Nuclear reactors for fundamental science

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Belgian Nuclear Society
SCK-CEN Lakehouse, 26/10/2016

Universiteit Antwerpen

A reductionist approach based on unification and atomism

Quantum Electro Dynamics (QED), Feynman, Schwinger

Quantum + Fields + Special Relativity

Schrödinger
(1926)
Quantum

Dirac
(1928)
Quantum Field
Elements of relativity

Feynman
(1950)
Fully relativistic
Quantum field

Electromagnetism → Light (photon)

Special relativity!

Elektrodynamics
Maxwell (1862)

Electricity + Magnetism

Elektrostatics
Coulomb (1783), Gauss (1835)

Magnetostatics
Faraday (1831), Ampère(1820

The Standard Model

Grand unified theory?
String theory?
…

Standard Model: U(1)xSU(2)xSU(3)
Englert, Higgs, 1964
T'Hooft, Veltman 1976

Electroweak Unification
Weinberg, 1967

Strong Nuclear Force QCD
Gell-Mann, 1964
Gross, Wilczek, 1973

Electromagnetism QED
Dirac, Feynman, …

Weak Nuclear Force
Enrico Fermi 1933

Quantum Gravity

QUANTUM QUESTIONS

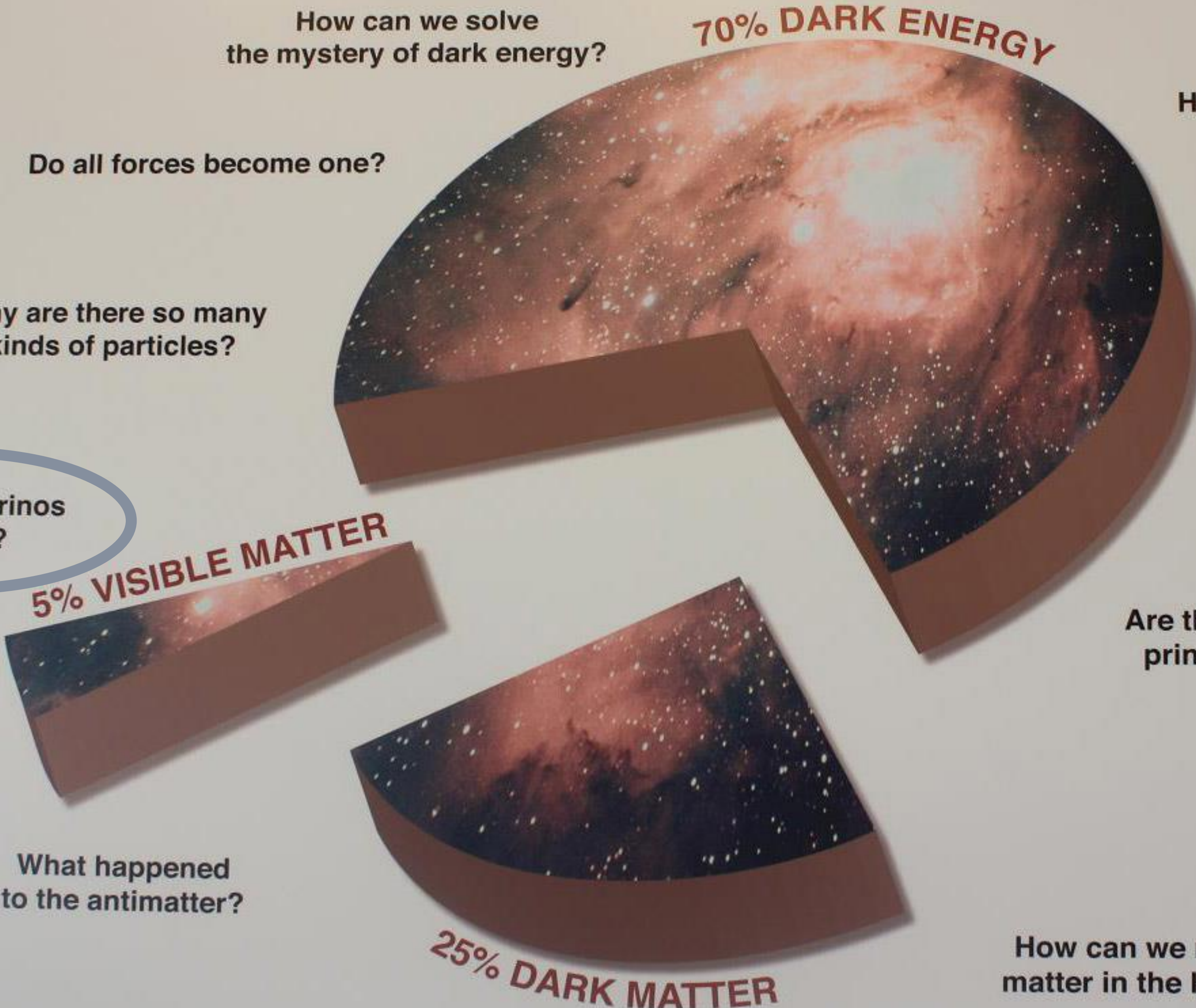
How can we solve the mystery of dark energy?

Do all forces become one?

Why are there so many kinds of particles?

What are neutrinos telling us?

What happened to the antimatter?



How did the universe come to be?

Are there extra dimensions of space?

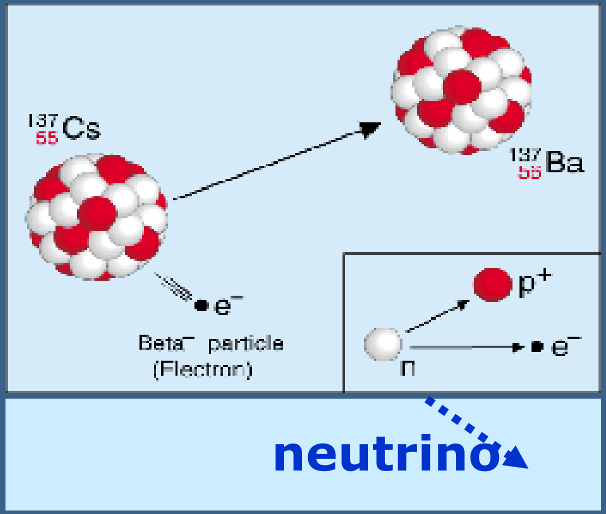
Are there undiscovered principles of nature?

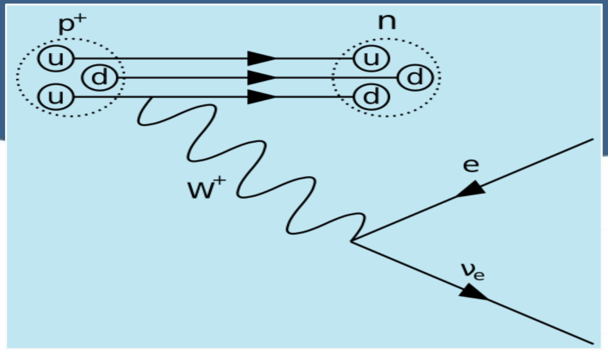
How can we make dark matter in the laboratory?

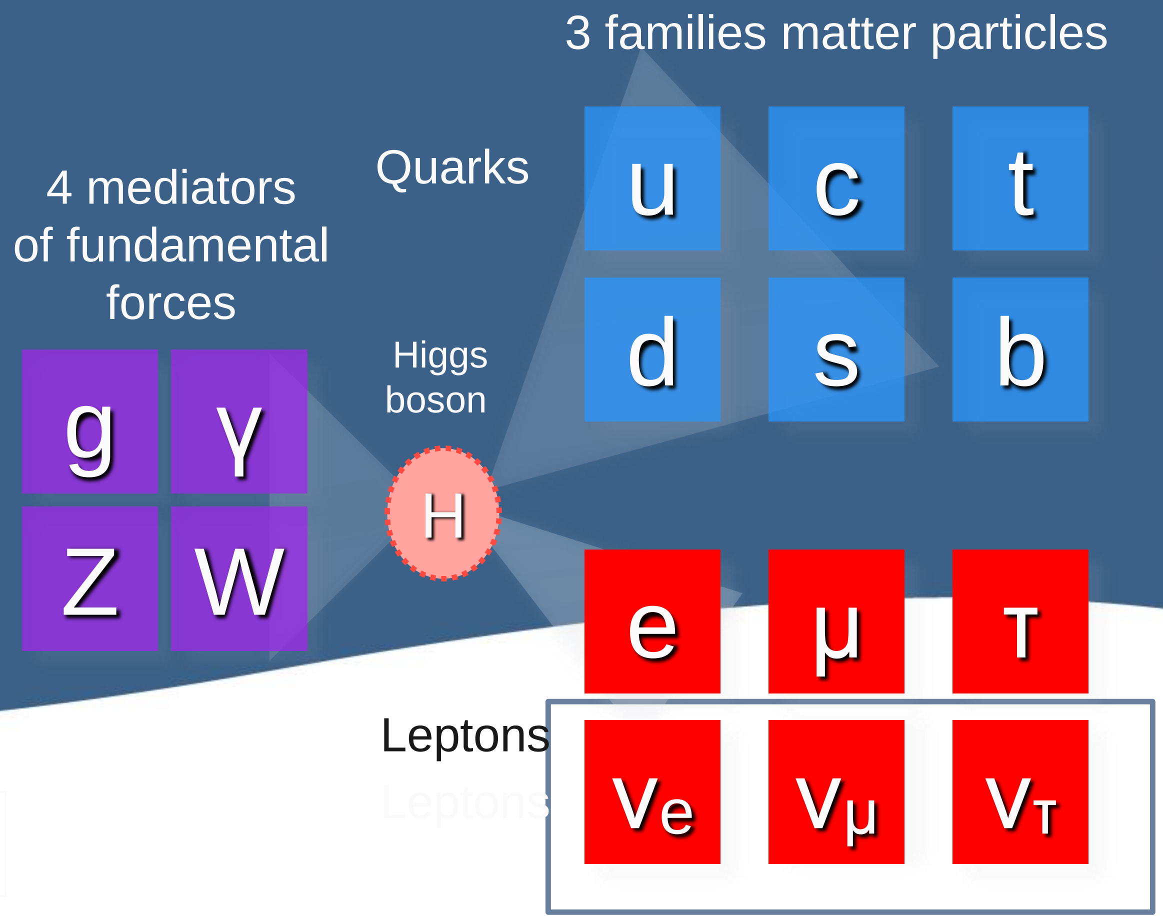
What is dark matter?

Neutrinos

- **Fundamental building blocks of matter**
- **Standard Model contains 3 species: ν_e, ν_μ, ν_τ**
- **Standard Model assumes them to be massless**
- **Play essential role in understanding the weak nuclear force**



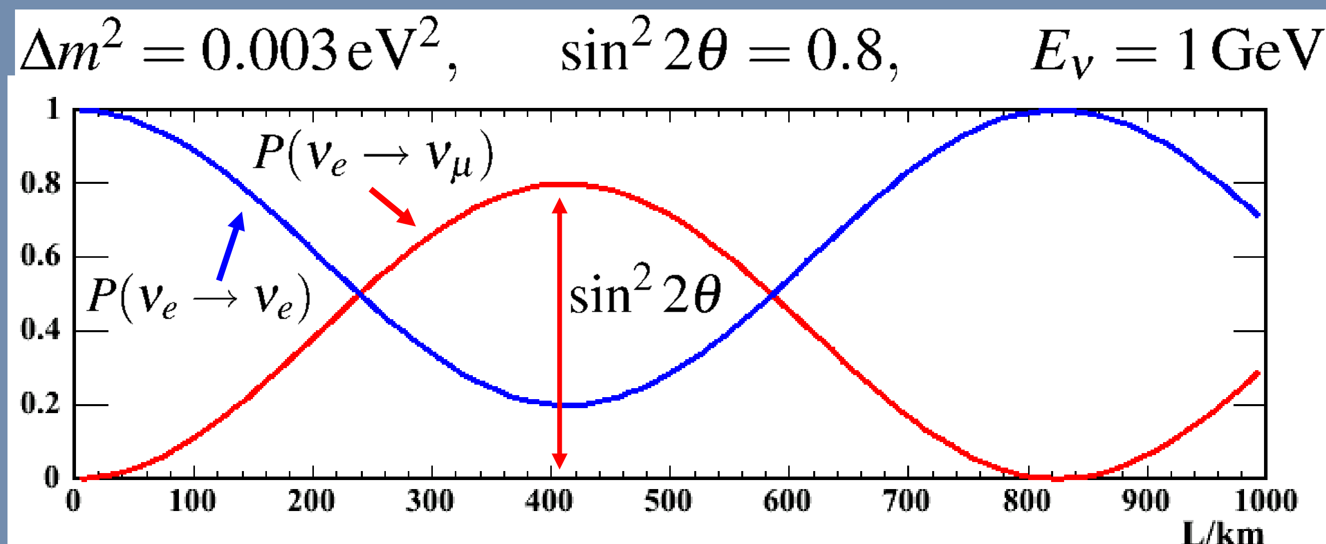


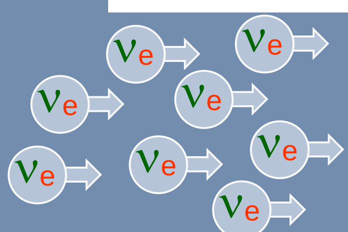


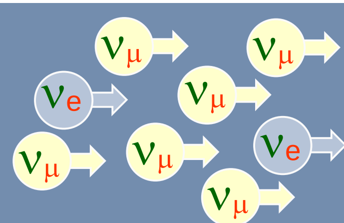
Oscillation of matter waves

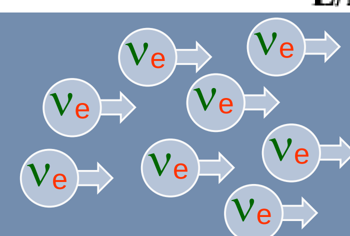
- Probability to observe ν_τ at time t if starting with pure ν_μ beam at time=0

$$\langle \nu_\tau(L) | \nu_\mu(0) \rangle = sin^2(2\theta) sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$









- wavelength

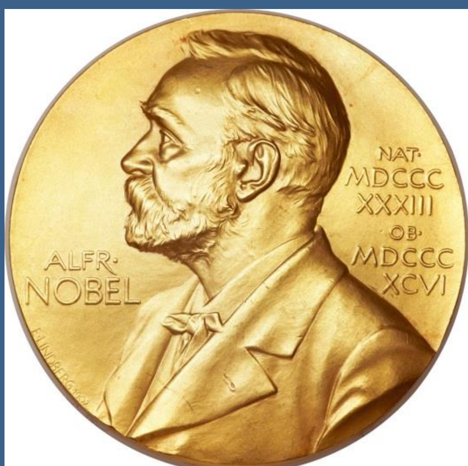
$$\boxed{\lambda_{osc} = \frac{4\pi E}{\Delta m^2}}$$

Problem of massive neutrinos

- 1998 Super Kamiokande experiment: Discovery of atmospheric neutrino oscillations --- > Neutrinos have mass!
- 2012: Experimental discovery of a new scalar particle (Higgs boson) --- > proof of the Brout-Englert-Higgs mechanism and the origin of mass!

