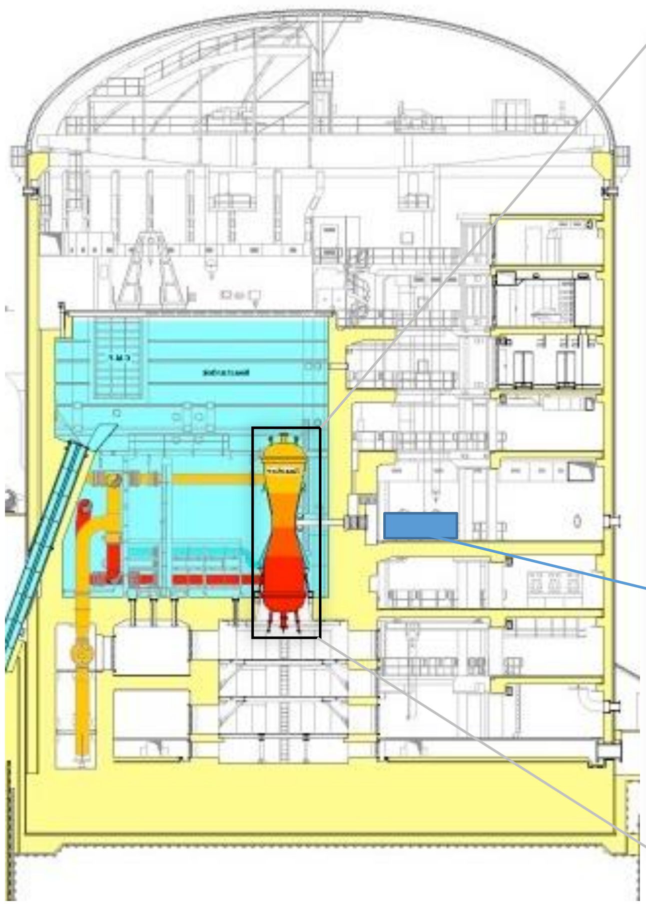
Th. Lasserre, Nu2012

SoLid baseline coverage

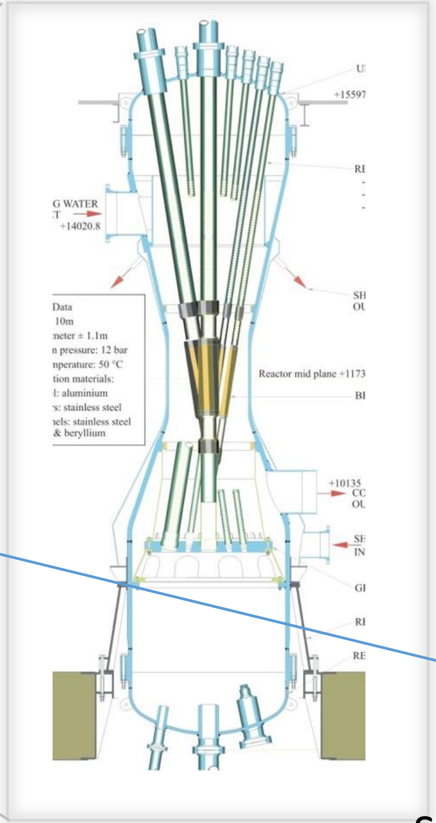


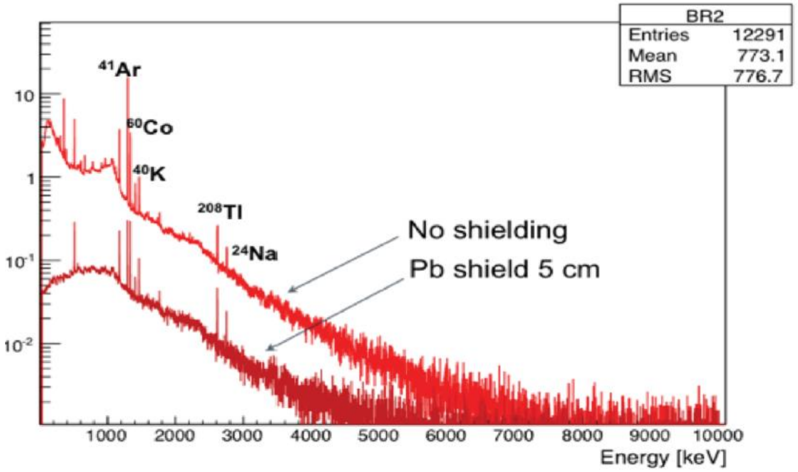
Belgian Reactor 2 (BR2)@ SCK•CEN: Unique environment

BR2 Confinement building



Aluminum pressure Vessel
Twisted core



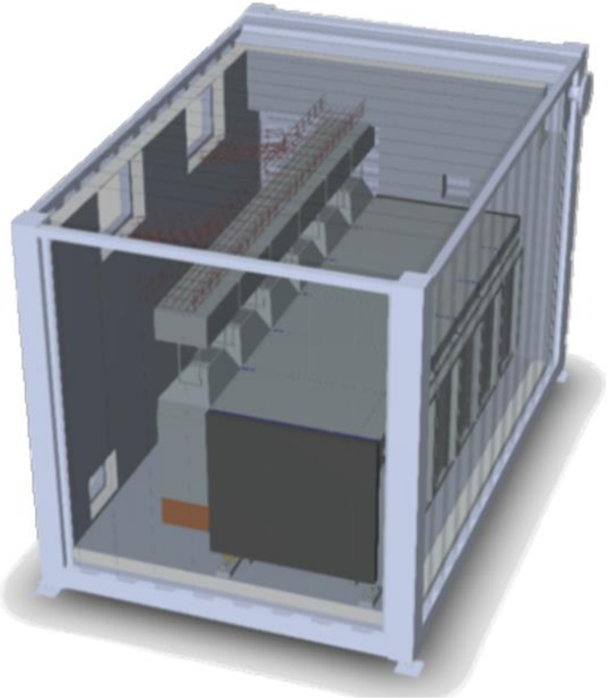


<u>BR2 reactor:</u>

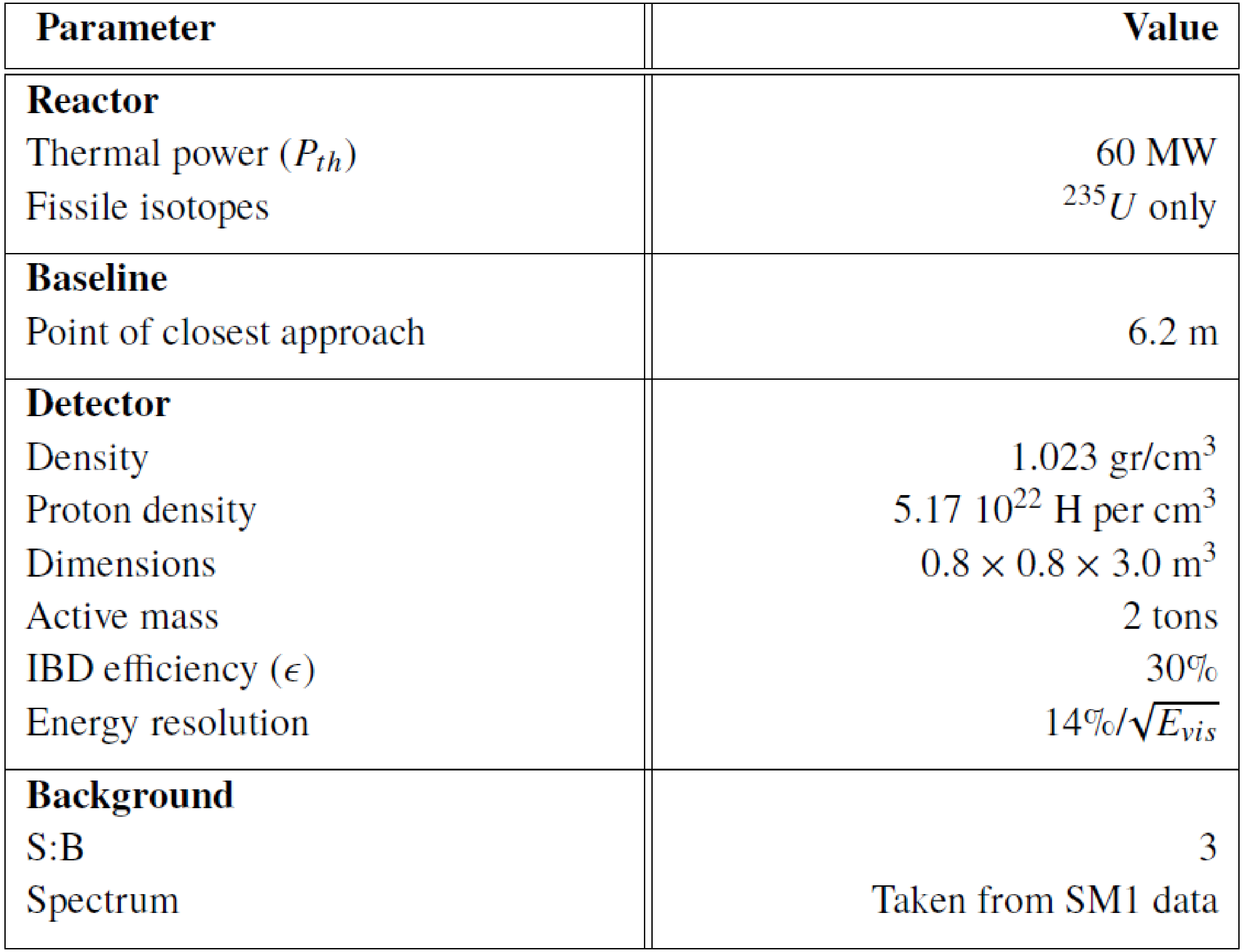
- 95% Enriched 235U
- Effective core diameter d=0.5m
- Peak power: 70-80 MW_{th}
- Duty cycle: ~ 150 days/year
- Low accidental background

