New neutrino roles

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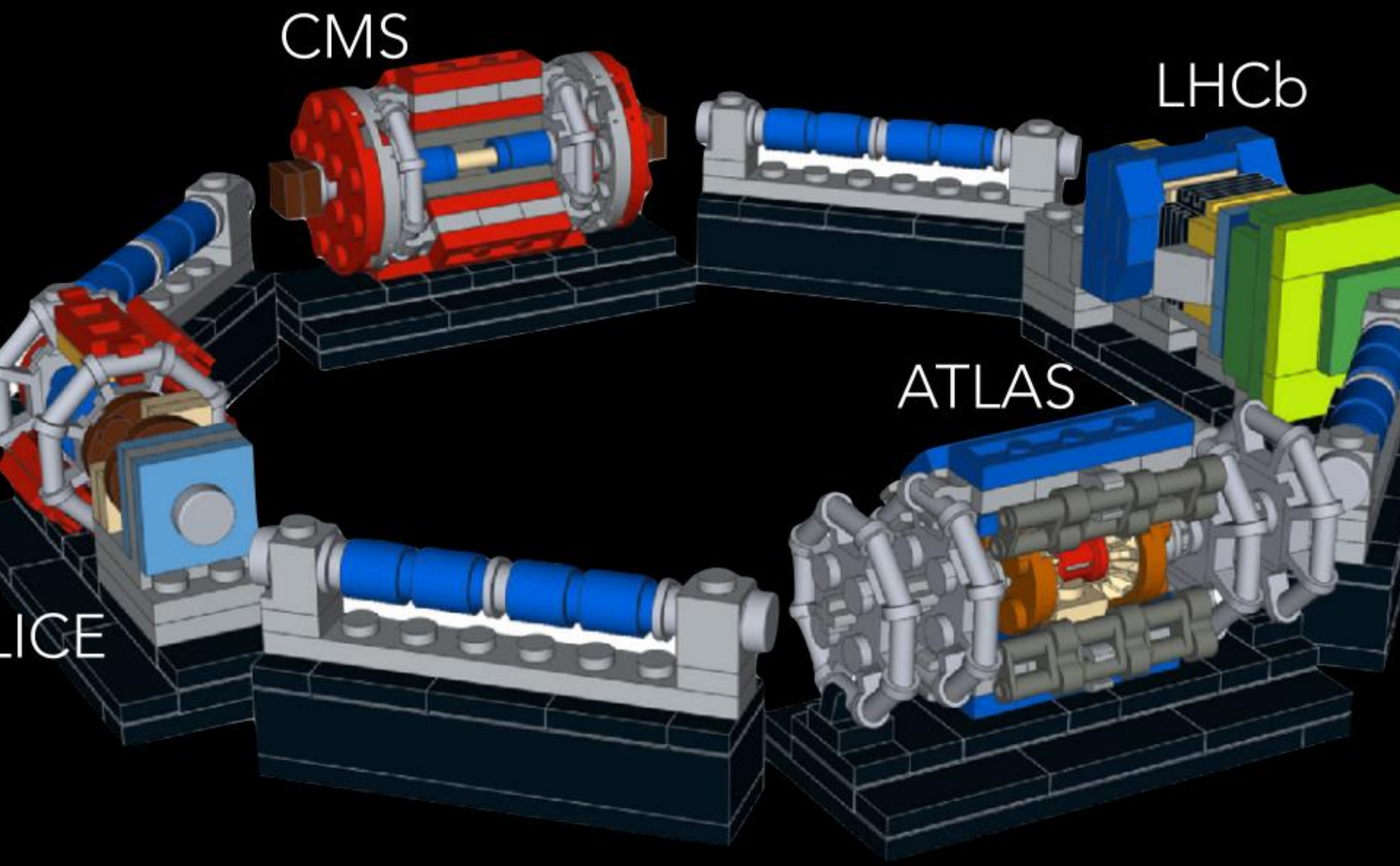
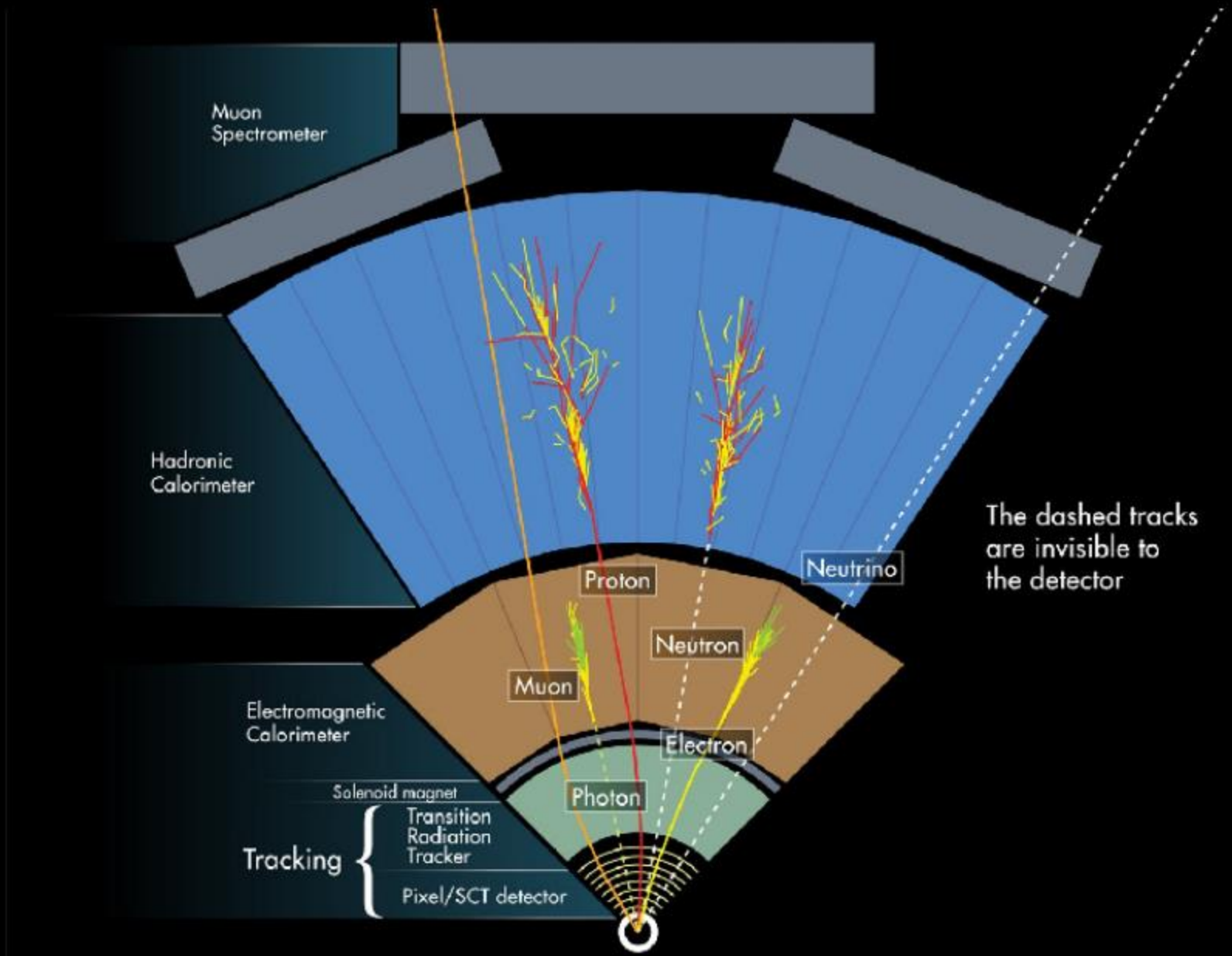
ACT IV: EW MEASUREMENTS @ LHC