F. Englert, ULB *P. Higgs, Edinburgh*

2013



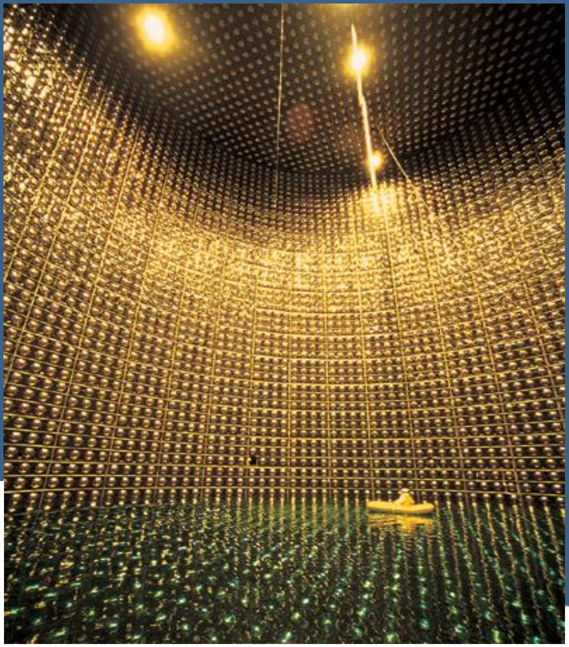


Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

2015

Open issues

- Currently ~10 large international projects
  - To establish details of 3 family neutrino mixings, measurement of CP violating phases in mixing matrix
    - Nova, LBNE/DUNE at Fermilab, USA
    - T2K in Japan
    - Daya Bay, Double Chooz, RENO, JUNO
  - To measure absolute masses of neutrinos
    - KATRIN in Karlsruhe
  - To measure majorana-dirac nature of neutrinos
    - Majorana in USA
    - (super)NEMO in France
    - GERDA in Italy

Sources of neutrinos

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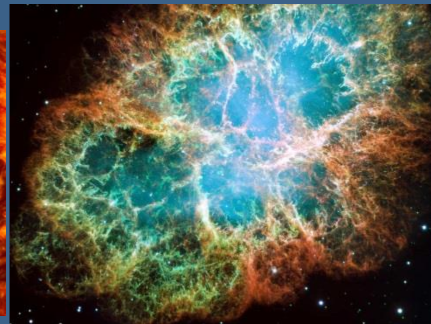
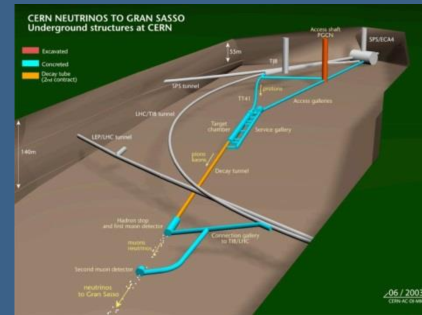
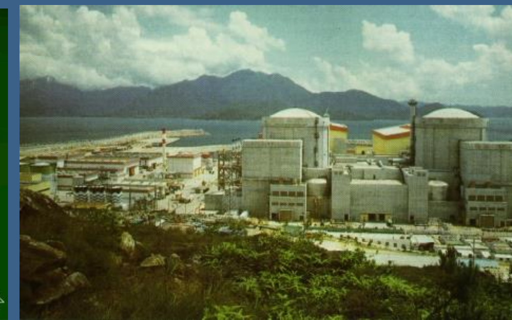
Sources of neutrinos







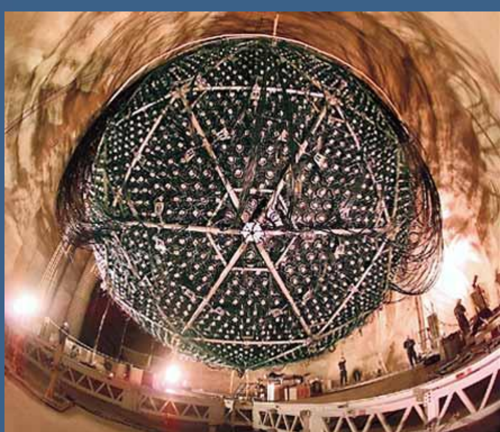
ν_e

ν_μ

Gran Sasso, Italy

ν_μ

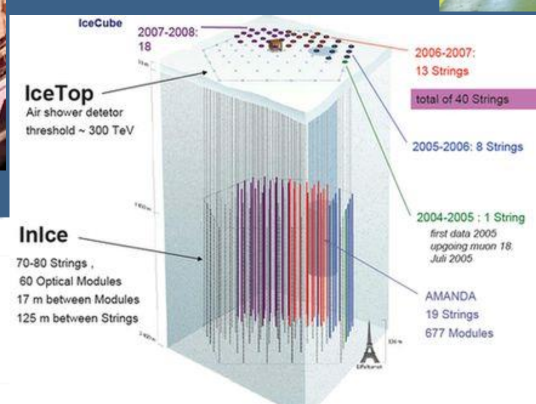
$\bar{\nu}_e$



IceCube, South Pole

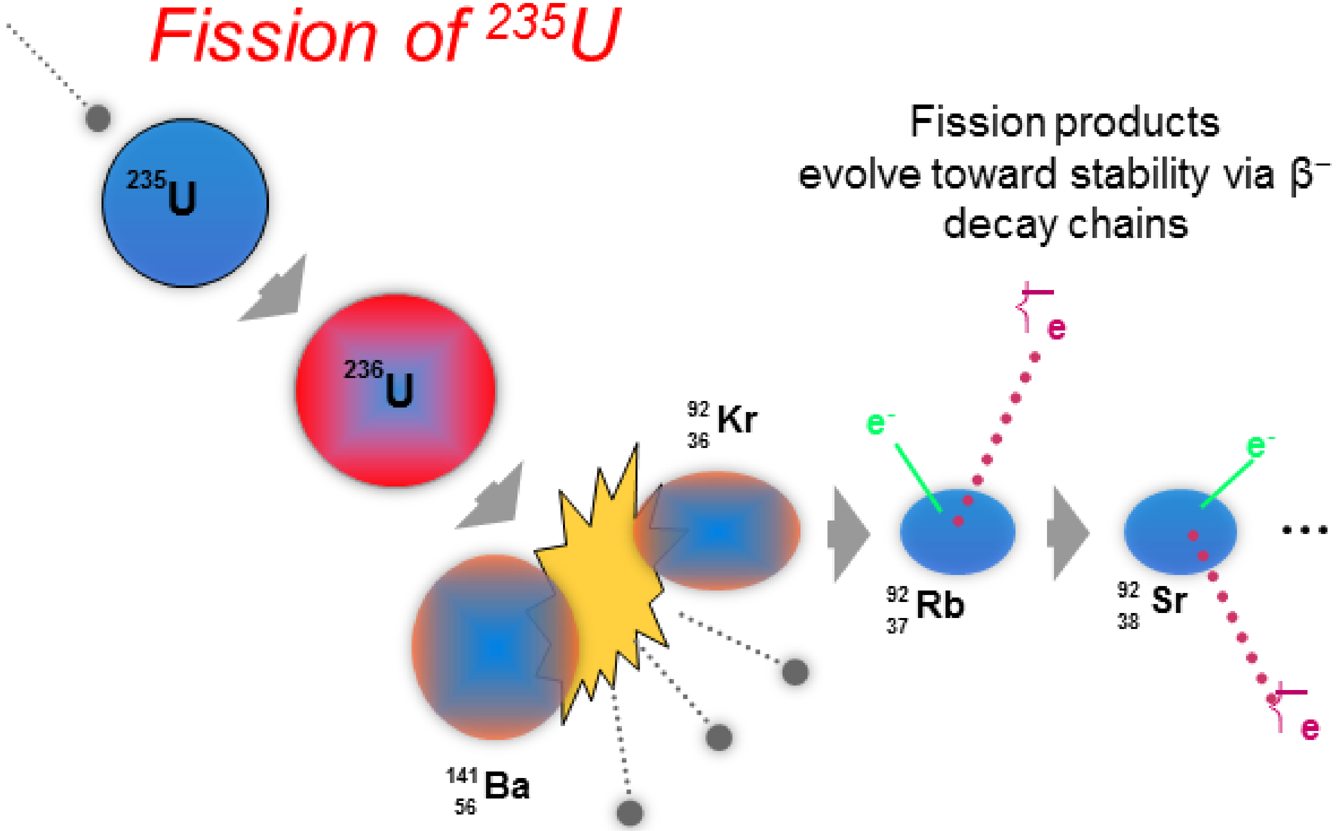
Daya Bay, China

Sudbury, Ontario



Reactor neutrinos

Fission of ^{235}U



Typical detection via
Inverse beta decay

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

$$\langle E_{PF} \rangle / fission = 201.7\, MeV$$

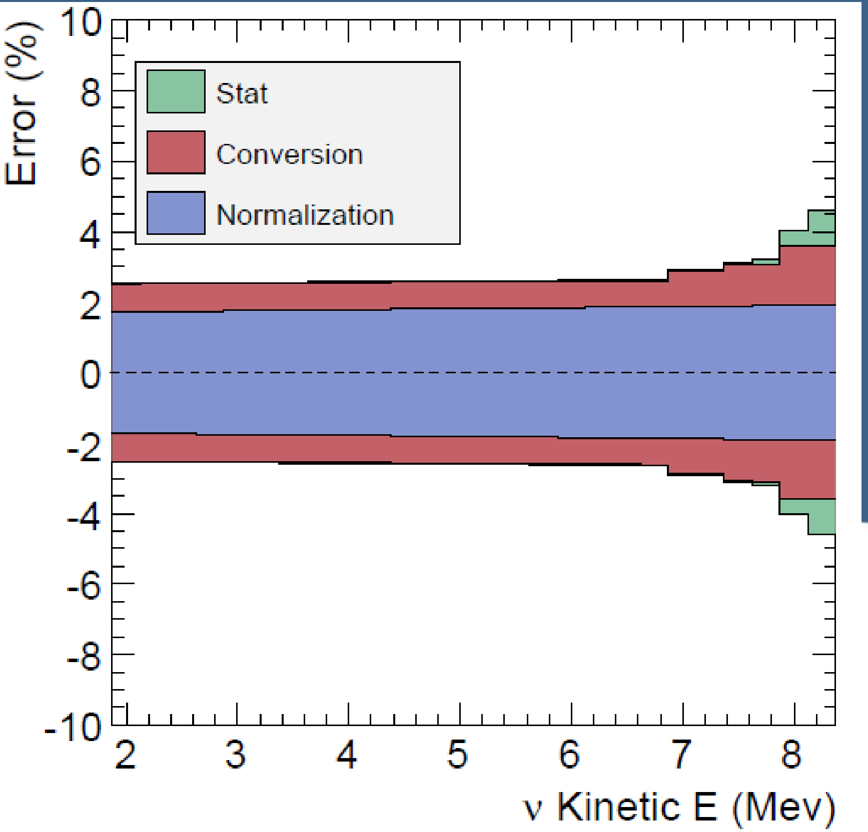
$$\langle E_{\bar{\nu}} \rangle / fission = 1.49\, MeV$$

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

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

Flux Calculations

- In preparation for Double Chooz (2011), Saclay group re-evaluated specific reactor ν_e flux for ^{235}U, ^{329}Pu, ^{241}Pu, ^{238}U
- Fission products cover hundreds of nuclei with various β decay chains each $\rightarrow$ 1000's of branches: accuracy of prediction 10-20%
- Very precise reference b spectra from ILL (Grenoble) per fissile nucleus
- Ab initio calculations fitted to ILL spectra by adding 5 fictuous β branches
- Final uncertainties are in range 2%