<u>SoLid $\bar{\nu}_e$ detector:</u>

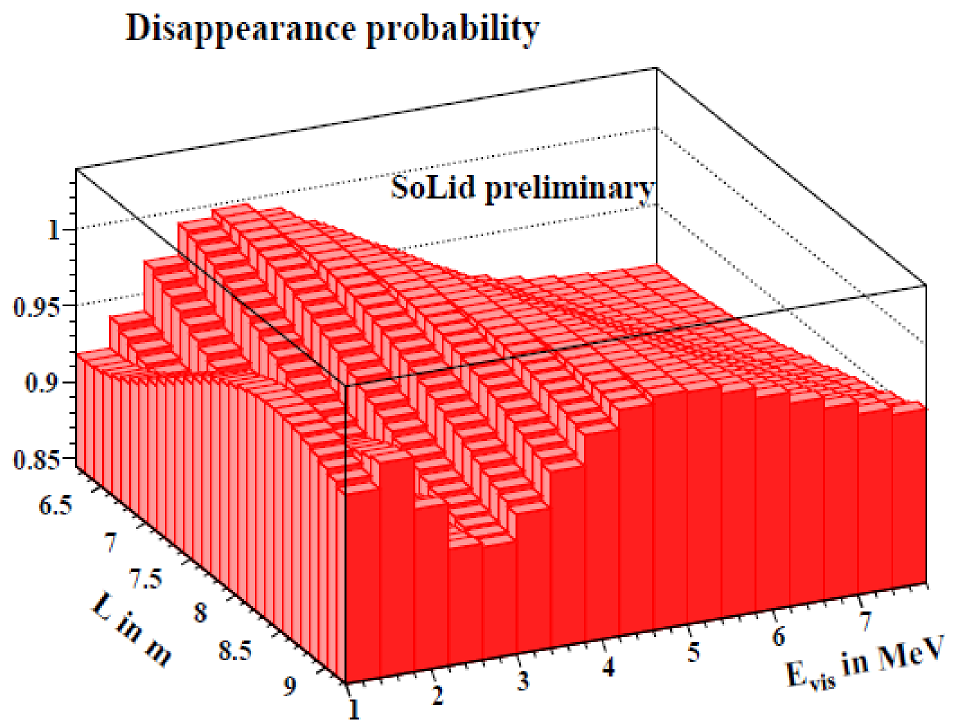
- 2 T fiducial, no overburden
- Baseline: 6.2 – 9.2m
- On-axis with reactor core
- ~400 triggered & selected $\bar{\nu}_e/day$



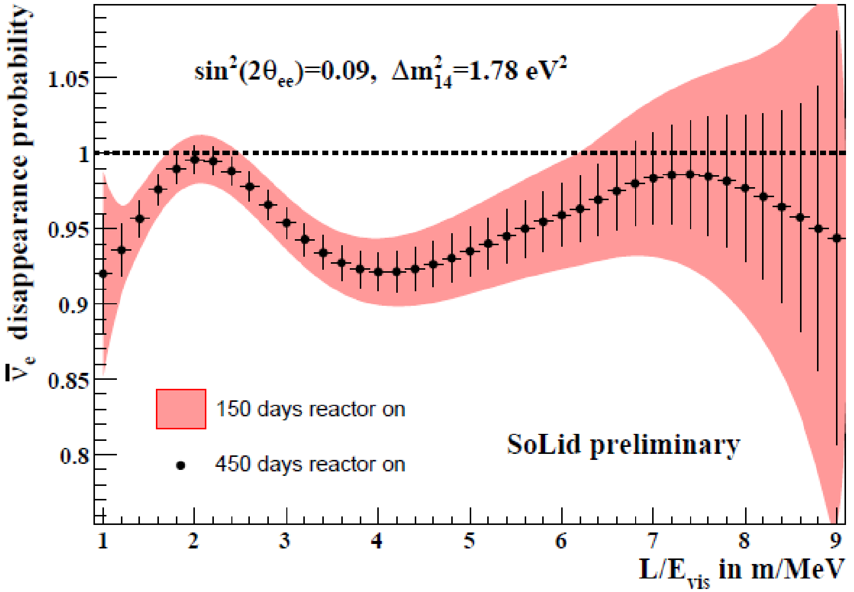
Main Features of SoLid



Parameter	Value
Reactor	
Thermal power (P_{th})	60 MW
Fissile isotopes	^{235}U only
Baseline	
Point of closest approach	6.2 m
Detector	
Density	1.023 gr/cm^3
Proton density	5.17 10^{22} H per cm^3
Dimensions	$0.8 \times 0.8 \times 3.0$ m^3
Active mass	2 tons
IBD efficiency (ϵ)	30%
Energy resolution	$14\%/\sqrt{E_{vis}}$
Background	
S:B	3
Spectrum	Taken from SM1 data



Expectations from detailed simulation



SoLid detection technology

Detection through the inverse beta decay (IBD) reaction

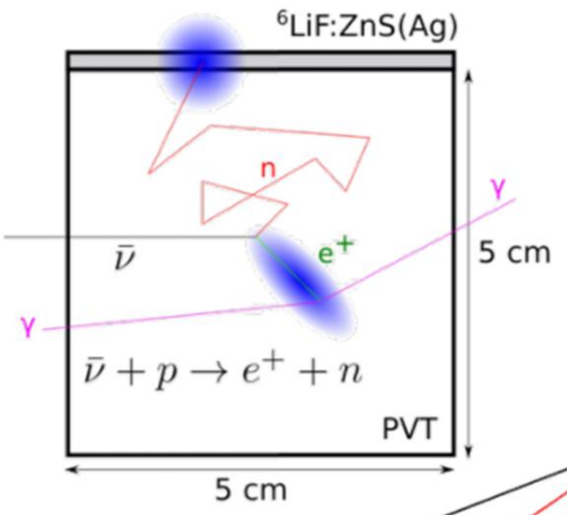
$\bar{\nu} + p \rightarrow e^{+} + n$

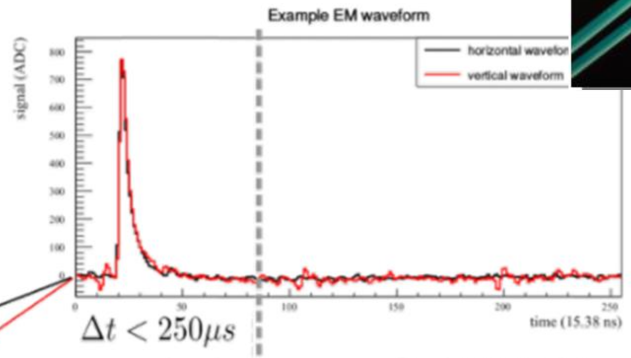
Composite detector unit cell

Pulse shape discrimination between neutron and EM

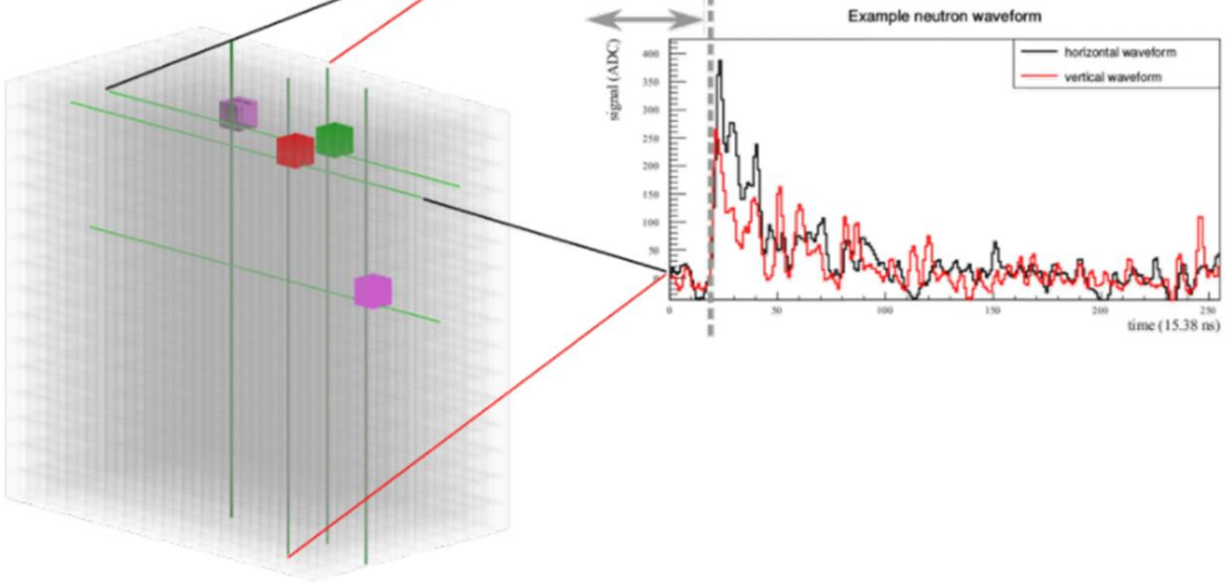
Highly segmented detector

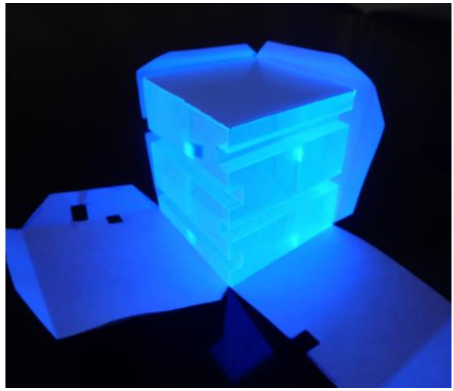
$n + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{H} + \alpha + 4.78\ \mathrm{MeV}$