All experiments participating, including LHCb

This talk focuses on ATLAS & CMS, which are most similar

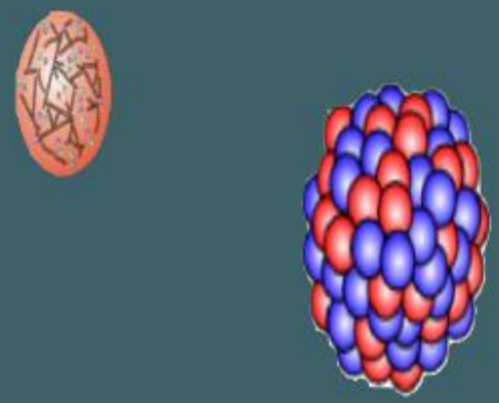
MEASUREMENTS IN ATLAS



COLLISIONS IN RUNS 1 & 2

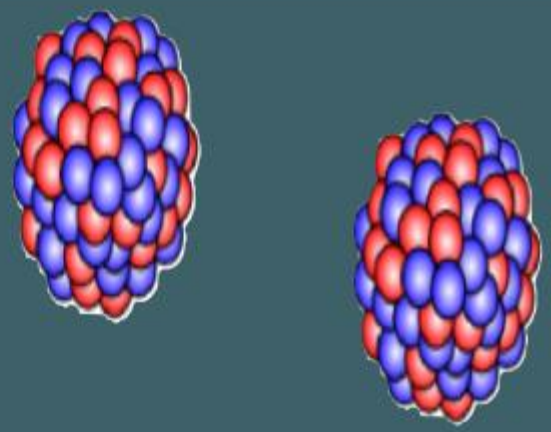
p+p

900 GeV (2009)
2.76 TeV (2013)
5.02 TeV (2015)
7 TeV (2010-11)
8 TeV (2012)
13 TeV (2015)



p+Pb

5.02 TeV (2012-13)
8.16 TeV (2016)



Pb+Pb

2.76 TeV (2010-11
5.02 TeV (2015)

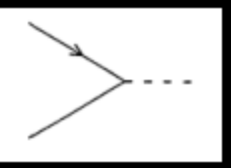
EVERY PB+PB & P+PB RUN HAS "REFERENCE" P+P RUN

On the SM

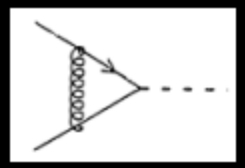
- The SM does not explain neutrino oscillation, dark matter and baryon asymmetry of the Universe.
- LHC discovered BEH boson and nothing new else.
- Now the SM is roughly completed experimentally.