Anomalies and open issues

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Gallium Anomaly

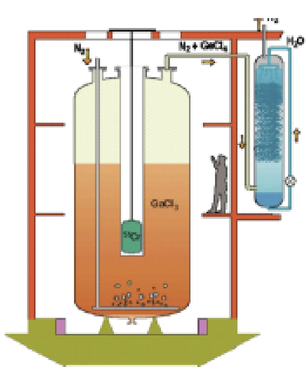
Based on Giunti & Laveder, PRD82, 053005 (2010)

Radiochemical experiments Gallex (left) & Sage (right)

GALLEX ($GaCl_3$) and SAGE (liquid Ga) were radiochemical experiments, counting the conversion rate of ^{71}Ga to ^{71}Ge by (solar) neutrino capture [cannot detect anti-ν_e]

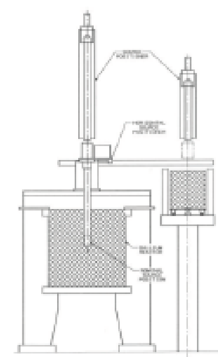
$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

GALLEX



30.3 tons of Gallium in an aqueous solution : $GaCl_3$ + HCl

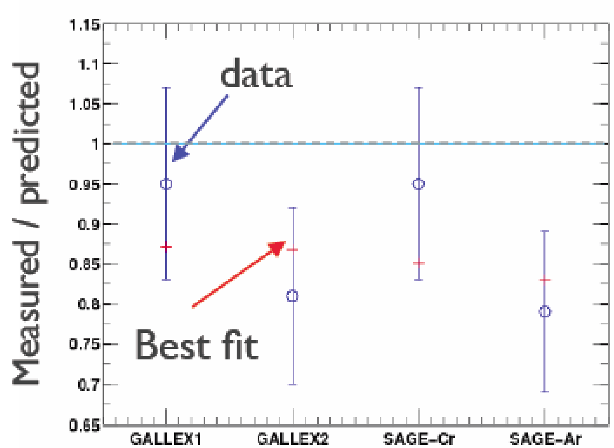
SAGE



30 to 57 tons of Gallium (metal) In 10 tanks

Calibration Data

- 2 runs at GALLEX with a ^{51}Cr source (720 keV n_e emitter)
- 1 run at SAGE with a ^{51}Cr source
- 1 run at SAGE with a ^{37}Ar source (810 keV n_e emitter)

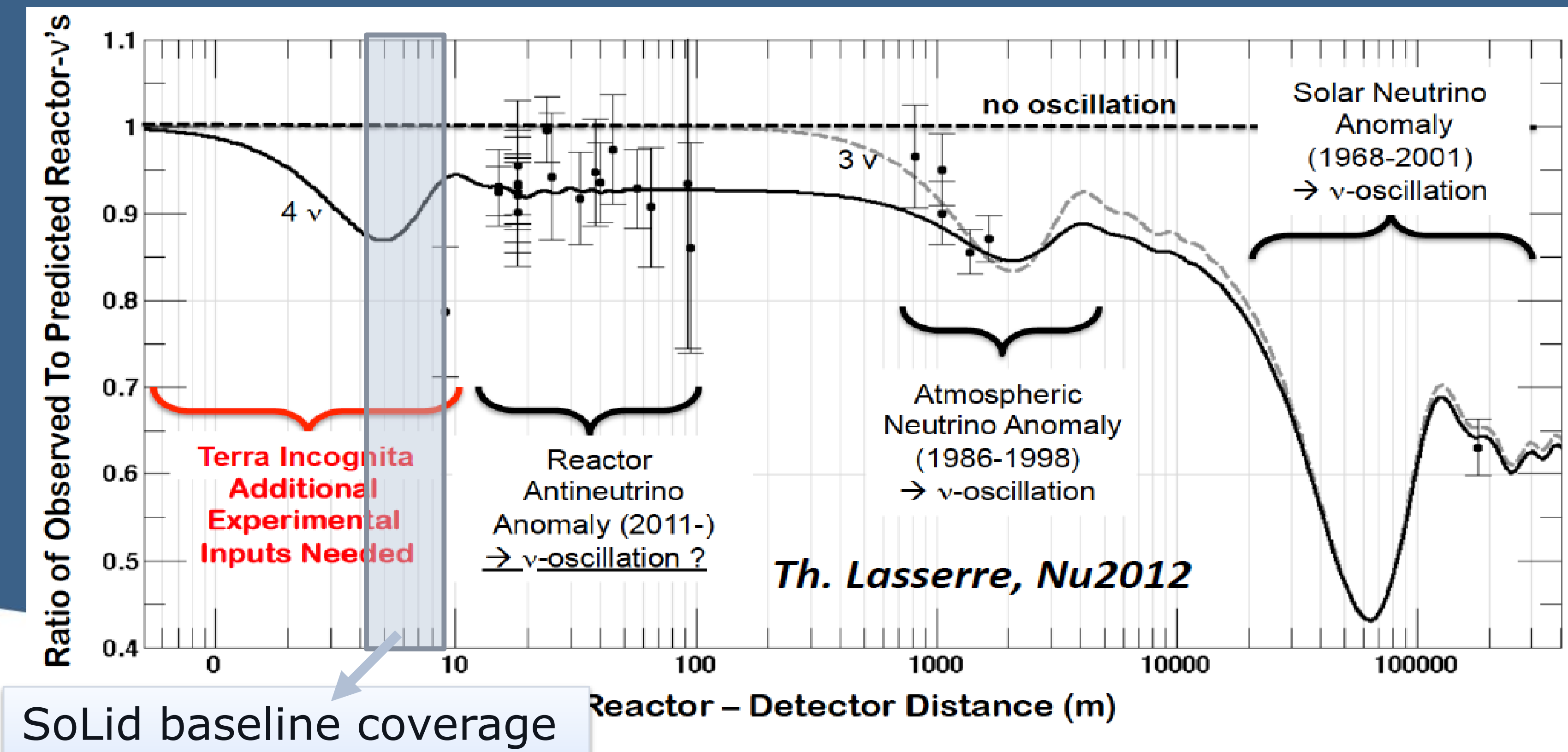


All observed a **deficit** of neutrino interactions **compared** to the **expected activity:**

R = meas./pred. rates = 0.86 ± 0.06(1 σ)

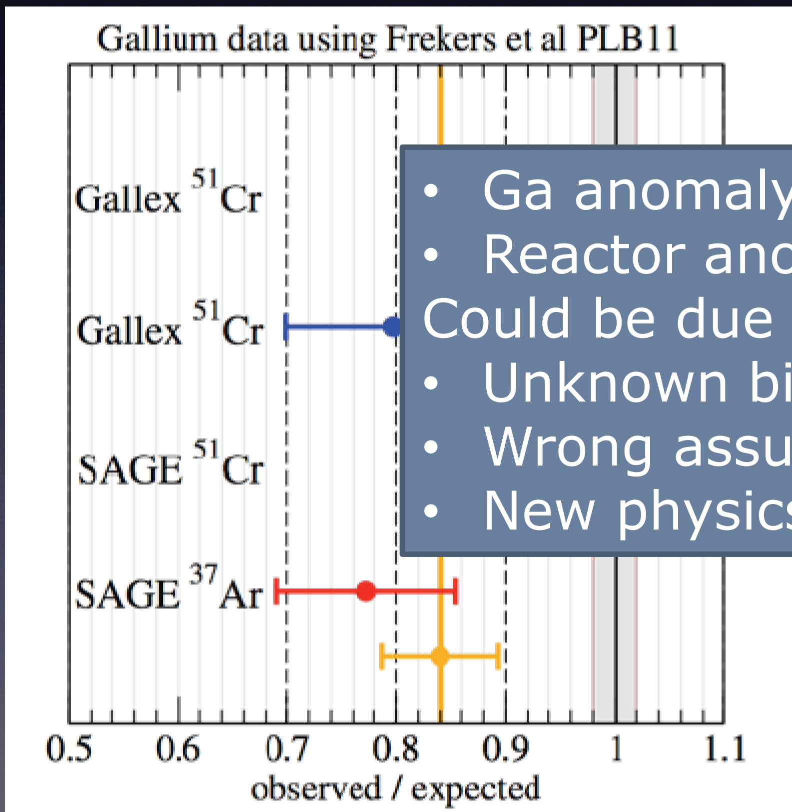
Reactor anomaly

- Reactor anomaly (Mention et al., Phys. Rev. D 83 073006 (2011))
  - Origin: Re-evaluation of reactor $\bar{\nu}_e$ flux calculations in 2011 (T.A. Mueller et al., Phys. Rev. C83, 054615 (2011).) increased the predicted rate of $\bar{\nu}_e$ for reactors
  - All short baseline reactor $\bar{\nu}_e$ rates systematically fall below new rate predictions: 6% deficit (2.7 σ)



Gallium & Reactor ν anomalies

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

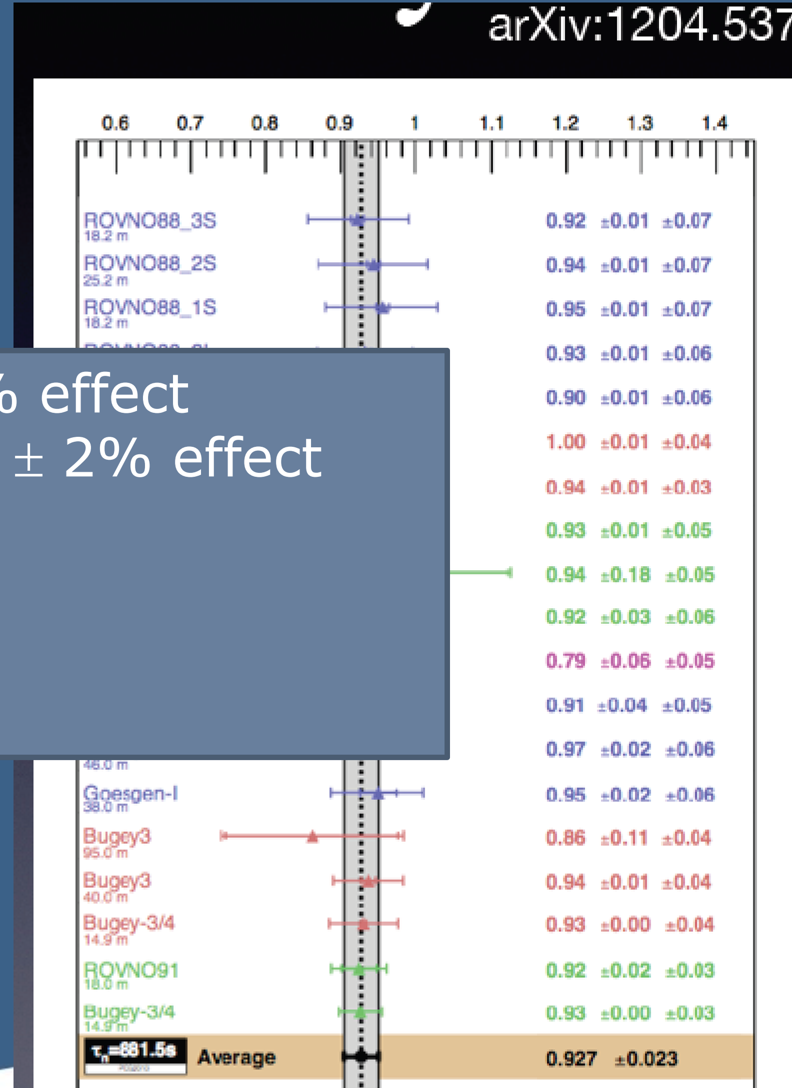


J. Kopp et al., hep/ph:1303.3011

- Ga anomaly: 14±6% effect
- Reactor anomaly: 7 ± 2% effect

Could be due to:

- Unknown biases
- Wrong assumptions
- New physics

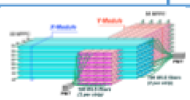
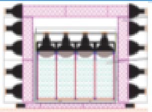
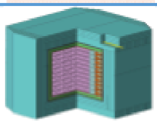
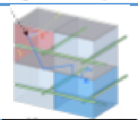
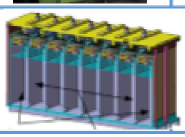


- Re-evaluation by C. Giunti & M. Laveder Phys. Rev C 83, 065504 (2011)