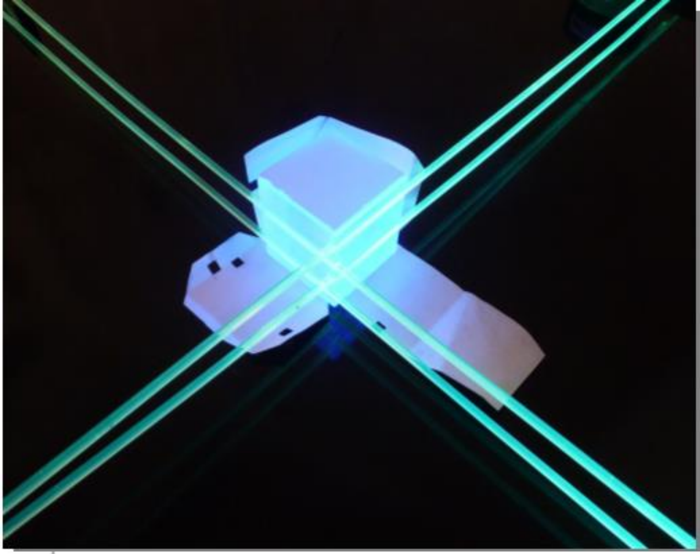


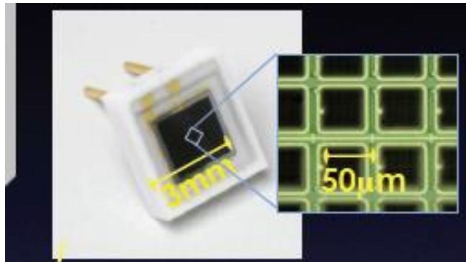


$\Delta t < 250\mu s$





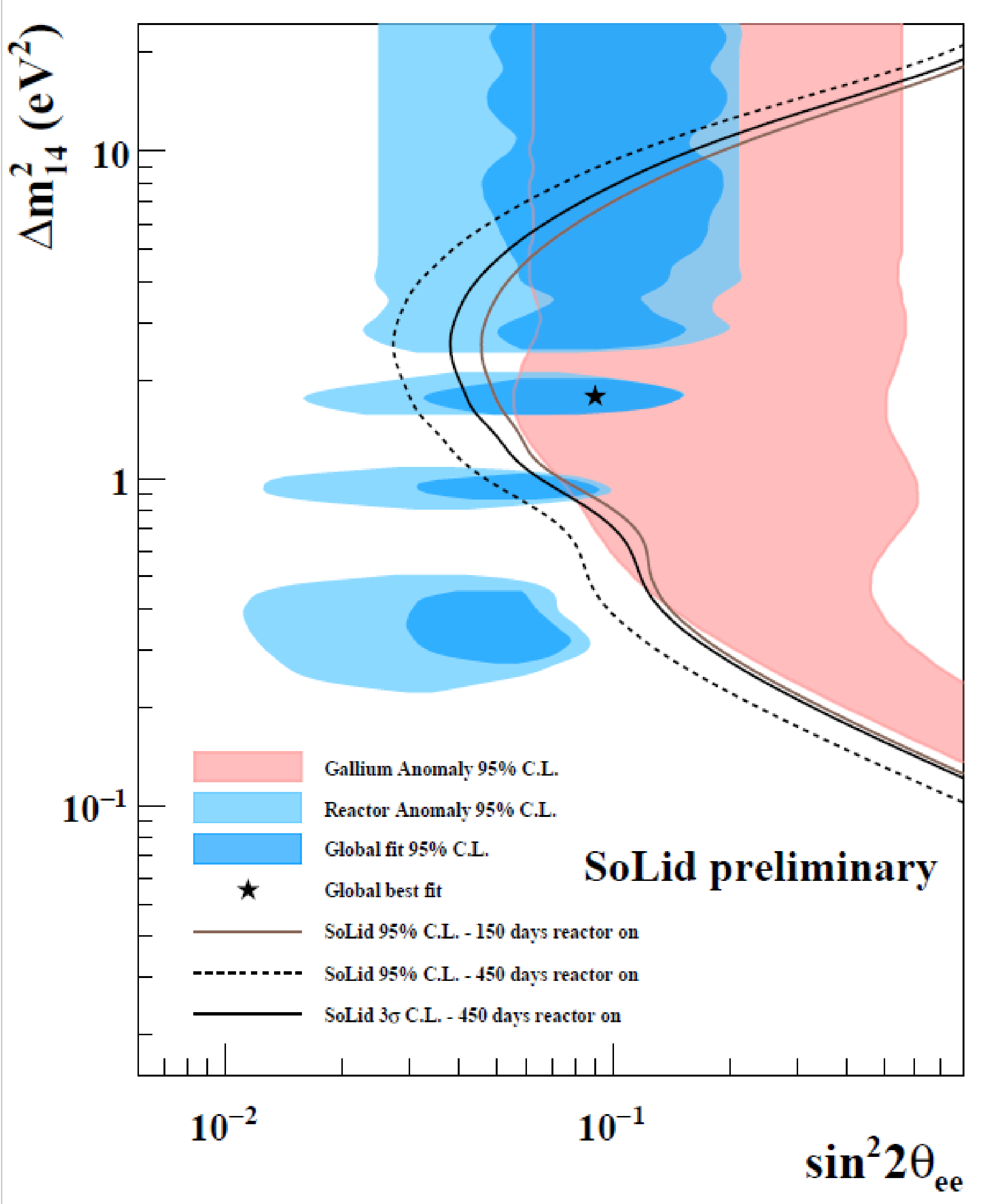




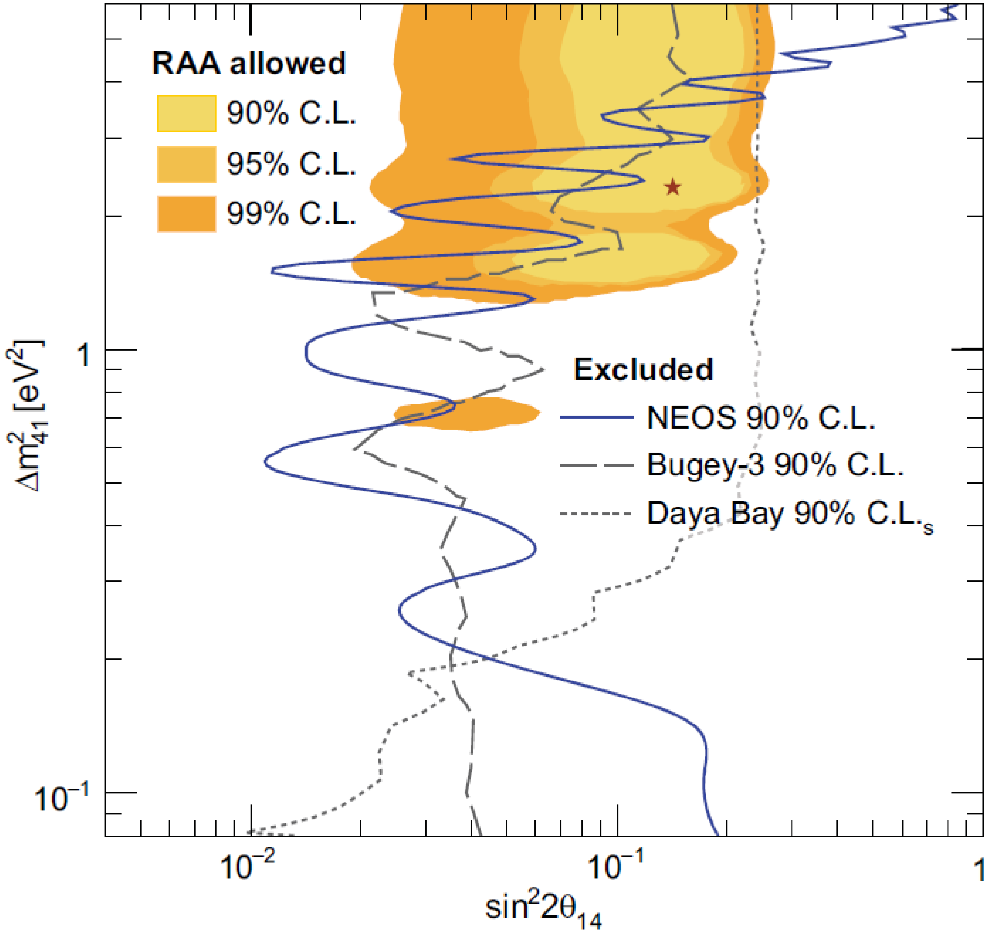
MPPC 3 mm x 3 mm
50 um pixel pitch
60-65% active area
Pixel RC cnst~13 ns
PDE ~ 30-40%