2011 flux reevaluation gives a net +3% shift in flux

- Th. Mueller et al. *Phys. Rev C 83, 054615 (2011)*

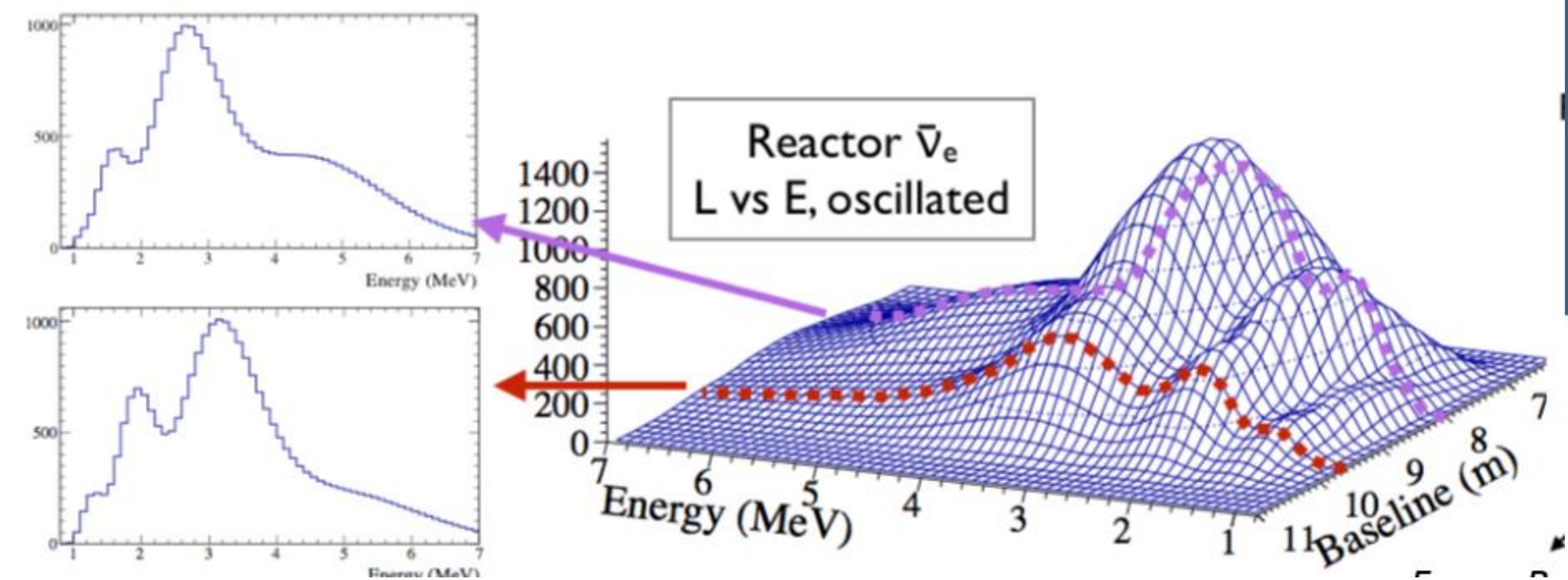
Short Baseline Reactor Experiments*

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Introduction of 1 extra(sterile) neutrino

- See eg. Kopp, Machado, Maltoni and Schwetz, JHEP05(2013)050
- Key strategy to probe new physics: Measure oscillation spectrum (in Energy and distance) over very short distances (metres) using the same source

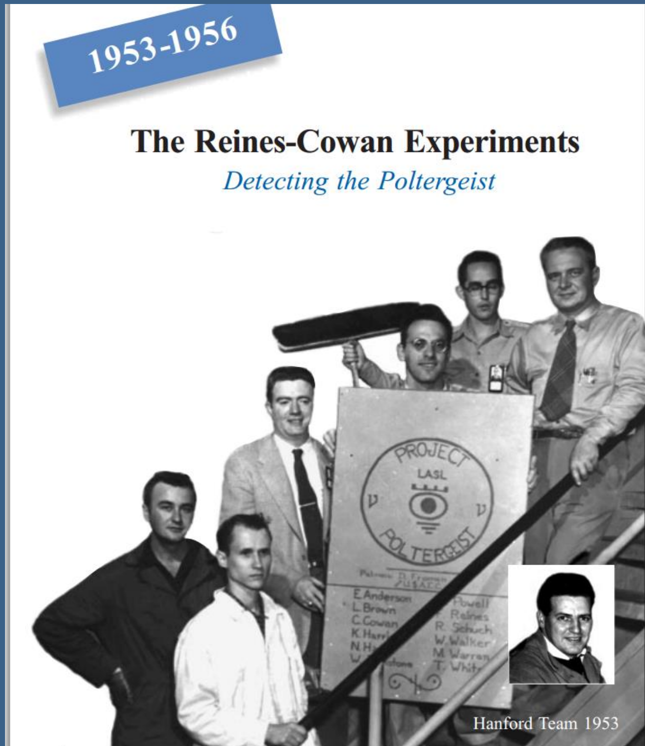
$$P_{ee}^{\mathrm{SBL},3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m_{41}^2 L}{4E}$$



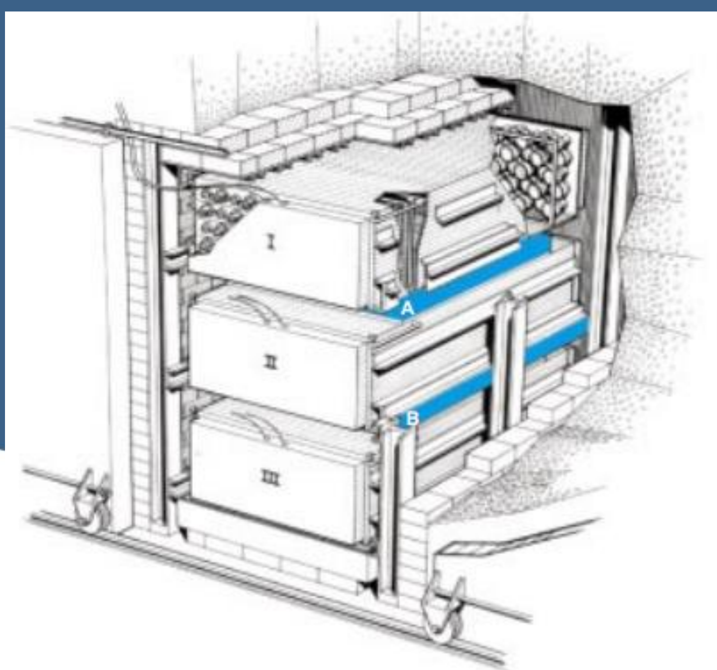
Problems with neutrino detection

- Neutrinos have no electric charge
- Interact only via weak nuclear forces
- Interaction cross sections with matter are extremely small: $\sigma_{\nu-N} \approx 10^{-10}\sigma_{e-N}$
- Detection of neutrinos at reactors needs:
  - Dense core, high thermal power, large duty cycle
  - Very low reactor induced background radiation
  - Protection from cosmic rays (deep underground)
  - Large sensitive detector mass: > 1Ton
  - Good energy resolution: O(10%) at 1 MeV
- Solar neutrino experiments: <10 events/day
- Long baseline accelerator experiments (~ 1000km): 10-30 events/kton/day

Pioneers

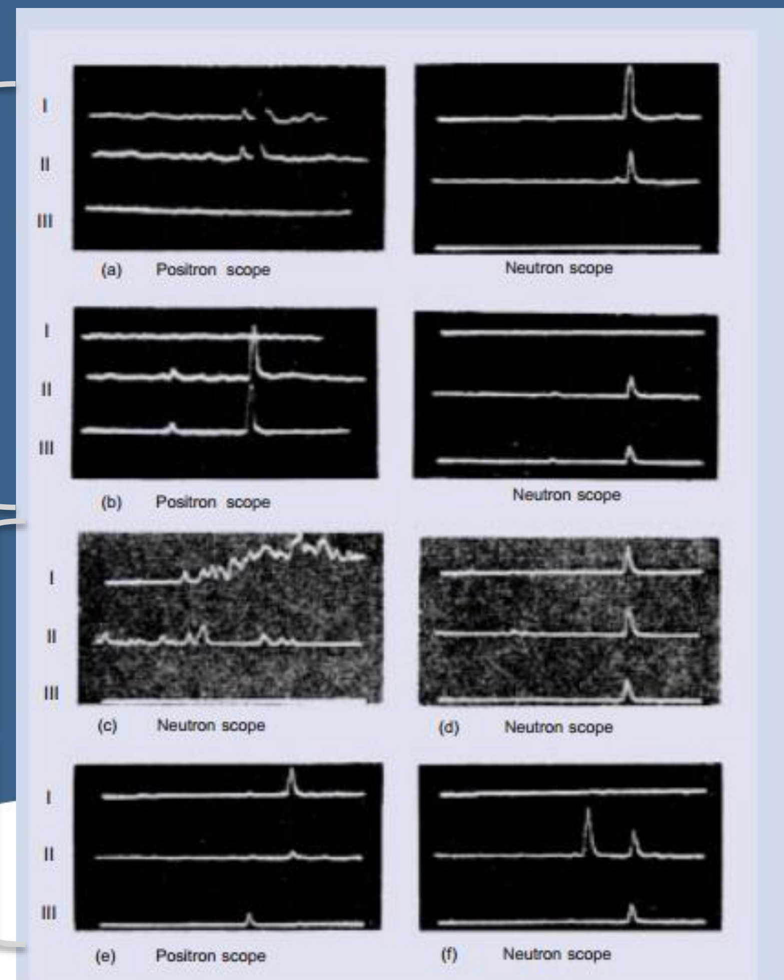


2 target tanks filled with H_2O + $CdCl_2$
Surrounded by 3 liquid scintillator detectors

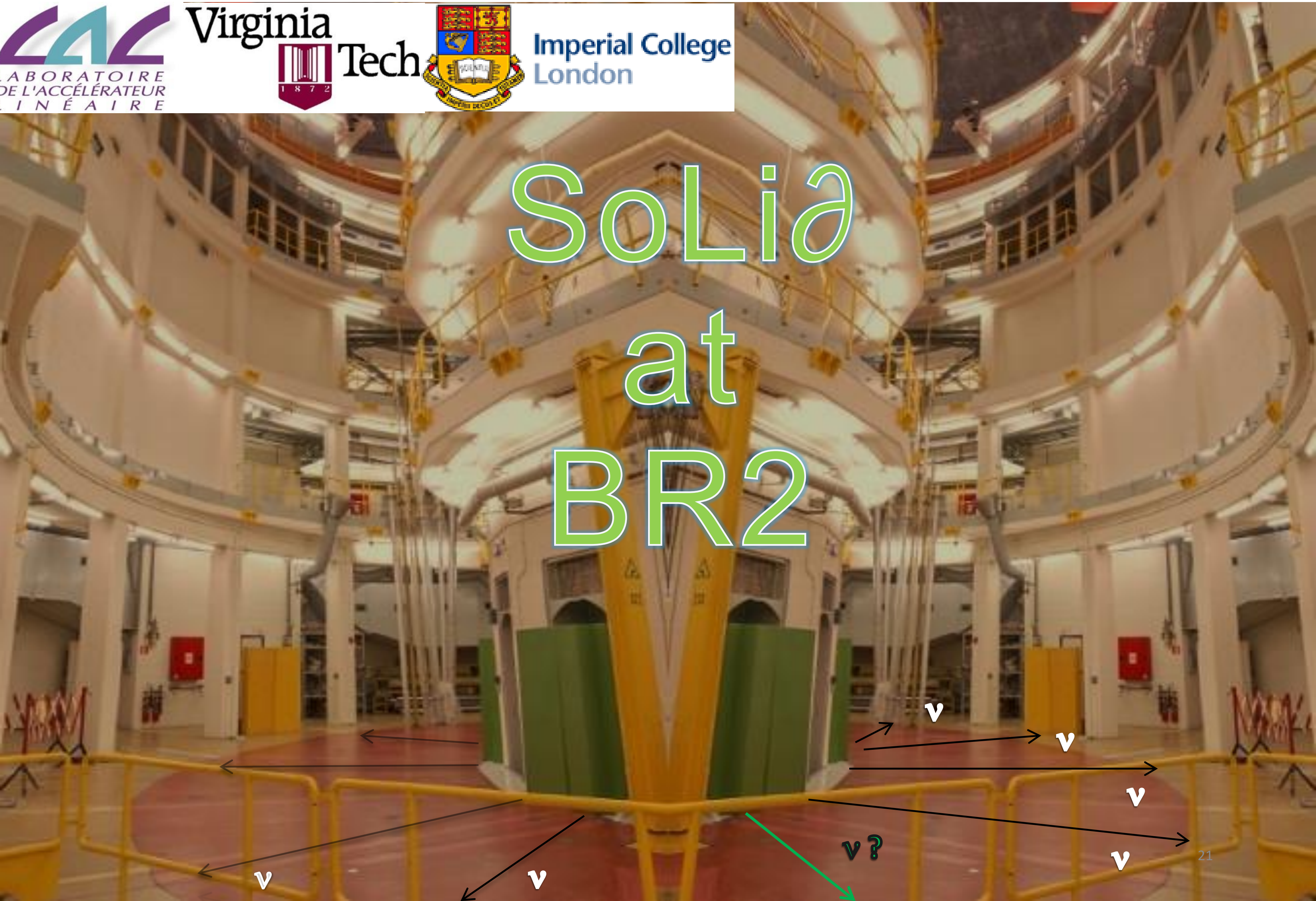


Signal

Background



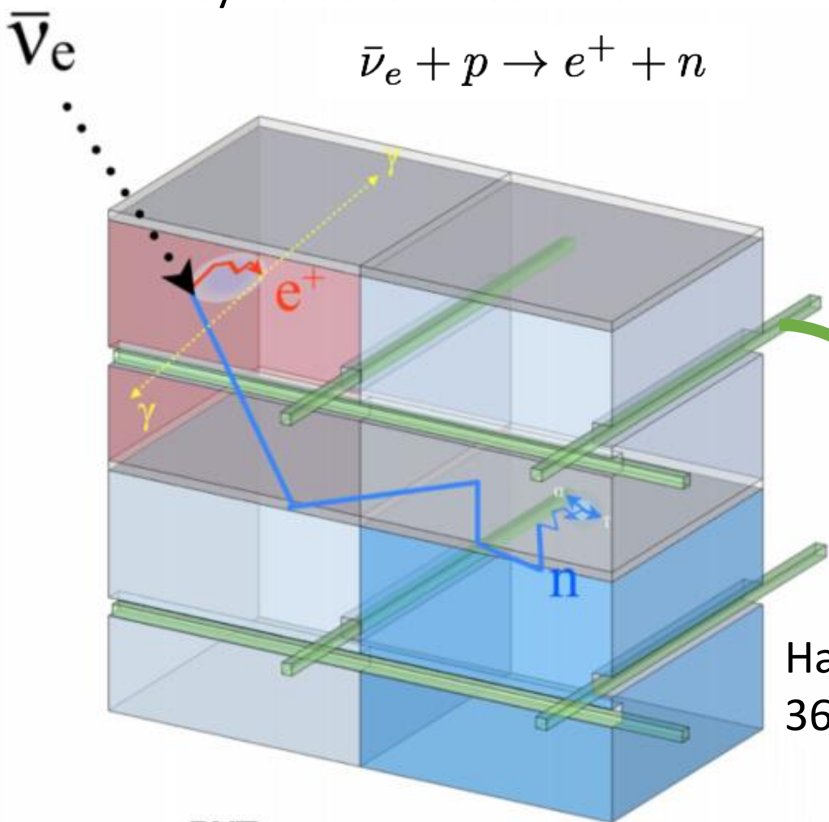
SoLi∂ at BR2

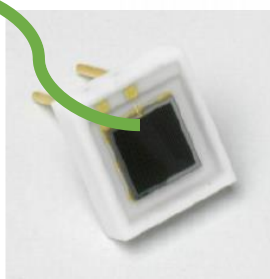


SoLid detector technolc

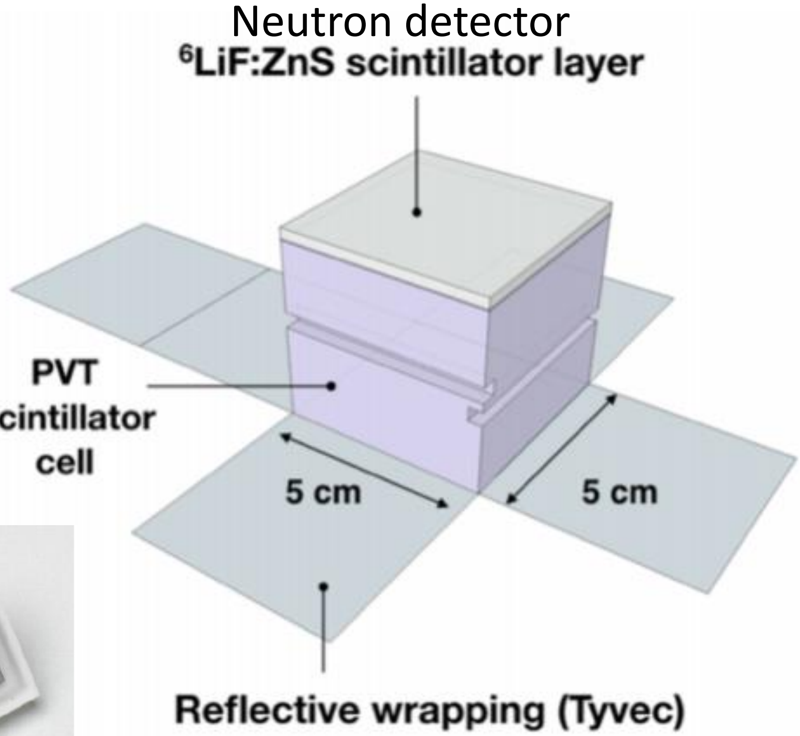
Key detection mechanism: IBD

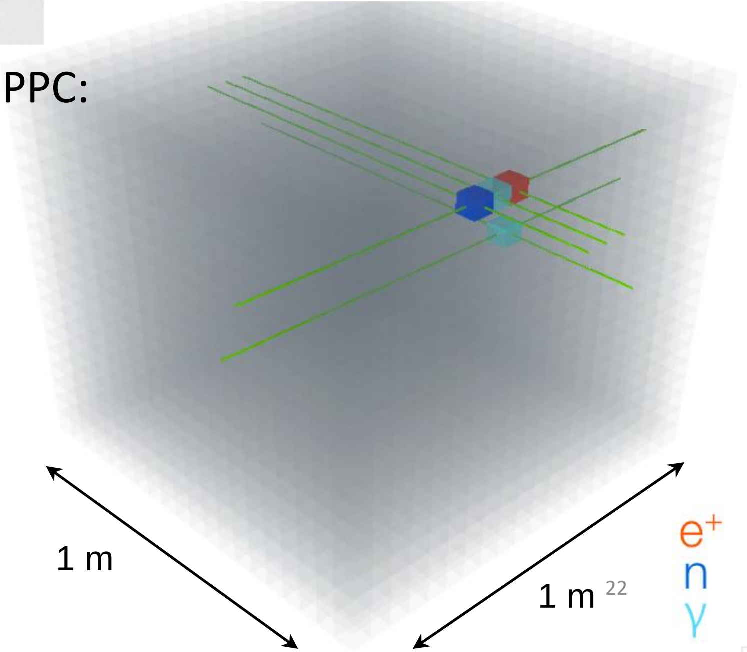
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

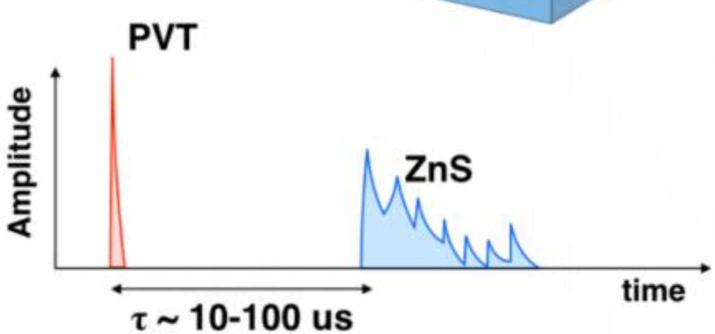




Hamamatsu MPPC:
3600 pixels

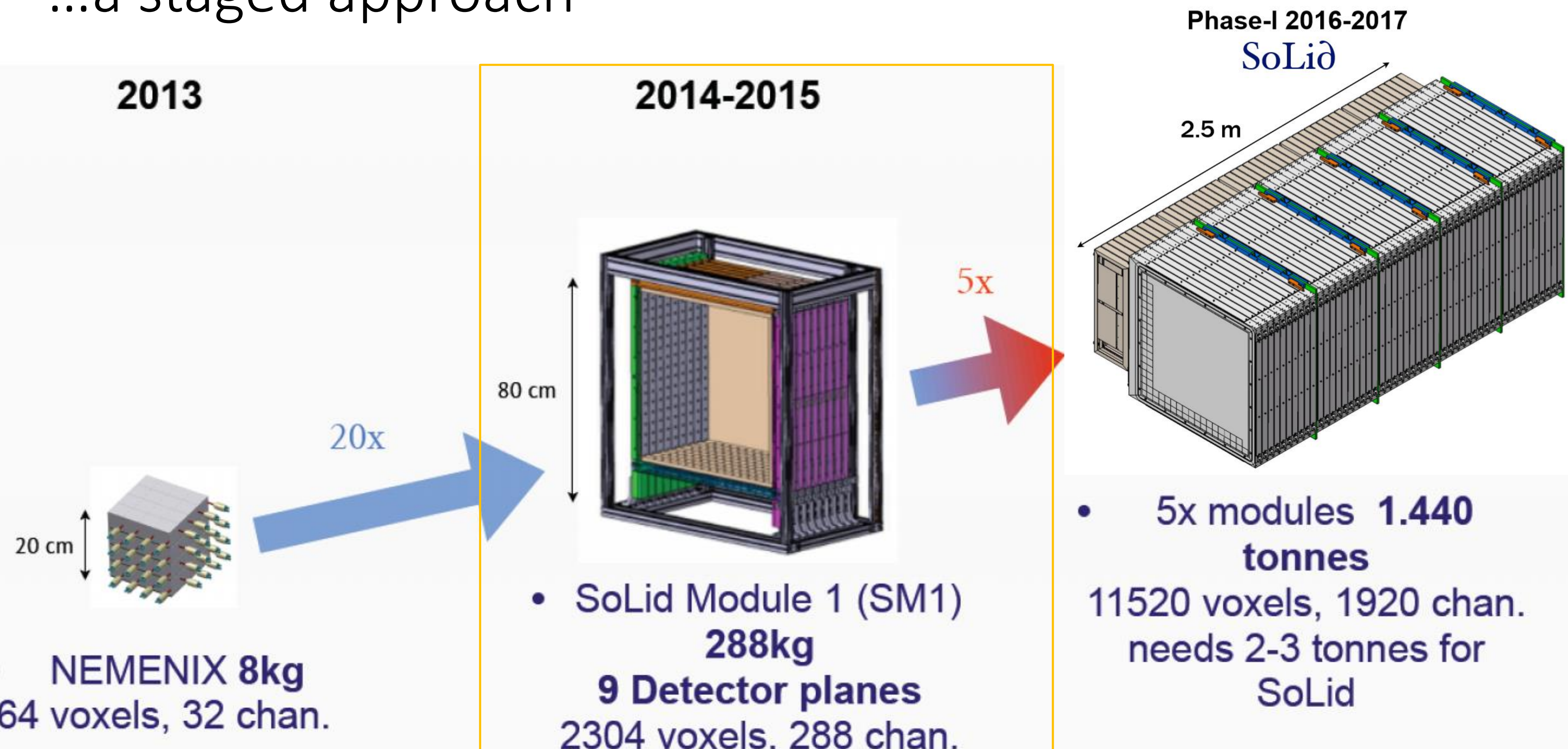






$${}^{6}_{3}Li + n \rightarrow {}^{4}_{2}He(2.05\ MeV) + {}^{3}_{1}T(2.75\ MeV)$$

Detector construction and operation …a staged approach



Proof of Concept

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

Real Scale Systems Test

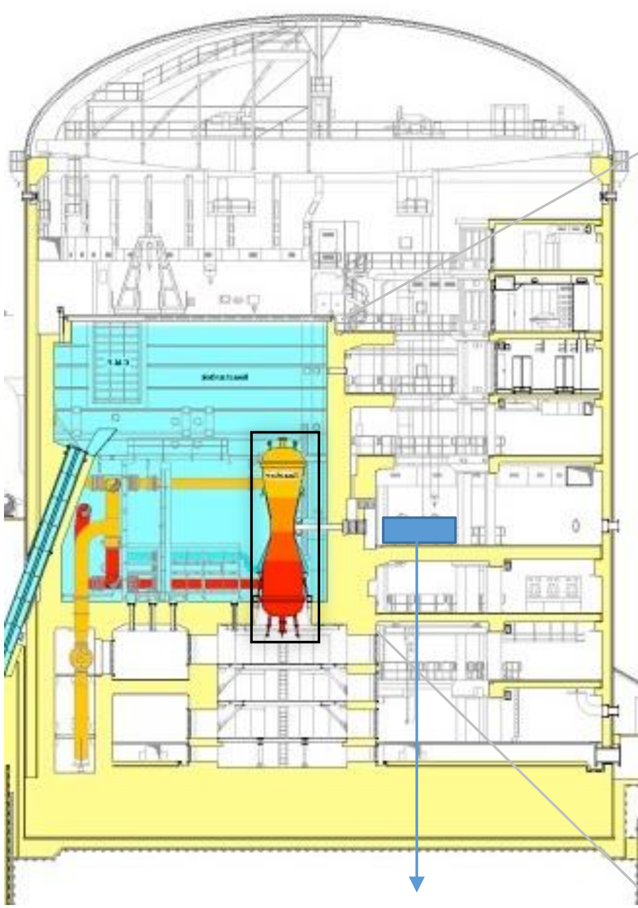
1. Demonstrate scalability
2. Test Production (schedule & procedures)
3. Demonstrate Power of Segmentation
4. Do Some Physics (?)