Squared BCF-91A fibre

SoLid sensitivity to sterile ν's

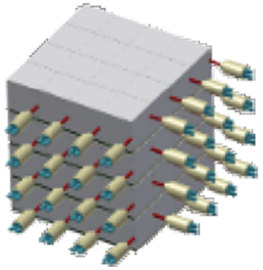


- Competing experiments:
  - NEOS (Korea): Completed
  - DANNS (Russia): Online
  - STEREO (France):Online
  - PROSPECT (USA): start 2017



SoLid Timeline

NEMENIX, 2013



4x4x4 cubes

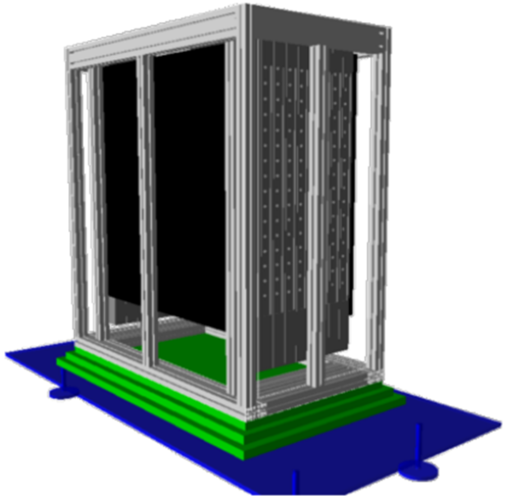
64 detection cells

~8 kg active mass

Proof of principle

- Validate neutron id
- Demonstrate prompt-delayed signal selection
- Background measurement

SM1 prototype, 2014-2015



9 planes of 16x16 cubes

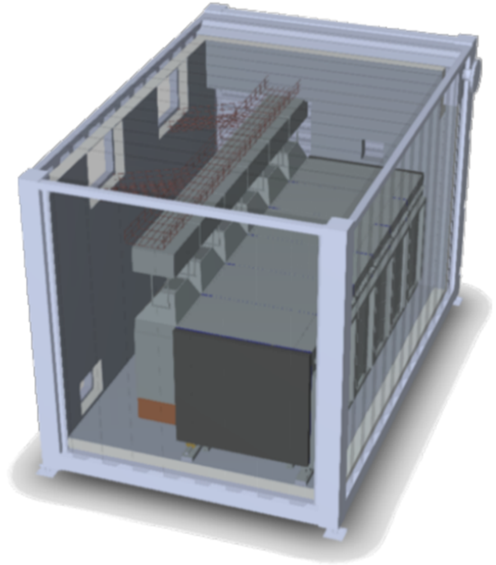
2304 detection cells

~288 kg active mass

First large scale prototype

- Demonstrate scalability and test production schedule
- Probe background rejections
- Analysis tools, physics results

Phase1 detector, 2017



60 planes of 16x16 cubes

15360 detection cells

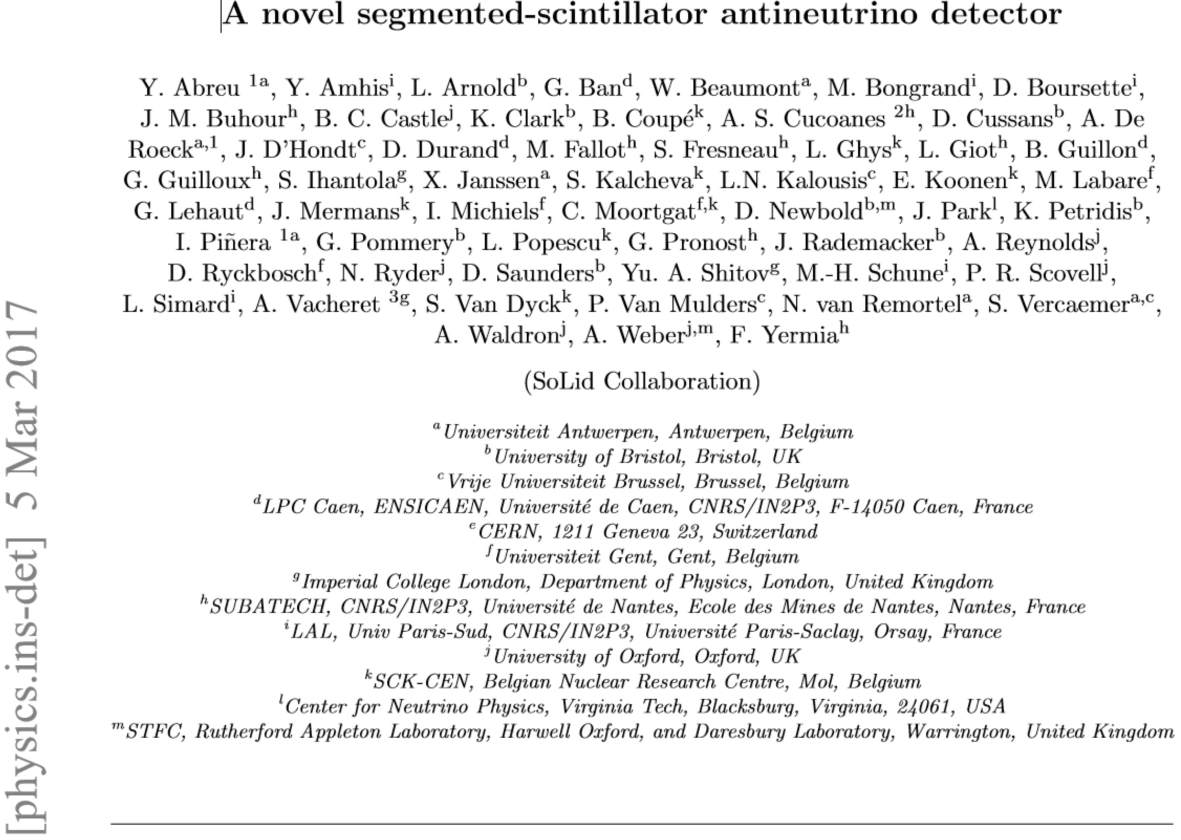
~2.0 t active mass

Real scale system

- Improved design
- Implement neutron trigger
- Perform high precision measurements

SM1 Highlights

- Demonstrated stability of operation on-site at BR2
- Calibration& equalization of response up to 2%
- Demonstrated achievable energy resolution of 14%@1 MeV
- Identified and measured main backgrounds: S/N= 3:1 achievable by exploiting:
    - Extra shielding
    - Topology cuts
    - Multiplicity & tracking
    - Neutron ID trigger at very low amplitude threshold
- Reactor group & Simulation: First predicted energy spectra & rates

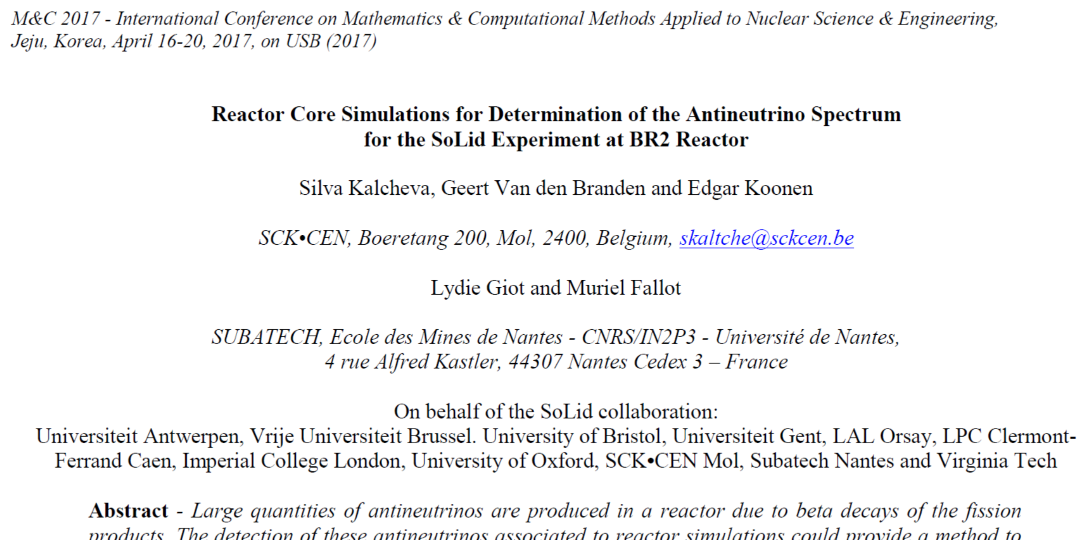


A novel segmented-scintillator antineutrino detector

Y. Abreu [1a], Y. Amhis[i], L. Arnold[b], G. Ban[d], W. Beaumont[a], M. Bongrand[i], D. Boursette[i], J. M. Buhour[h], B. C. Castle[j], K. Clark[b], B. Coupé[k], A. S. Cucoanes [2h], D. Cussans[b], A. De Roeck[a,1], J. D'Hondt[c], D. Durand[d], M. Fallot[h], S. Fresneau[h], L. Ghys[k], L. Giot[h], B. Guillon[d], G. Guilloux[h], S. Ihantola[g], X. Janssen[a], S. Kalcheva[k], L.N. Kalousis[c], E. Koonen[k], M. Labare[f], G. Lehaut[d], J. Mermans[k], I. Michiels[f], C. Moortgat[f,k], D. Newbold[b,m], J. Park[l], K. Petridis[b], I. Piñera [1a], G. Pommery[b], L. Popescu[k], G. Pronost[h], J. Rademacker[b], A. Reynolds[j], D. Ryckbosch[f], N. Ryder[j], D. Saunders[b], Yu. A. Shitov[g], M.-H. Schune[i], P. R. Scovell[j], L. Simard[i], A. Vacheret [3g], S. Van Dyck[k], P. Van Mulders[c], N. van Remortel[a], S. Vercaemer[a,c], A. Waldron[j], A. Weber[j,m], F. Yermia[h]