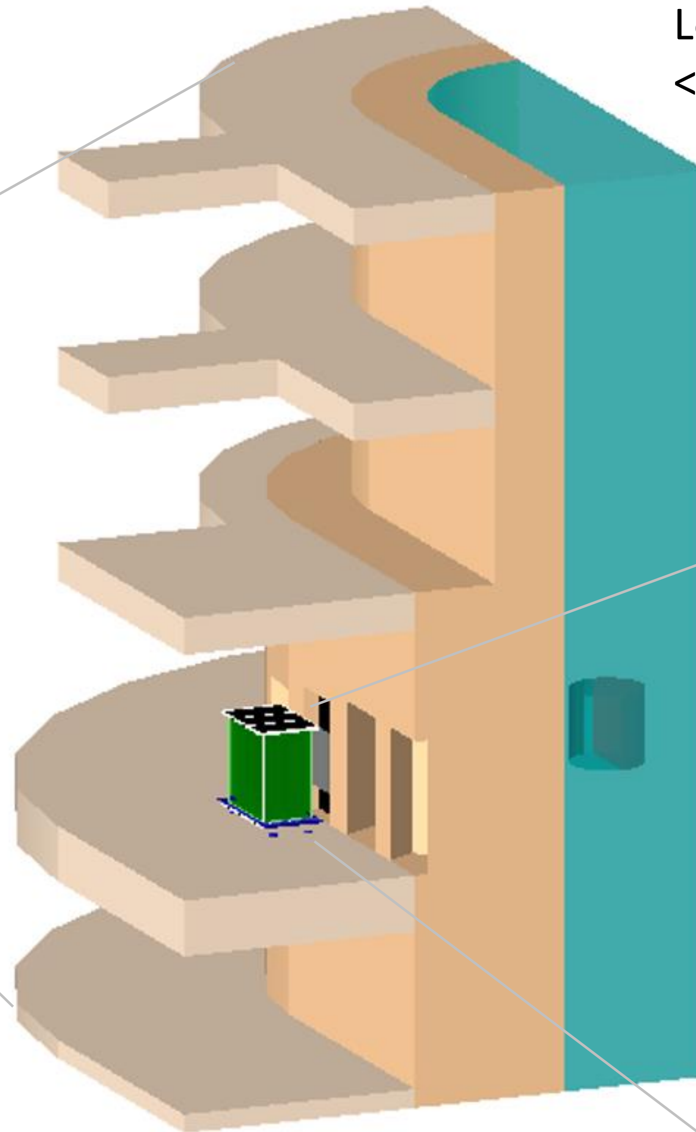
Physics Scale Detector

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

Belgian Reactor 2 (BR2)@ SCK•CEN

BR2 Confinement building





Low vertical overburden
< 10m WE

SM1:
Full scale module
300 kg
2300 voxels

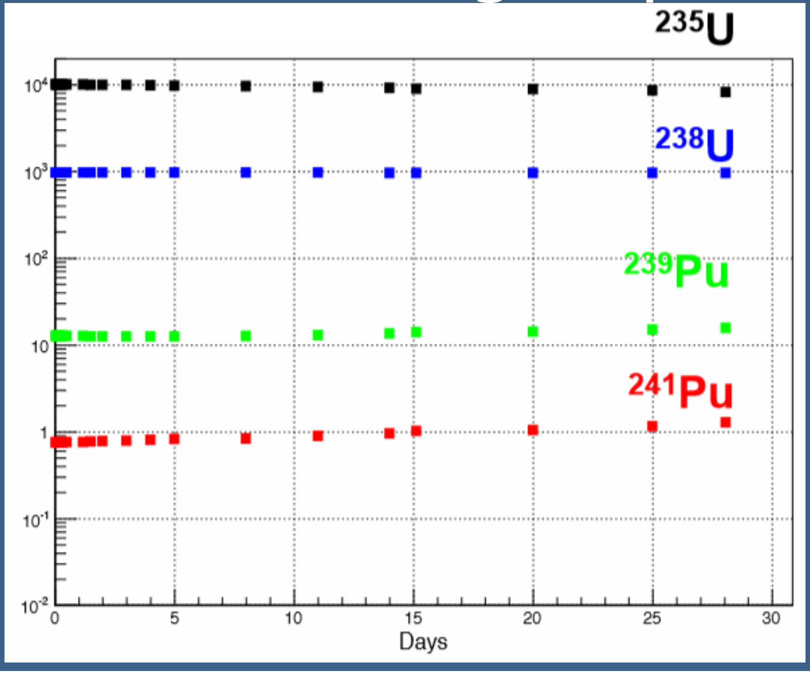
SoLid $\bar{\nu}_e$detector:

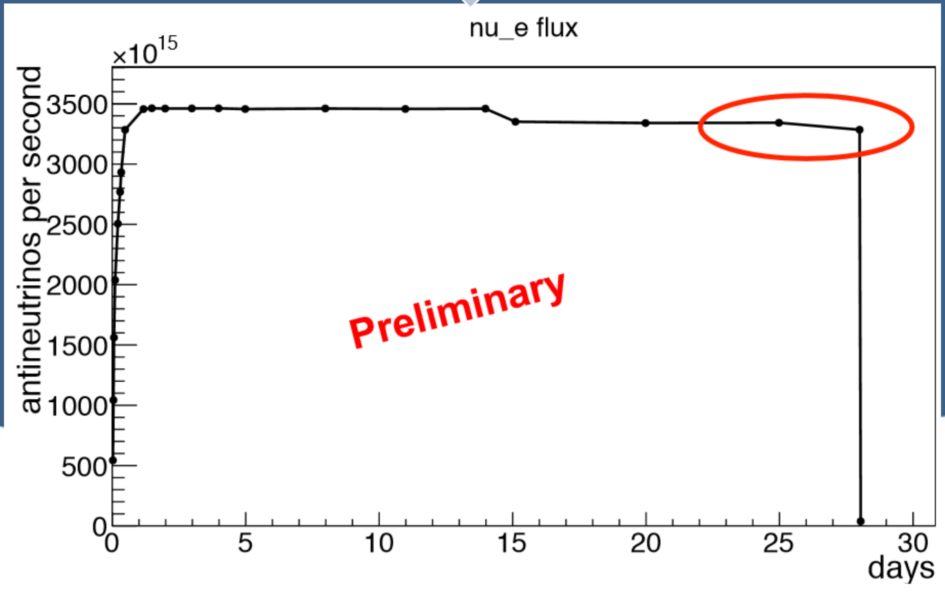
- 1.5 T fiducial
- Baseline: 5.5 – 12m
- On-axis with reactor core

Predictions from BR2/SoLid reactor group

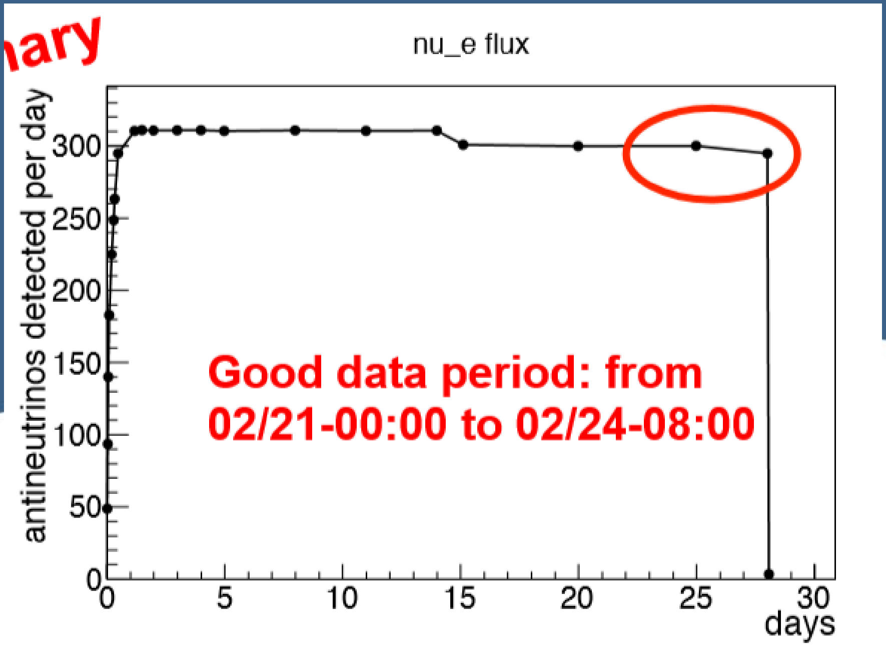
S. Kalcheva (SCK/BR2)
M. Fallot & L. Giot (SUBATECH, Nantes)

BR2 operating in 2015
at 60 MWth
With 1 SoLid module of 388 kg
At 6m





Good data period: from 02/21-00:00 to 02/24-08:00



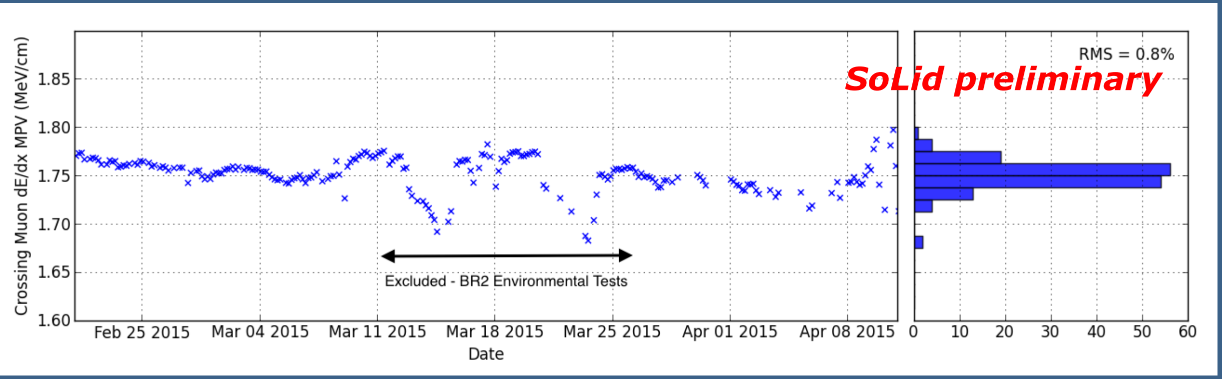
SM1 results

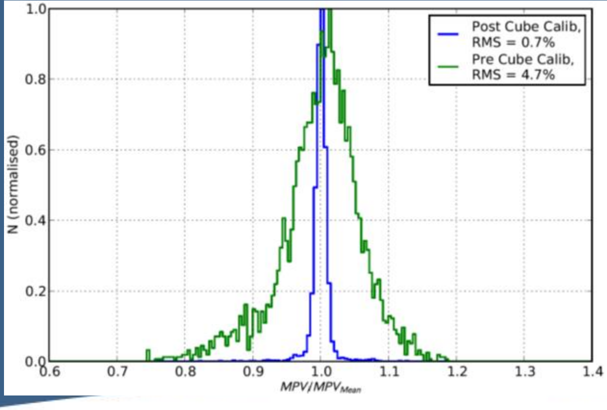
Datataking and operations

	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

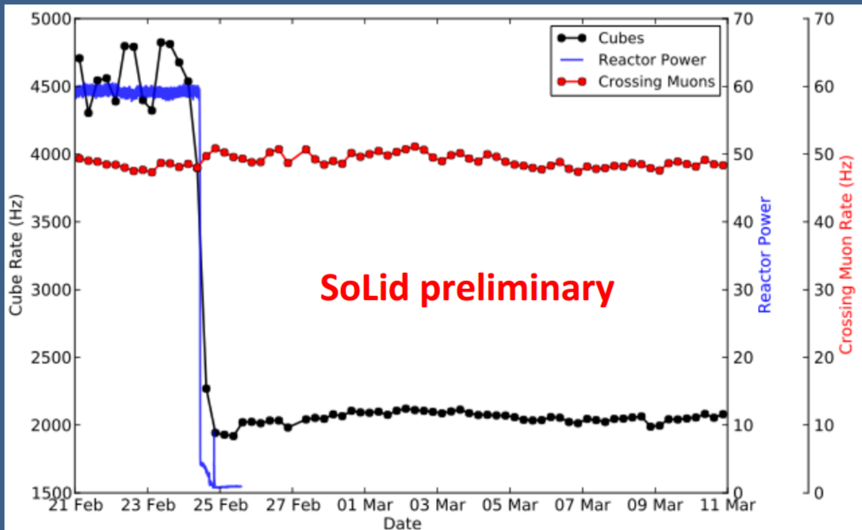
Energy response very uniform & very stable over time



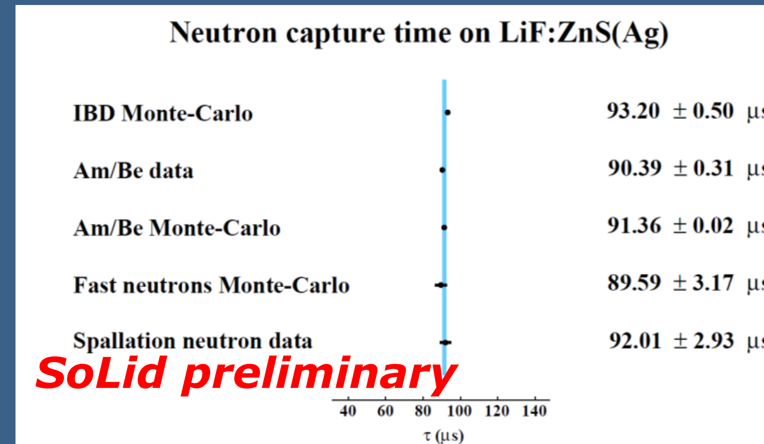


SM1 results

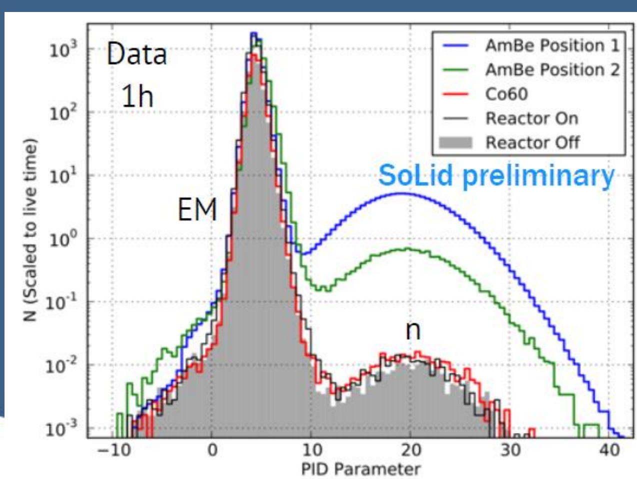
Stable Em rates, following reactor power