(SoLid Collaboration)

[a] *Universiteit Antwerpen, Antwerpen, Belgium*
[b] *University of Bristol, Bristol, UK*
[c] *Vrije Universiteit Brussel, Brussel, Belgium*
[d] *LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, F-14050 Caen, France*
[e] *CERN, 1211 Geneva 23, Switzerland*
[f] *Universiteit Gent, Gent, Belgium*
[g] *Imperial College London, Department of Physics, London, United Kingdom*
[h] *SUBATECH, CNRS/IN2P3, Université de Nantes, Ecole des Mines de Nantes, Nantes, France*
[i] *LAL, Univ Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[j] *University of Oxford, Oxford, UK*
[k] *SCK-CEN, Belgian Nuclear Research Centre, Mol, Belgium*
[l] *Center for Neutrino Physics, Virginia Tech, Blacksburg, Virginia, 24061, USA*
[m] *STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, United Kingdom*



M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017, on USB (2017)

Reactor Core Simulations for Determination of the Antineutrino Spectrum for the SoLid Experiment at BR2 Reactor

Silva Kalcheva, Geert Van den Branden and Edgar Koonen

SCK•CEN, Boeretang 200, Mol, 2400, Belgium, skaltche@sckcen.be

Lydie Giot and Muriel Fallot

SUBATECH, Ecole des Mines de Nantes - CNRS/IN2P3 - Université de Nantes,
4 rue Alfred Kastler, 44307 Nantes Cedex 3 – France

On behalf of the SoLid collaboration:
Universiteit Antwerpen, Vrije Universiteit Brussel. University of Bristol, Universiteit Gent, LAL Orsay, LPC Clermont-Ferrand Caen, Imperial College London, University of Oxford, SCK•CEN Mol, Subatech Nantes and Virginia Tech

Abstract - *Large quantities of antineutrinos are produced in a reactor due to beta decays of the fission products. The detection of these antineutrinos associated to reactor simulations could provide a method to*

SM1 deployment @ BR2

2015

Specific contributions

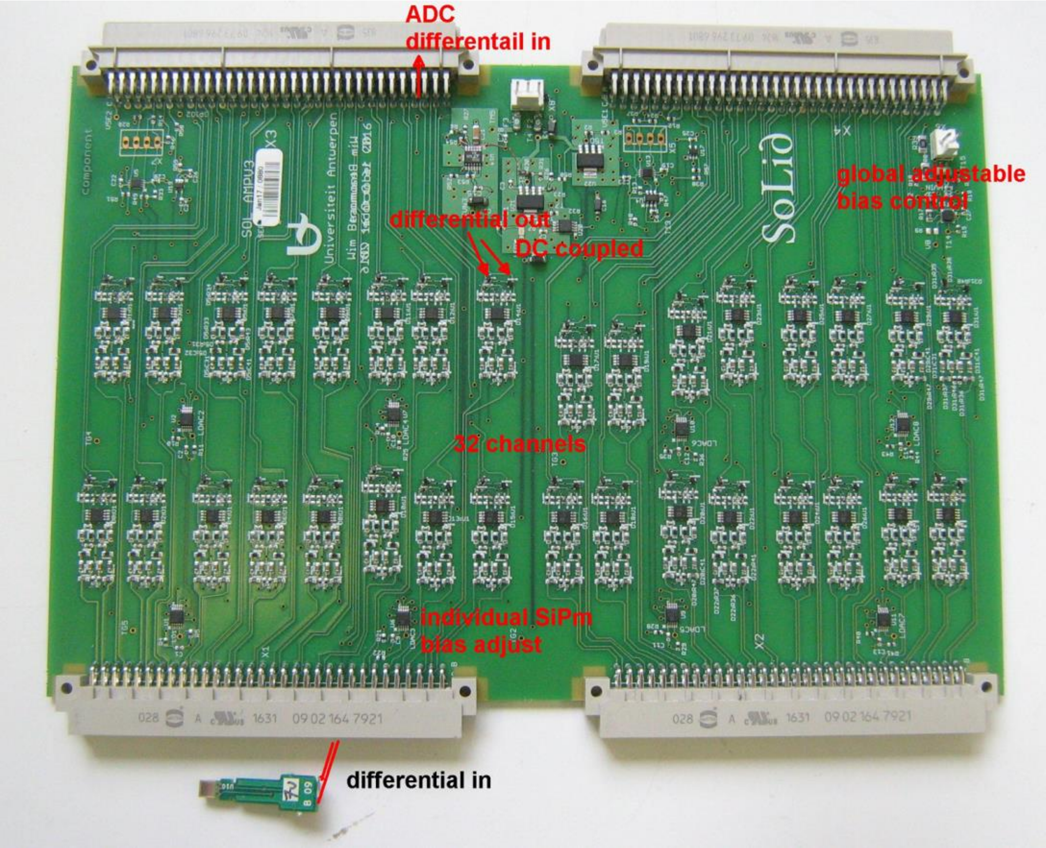
- Neutron ID: S. Vercaemer, Y. Abreu
- Cosmogenic backgrounds: L. Kalousis, P. van Mulders, I. Pinera, C. Moortgat
- Reactor backgrounds: L. Ghys, P. van Mulders
- Simulation: geometry, reactor building, detector & readout: M. Verstraeten, I. Pinera, …
- Sensitivity, Limits, Oscillometry: L. Kalousis, S. Vercaemer
- Intrinsic backgrounds: Y. Abreu
- Databases & Quality control: M. Labare

R&D and Construction

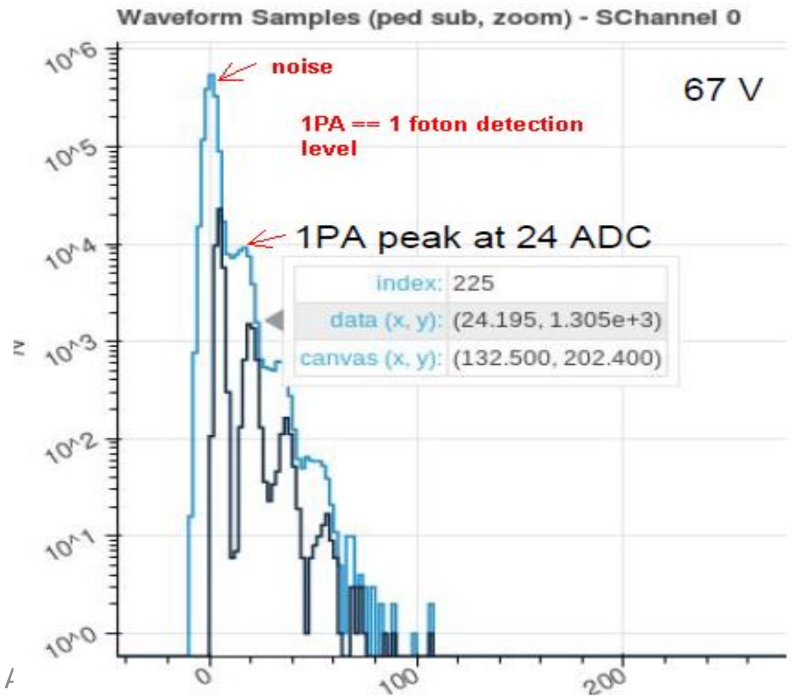
2016-2017

SOLID SiPm amplifier

- To achieve : detect 1 photon signals from the ws fiber
  - SM1 lesson : to much noise pickup
  - Long signal cables between SiPm and amplifier still optimal choice for integration.



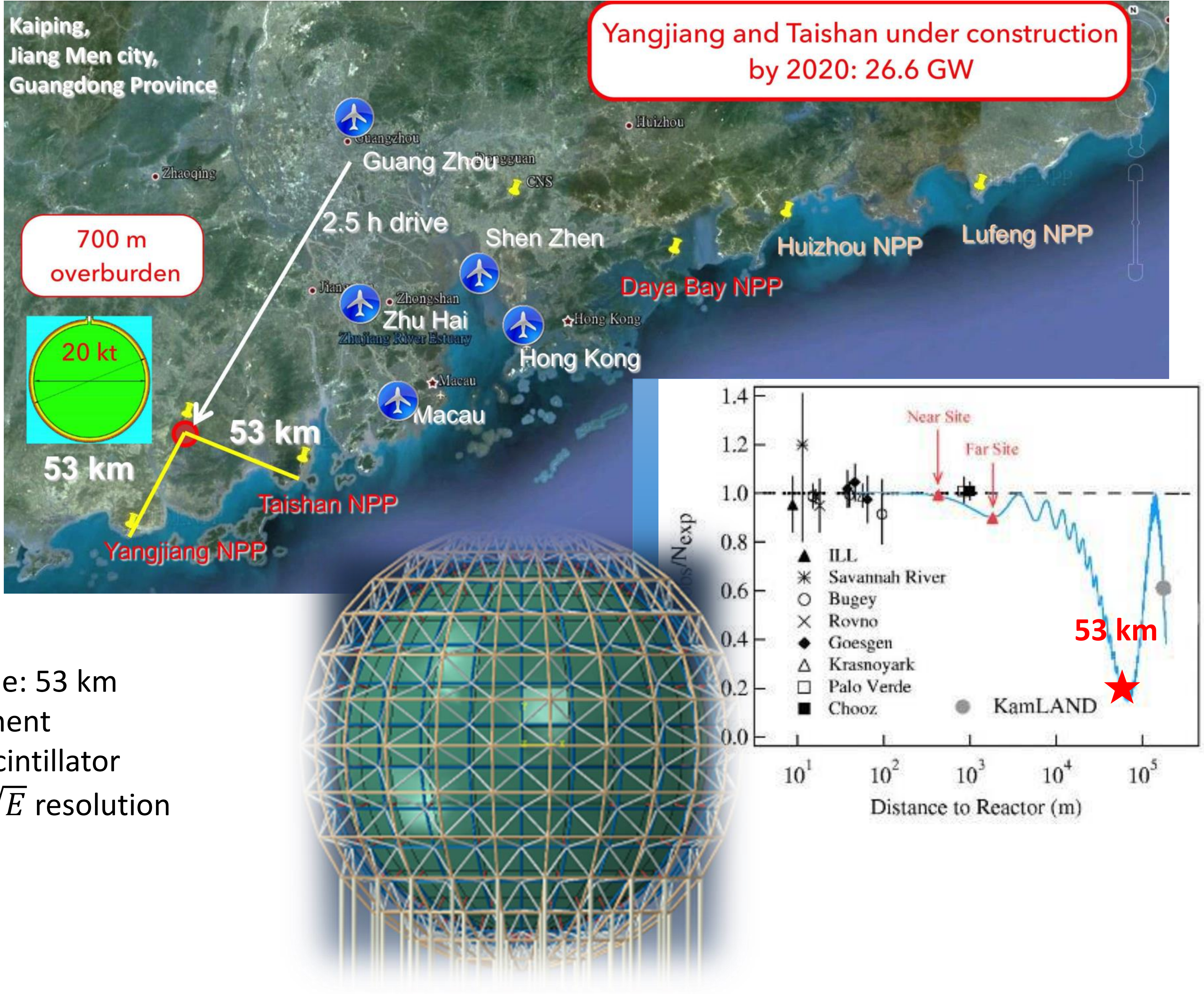
Full differential signal, from SiPm up to the ADC



Construction& Assembly & Quality control 2016-2017

- Production & assembly in Gent and RAL (UK)
- Site preparation: SCK
- Quality Control & Calibration: Gent
- Physics run: Start July 2017
- Complete detector before Sept
- 150 days reactor time/year: 2018-2019
- Ideas for extension: CHANDLER technology

JUNO



Medium baseline: 53 km
Reactor experiment
20 kTon liquid scintillator
Providing $3\%/\sqrt{E}$ resolution

Belgium @ JUNO

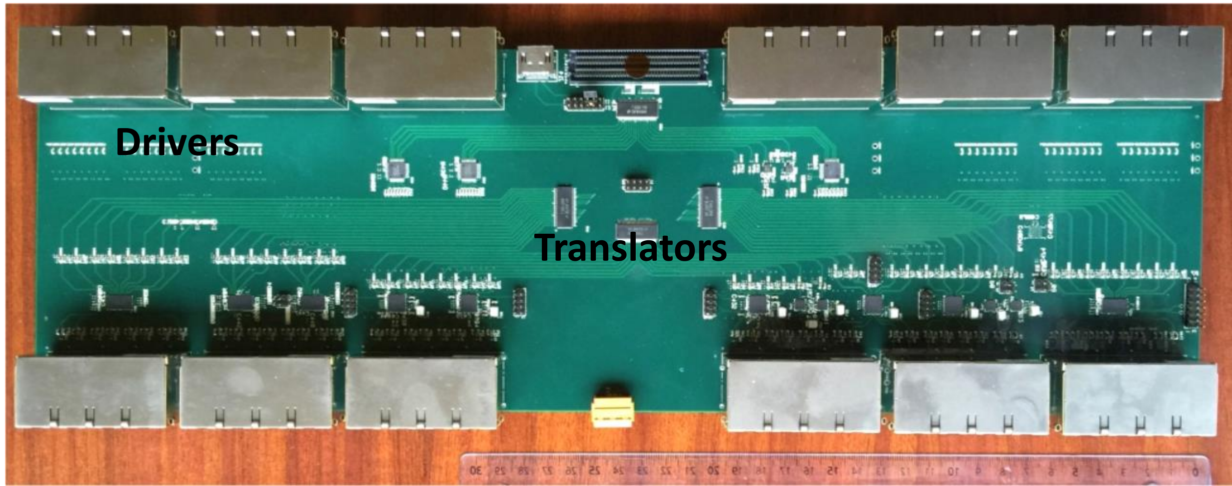
- JUNO: 70 institutions, 521 collaborators

- Belgian participation since 2015, via:
  - ULB (IIHE):
    - B. Clerbaux & Y. Yang
  - Design & production of Back End readout Card(BEC)
  - Later participation in simulation & Analysis

- **Collaboration with EU-JUNO : well established** – EU fund requested for a ITN
- **Collaboration with China : via CSC PhD scholarship** : well established

  (IIHE has 7 CSC/master students from Tsinghua, IHEP, PKU, Beihang)

- Global JUNO Budget: 300 Meur, 45 Meur covered by non-Chinese
- Belgian Funding:
  - 230 kEuros (spread on 4 years) from the IISN (FNRS) : Finalization of the design, test and prototypes on the BECs and construction and assembly of a total of 435 BECs (prize : 528 **€/BEC)**

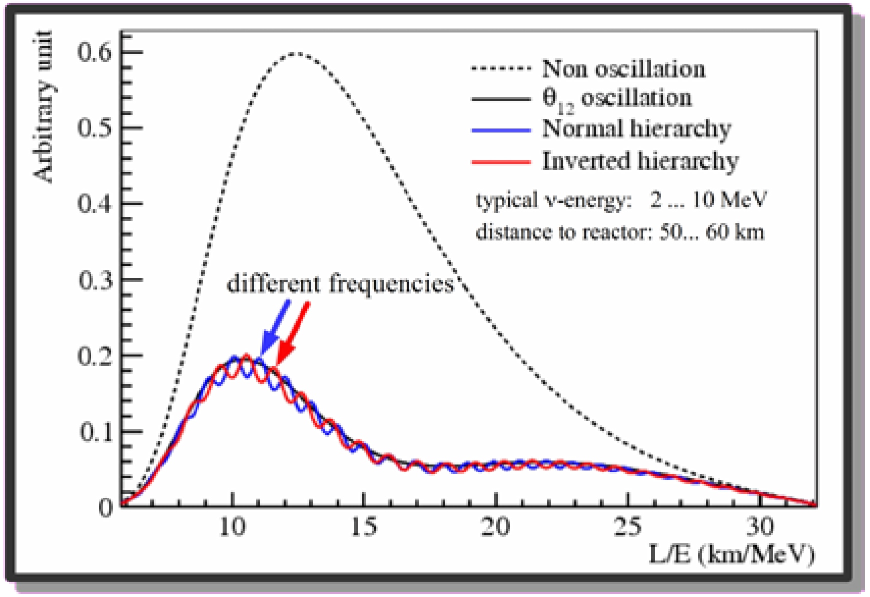


JUNO physics

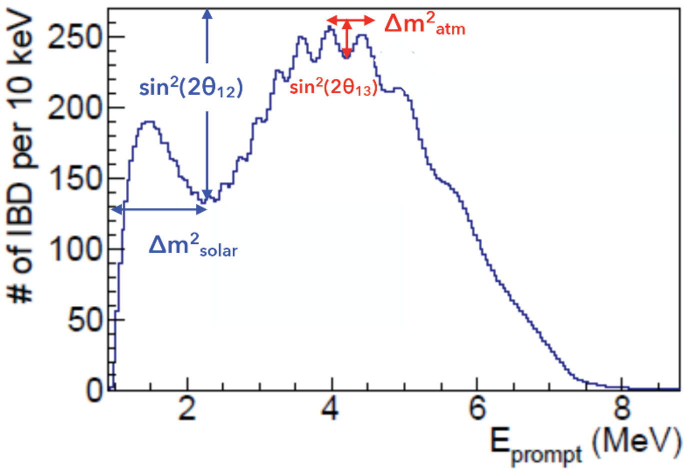
- Probing the mass hierarchy
- Three oscillation parameters : Δm^2_{12}, $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{12}$ can be measured with precision better than 1%.
- → Probing the unitarity of U_{PMNS} to ~1% level
  - NMH : For σ(E) = 3% at 1 MeV → 3σ sensibility (ΔX=9) for 100 000 events (20Kt x 36 GW x 6 years of data taking)

The L/E spectrum contains the NMH information !