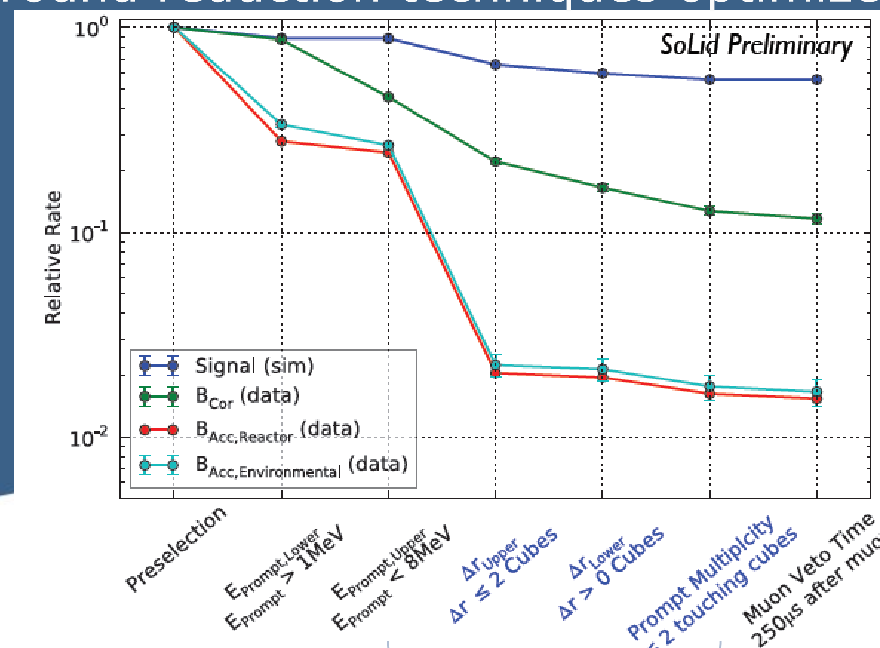
Neutron capture times well understood



Neutron signals separated from EM radiation



Background reduction techniques optimized



Unique for SoLid

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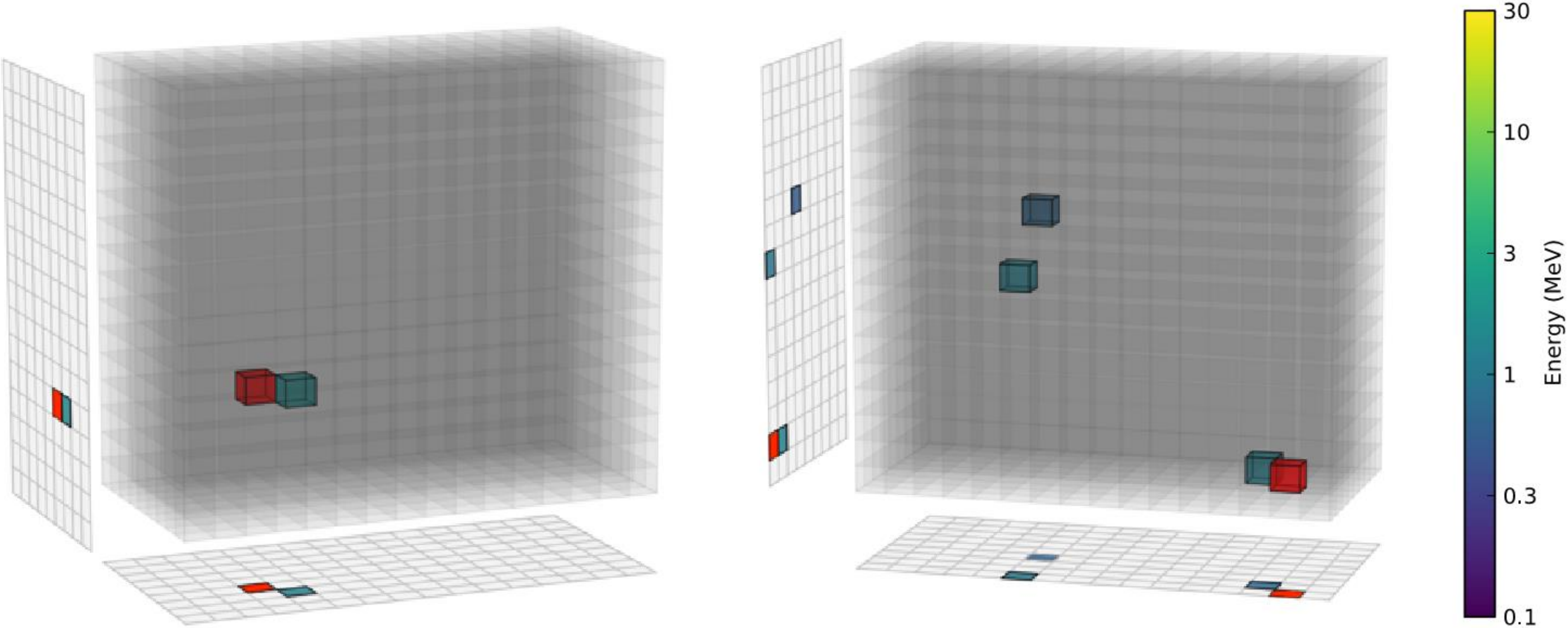
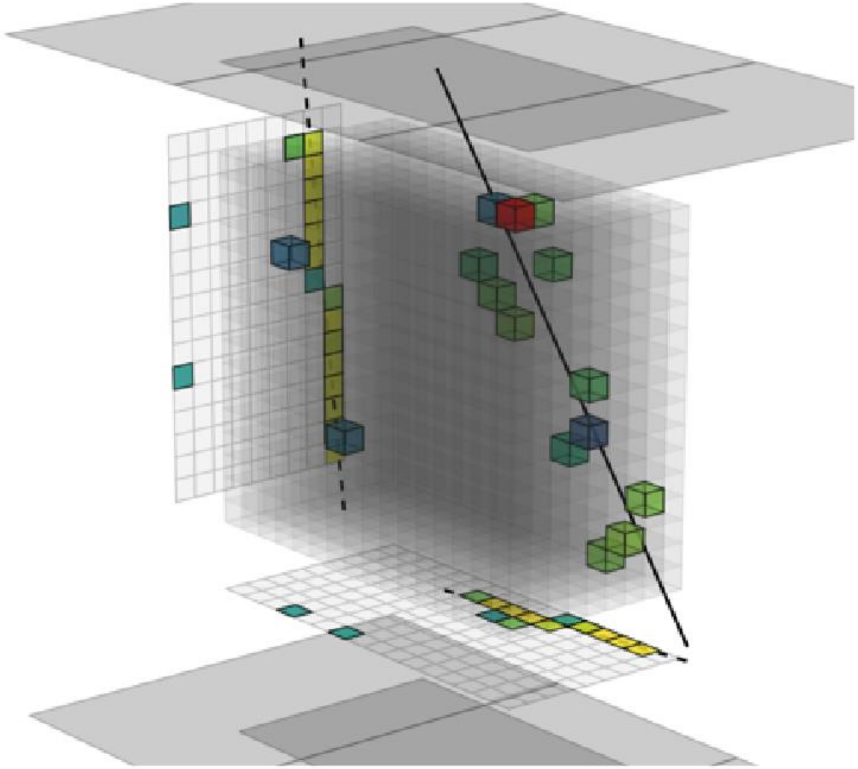
Anti neutrino candidates

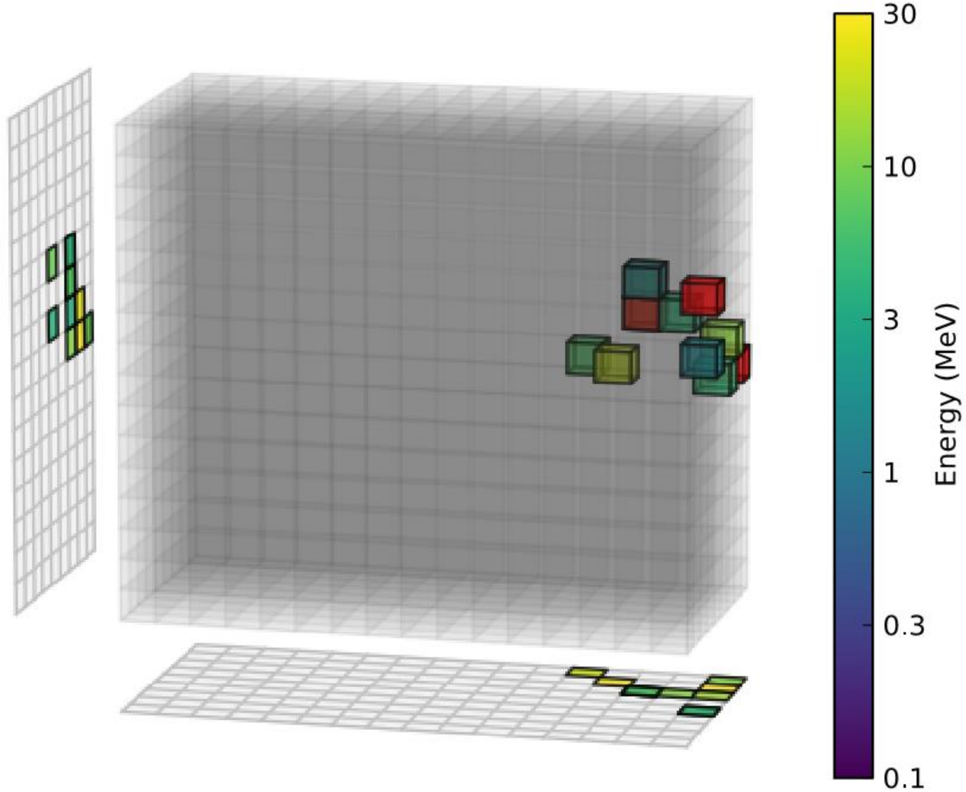


Backgrounds

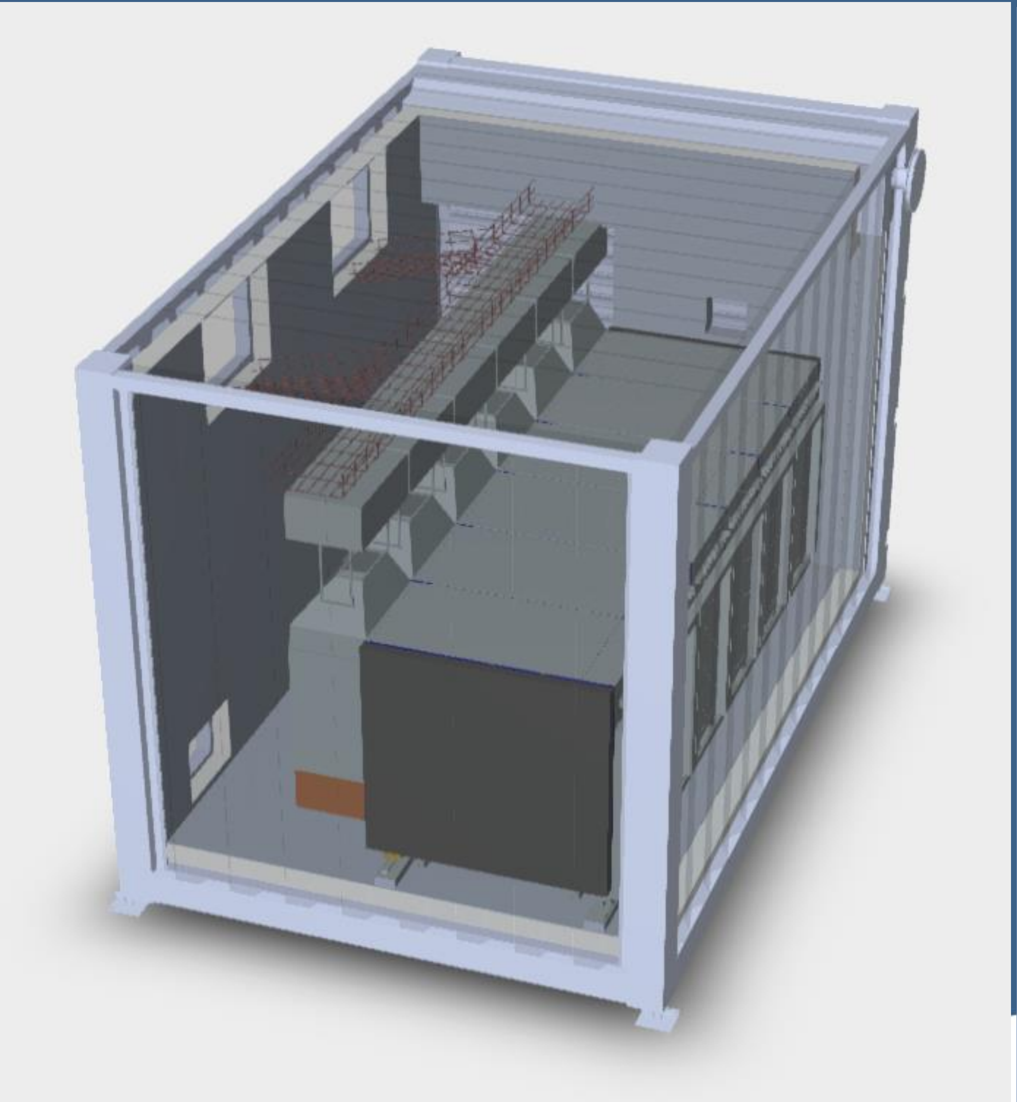
Cosmic ray muon



Fast neutron with recoils



Towards Phase 1: 1.5 Ton by spring 2017



Implemented design changes to:

- Operate at lower energy tresholds: higher efficiency
- Cool down detector: Lower thermal noise in sensors
- Double Li content: better signal efficiency
- Dedicated neutron triggers: Keep data volume low at high efficiency
- Water shielding: reduce cosmic background

Construction started in phased approach

- 2T plastic scintillator being processed by Flemish industry
- First modules ready by Feb-March 2017
- Provide precise measurement of ^{235}U $\bar{\nu}_e$ spectrum by fall 2017
-

Long term perspectives

- Complement SoLid with 1m3 HiRES (6% σ_E/E) CHANDLER near-detector module developed by Virginia Tech
- 8x8x5 voxel module currently under construction


Thank You!