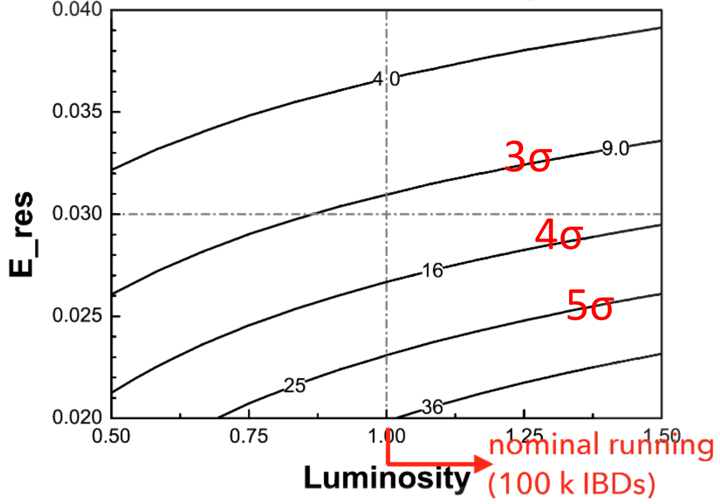
Define a discriminator : $\Delta\chi^2_{\mathrm{MH}} = |\chi^2_{\mathrm{min}}(\mathrm{N}) - \chi^2_{\mathrm{min}}(\mathrm{I})|$



Energy spectrum for 100k IBD



iso-$\Delta\chi^2_{MH}$ contour plot

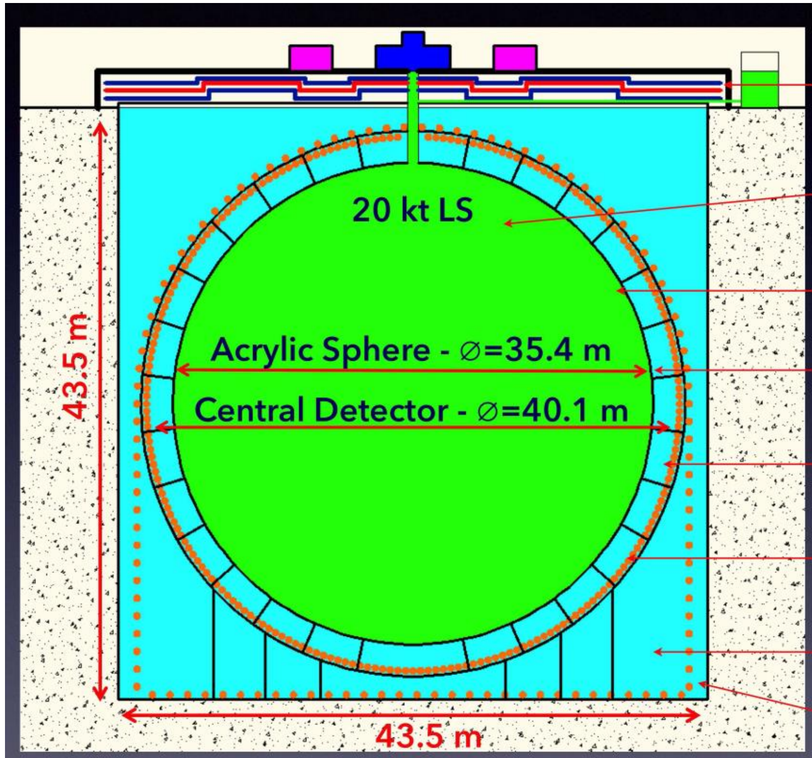


But also :

- Neutrino from supernova burst
- Solar neutrinos
- atmospheric neutrinos
- Geoneutrinos
- Exotic searches as nucleon decay and dark matter

JUNO Technology

Signal rate : 60 events/day
Background rate : 3.8 events/day



Top muon veto: plastic scintillator strips

LS: 20 kton LAB based

LS container: acrylic. The maximum stress should be <35 MPa.

Buffer: water

PMTs: 17000 20″ PMTs + 34000 3″ PMTS for a ~77.8% coverage

Buffer/PMT support: Stainless steel structure

Water Cherenkov veto: 20 kton water

PMTs: 2000 20″ veto PMTs

Energy resolution requirement : 3%/√E (MeV)

- LS : Scintillator attenuation length
- PMT : high light yield :
  high photocathode coverage and
  high detection efficiency of PMT’s
- PMT with low dark current

Energy scale require calibration at the sub-percent level :

- Comprehensive calibration program (cable loop system, remotely operated vehicle, guide tube) to address both the non-uniformity and non-linearity
- Double calorimetry : Large PMT and **small PMT systems**

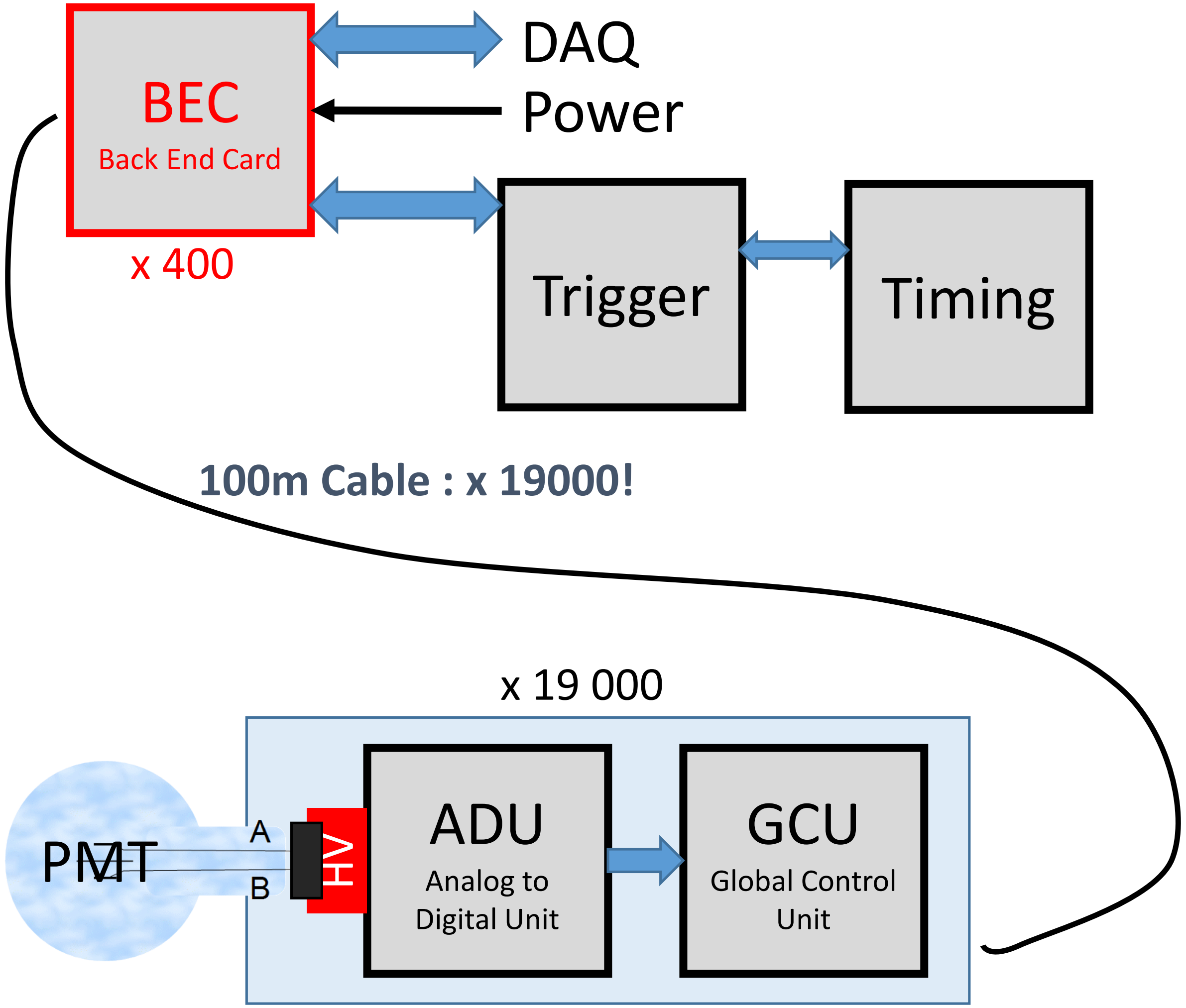
Neutrinos are observed via **Inverse Beta Decay (IBD) :** $\bar{\nu}_e + p \to e^+ + n$

$\tau \simeq 200\mu\text{sec}$ $\to n + p \to d + \gamma$

→ Very clean signature → Energy : (2 to 8) MeV

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E

PMT & readout



BEC
Back End Card
x 400

DAQ
Power

Trigger

Timing

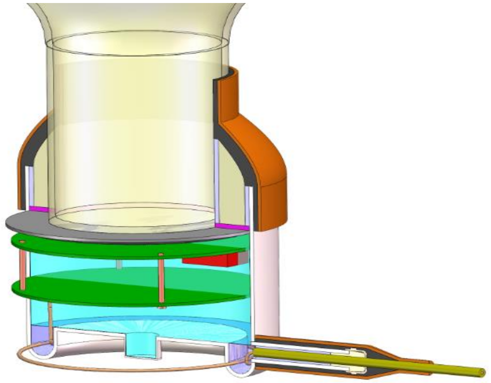
100m Cable : x 19000!

x 19 000

PMT
A
B
HV

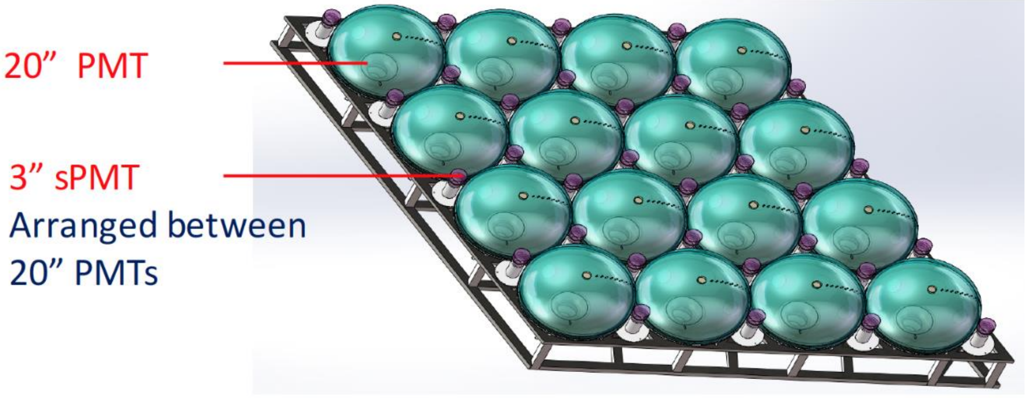
ADU
Analog to Digital Unit

GCU
Global Control Unit



RELIABILITY Goal :
< 0.5% failure of
electronics
within 6 years
(1% whole system including PMTs)