Backup

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Oscillation of matter waves

- Quantum mechanics principle of superposition: weak eigenstates are superposition of mass eigenstates (mixing)

$$\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

Weak eigenstates

Mixing matrix

Mass eigenstates

Assume that ν_1 and ν_2 have different masses

Oscillation of matter waves

- Schrödinger equation: propagation of matter waves

$$|\nu_1(t)\rangle = e^{iE_1 t}\ |\nu_1(0)\rangle$$
$$|\nu_2(t)\rangle = e^{iE_2 t}\ |\nu_2(0)\rangle$$

If ν_1 and ν_2 have different masses (energies $E_{1,2}$) they propagate with different phase velocities

Admixture of neutrino species after time t

$$\begin{pmatrix} |\nu_\mu(t)\rangle \\ |\nu_\tau(t)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{iE_1 t} & 0 \\ 0 & e^{iE_2 t} \end{pmatrix} \begin{pmatrix} |\nu_1(0)\rangle \\ |\nu_2(0)\rangle \end{pmatrix}$$

$$\begin{pmatrix} |\nu_\mu(t)\rangle \\ |\nu_\tau(t)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{iE_1 t} & 0 \\ 0 & e^{iE_2 t} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\mu(0)\rangle \\ |\nu_\tau(0)\rangle \end{pmatrix}$$

Oscillation patterns

Oscillation of a pure source of 1 MeV reactor $\bar{\nu}_e$

Dominant pattern due to $\bar{\nu}_\mu, \bar{\nu}_\tau \leftrightarrow \bar{\nu}_e$ oscillation

$\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ oscillate in phase.

Oscillation length:

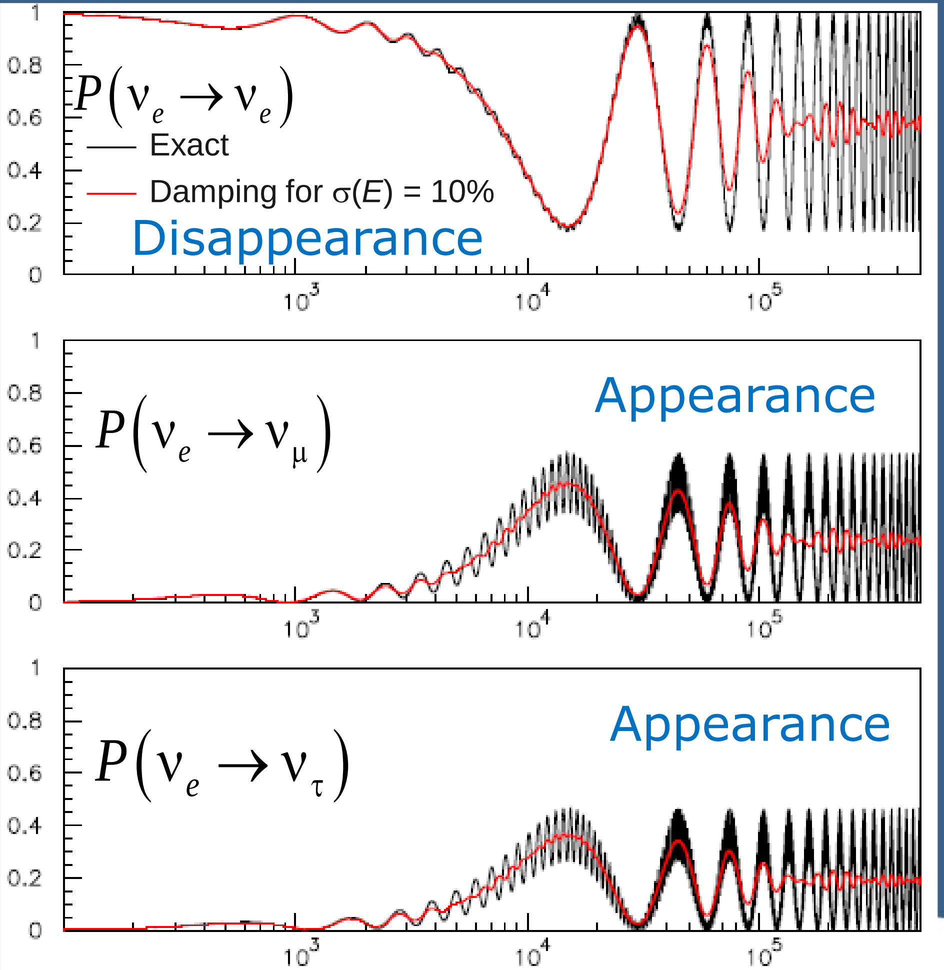
$$L_{osc}\left[m\right] = \frac{\pi}{1.27}\frac{E\left[MeV\right]}{\Delta m_{12}^2\left[eV^2\right]} \approx 2.47\frac{1}{7.5\cdot 10^{-5}} \approx 30\,000\,m$$

Subdominant pattern from $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$ oscillation

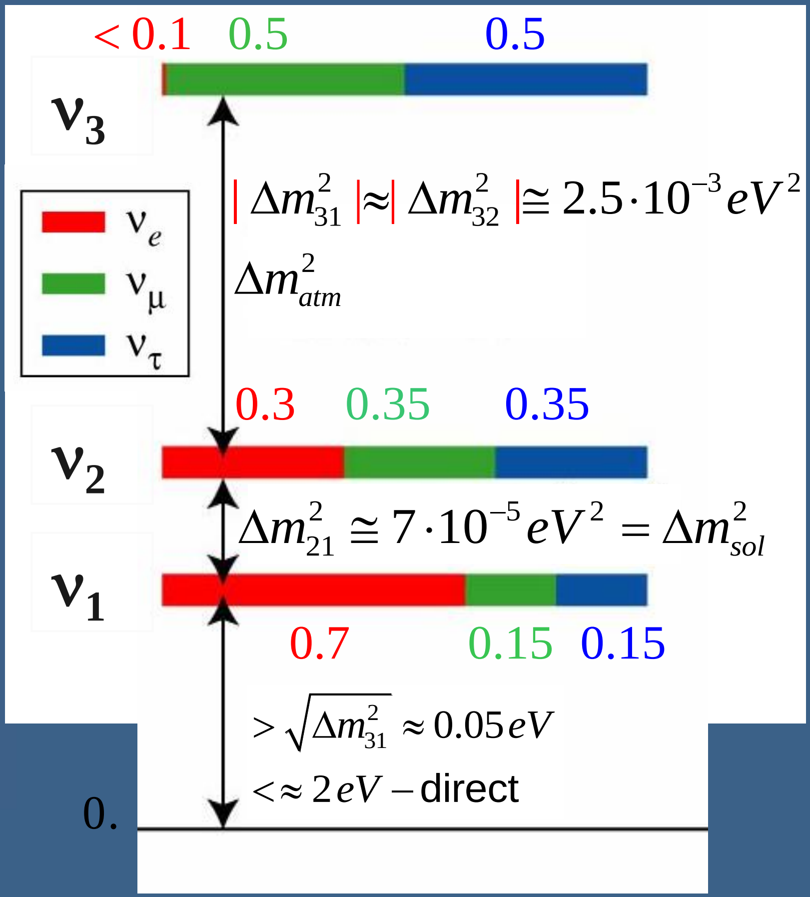
$\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ oscillate out of phase.

Oscillation length:

$$L_{osc}\left[m\right] = \frac{\pi}{1.27}\frac{E\left[MeV\right]}{\Delta m_{23}^2\left[eV^2\right]} \approx 2.47\frac{1.}{2.5\cdot 10^{-3}} \approx 1\,000\,m$$



Results from decades of measurements



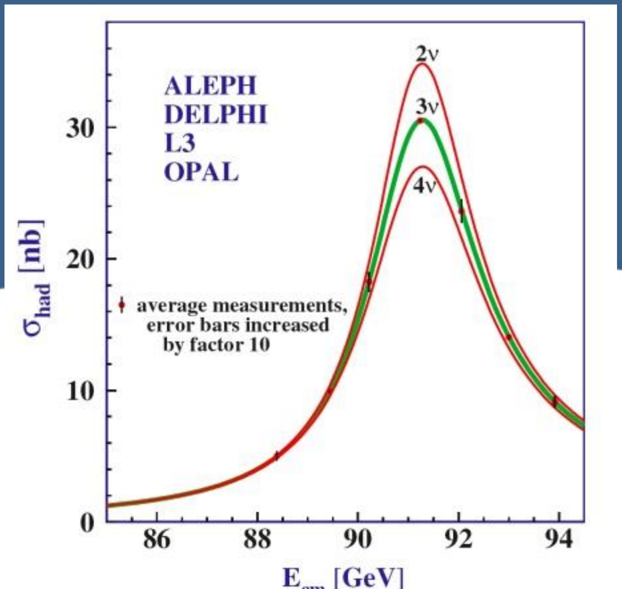
Elements of mixing matrix $|U_{jk}|^2$
Measured from oscillation amplitudes

Mass differences $\Delta m_{jk}{}^2$ measured from oscillation periods

Absolute masses are unknown from Oscillation experiments
Measurement from b-decay, mostly Tritium

$$m_{eff,ve}{}^2 = \sum_{k=1,3} |U_{ek}|^2 m_k{}^2$$

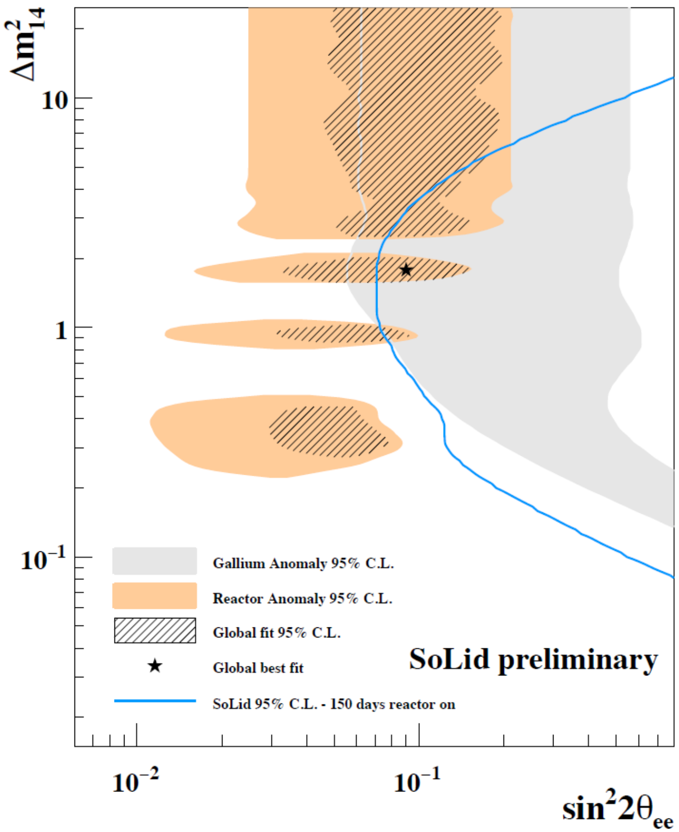
From precision measurements of Z-boson decay
At LEP accelerator:
Exactly 3 species of light+interacting neutrinos



Introduction of 1 extra(sterile) neutrino

- See eg. Kopp, Machado, Maltoni and Schwetz, JHEP05(2013)050
- Key strategy to probe new physics: Measure oscillation spectrum (in Energy and distance) over very short distances (metres) using the same source

$$P_{ee}^{\mathrm{SBL},3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m_{41}^2 L}{4E}$$



Necessary requirements to probe these parameters

- Reactor and reactor facilities:
  - Power * duty cycle $\propto$ integrated neutrino flux
  - Fuel: Simple composition, HE ^{235}U preferred
  - Compact core: effective diameter <1m
  - Detector-to-core distance: 1m – 10m
  - Low Reactor background: accidental rate
  - Large overburden or effective shielding: cosmic or cosmic induced bg
- Antineutrino detector:
  - Target mass and acceptance: >1T on-axis with reactor core
  - High $\bar{\nu}_e$ detection efficiency
  - Position and energy resolution: Δ(x,y,z)=O(cm), $\sigma_E/E<15\%/\sqrt{E}$