→ Small PMT system recently approved



Arranged between 20” PMTs

BEC card

Y. Yang (ULB)

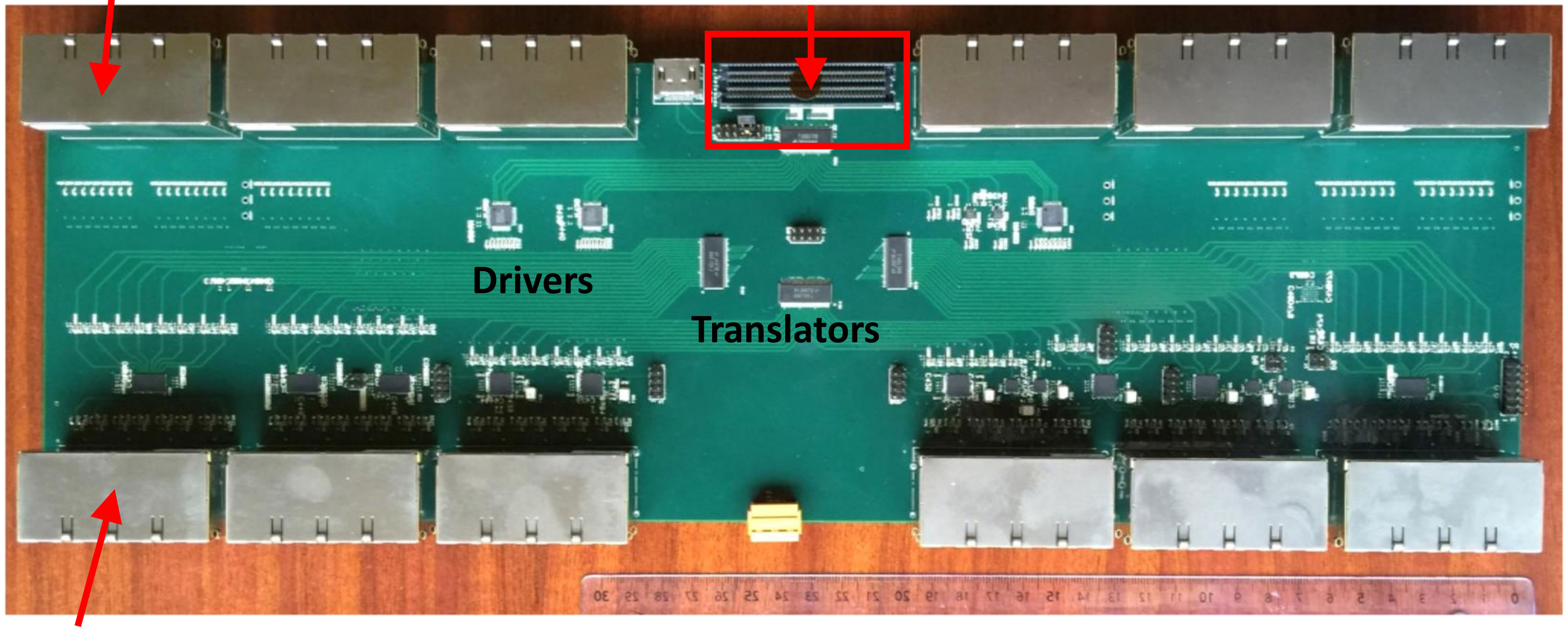
DAQ

Trigger/Clock/DCS

8 layer PCB
48 cm x15 cm

8 Ethernet connectors (RJ45)

Connectors for the
mezzazine card with FPGA



Equalizers

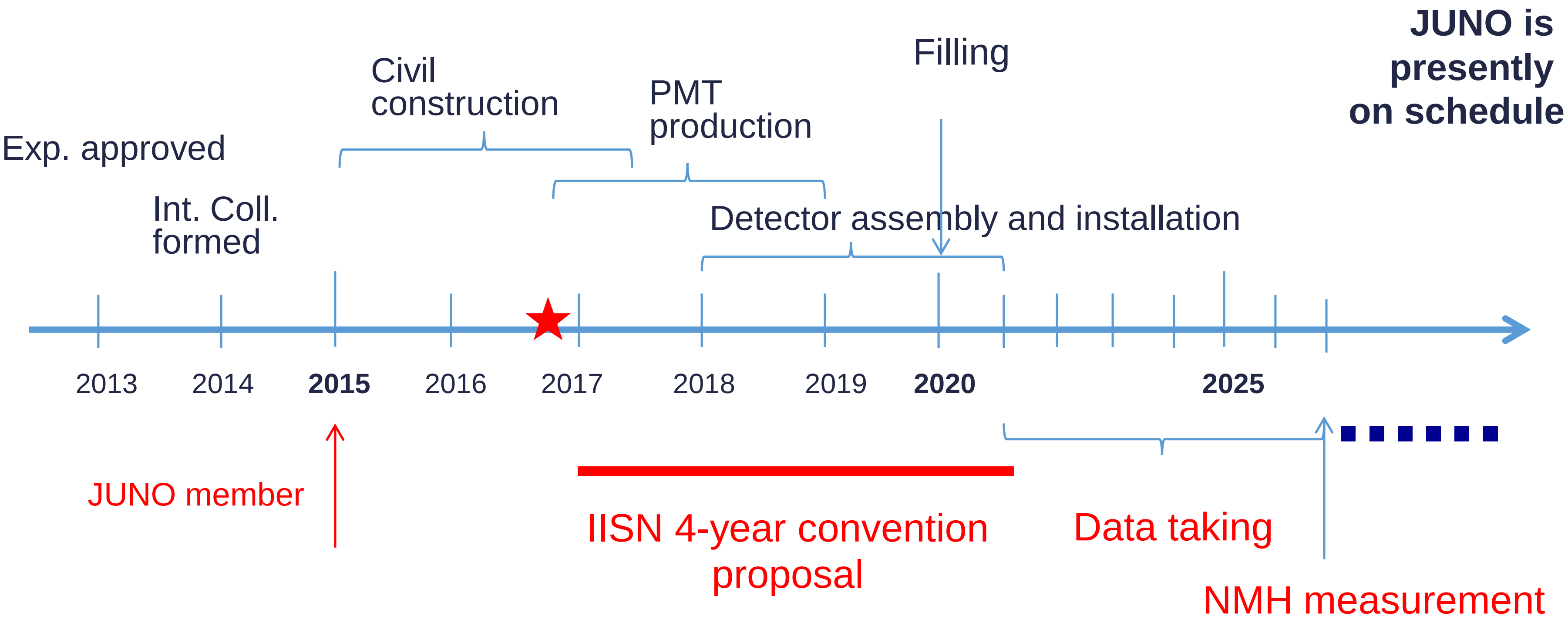
8 Ethernet connectors

GCU

Short term future : Combine test for

- Power injection test (with Aachen group)
- Signal quality test (PRBS)
- Full data chain test (with Padova group)

Time Schedule



JUNO is presently on schedule

Exp. approved

Int. Coll. formed

Civil construction

PMT production

Filling

Detector assembly and installation

2013

2014

2015

2016

2017

2018

2019

2020

2025

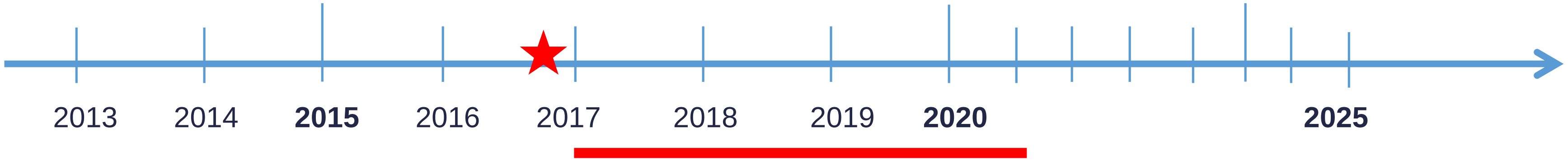
JUNO member

IISN 4-year convention proposal

Data taking

NMH measurement

Proposed Research



IISN 4-year convention proposal

- **A contribution to the electronics readout system : BECs**
  - Finalize the R&D and design –prototype construction with final components
  - Design of the test and quality control systems
  - Participate to large size JUNO prototype detector in IHEP
  - Mass production in 2018/2019 - installation and commissioning in 2020

In Collaboration with Padova - Aachen – Tsinghua – IHEP – SunYatSen and Wuhan U.

- **Contribution to the data analysis preparation using simulation :**
  - Software development of JUNO – Small PMT systems – not yet available
  - Use of the small PMT system to monitor the energy resolution of the LPMT
  - Complementary approach to be optimized using simulations
  - Goal : improvement of the non-stochastic term of ΔE/E
  - Crucial to be ready in 2020 when the data arrive

In Collaboration with APC Paris – Mainz/Jülich

Conclusion

- Belgium is ramping up involvement in new generation neutrino experiments
- Following a long standing tradition
- Funding small compared to flagship experiments
- Mostly R&D and construction
- Soon data taking and physics data analysis
- Lots of new & Enthousiastic students/postdocs involved
- Opportunity for visibility