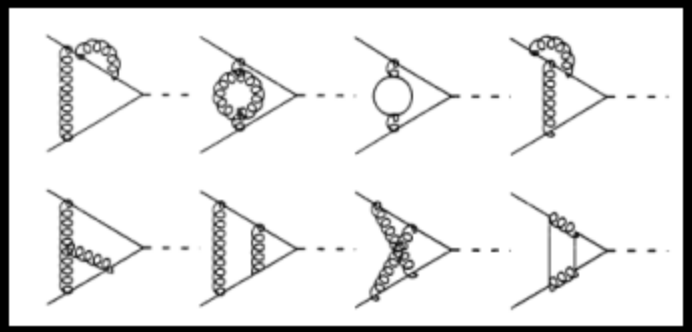
CORRECTIONS TO ELECTROWEAK PRODUCTION

LO



NLO

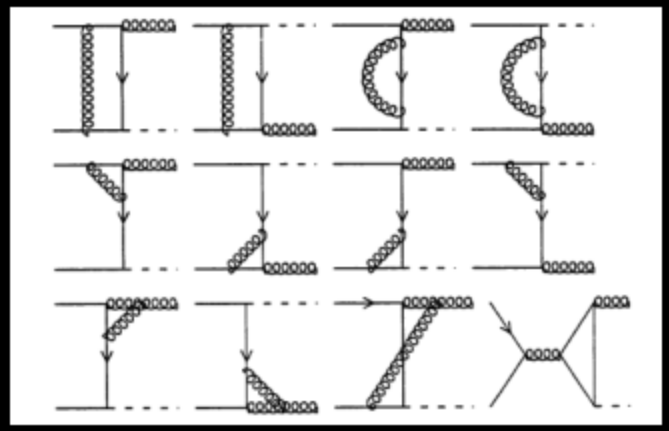




NNLO

W/Z/γ-on

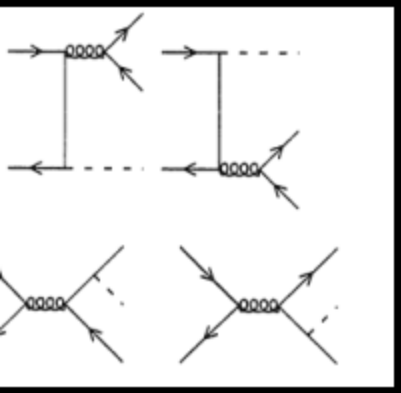
NLO



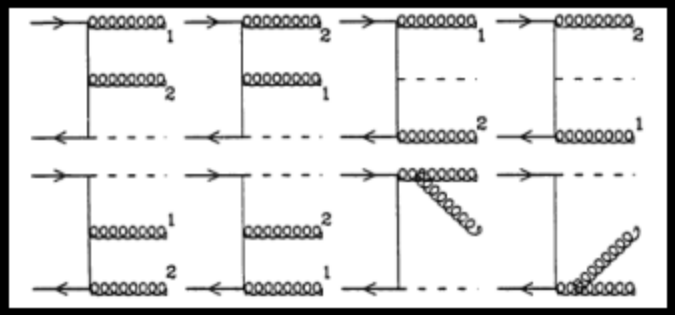
NNLO

W/Z/γ+jet

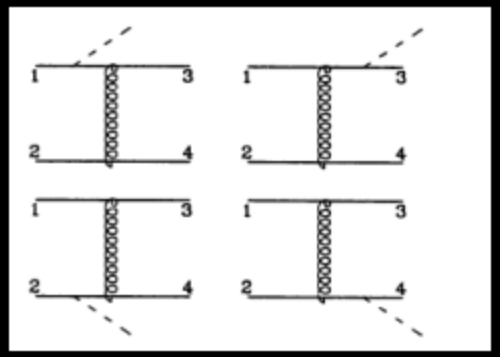
NNLO



NNLO



NNLO



W/Z/γ
+2-jet

The QCD corrections get complicated quickly

Introduction

$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly	
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry	
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates	$R_{D^{(*)}}$
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$	
$2-3\sigma$	anomaly in $B \to K^*\mu^+\mu^-$ angular distributions	P_5'
$2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result	
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$	R_K
$\sim 2.5\sigma$	non-zero $h \to \tau\mu$	

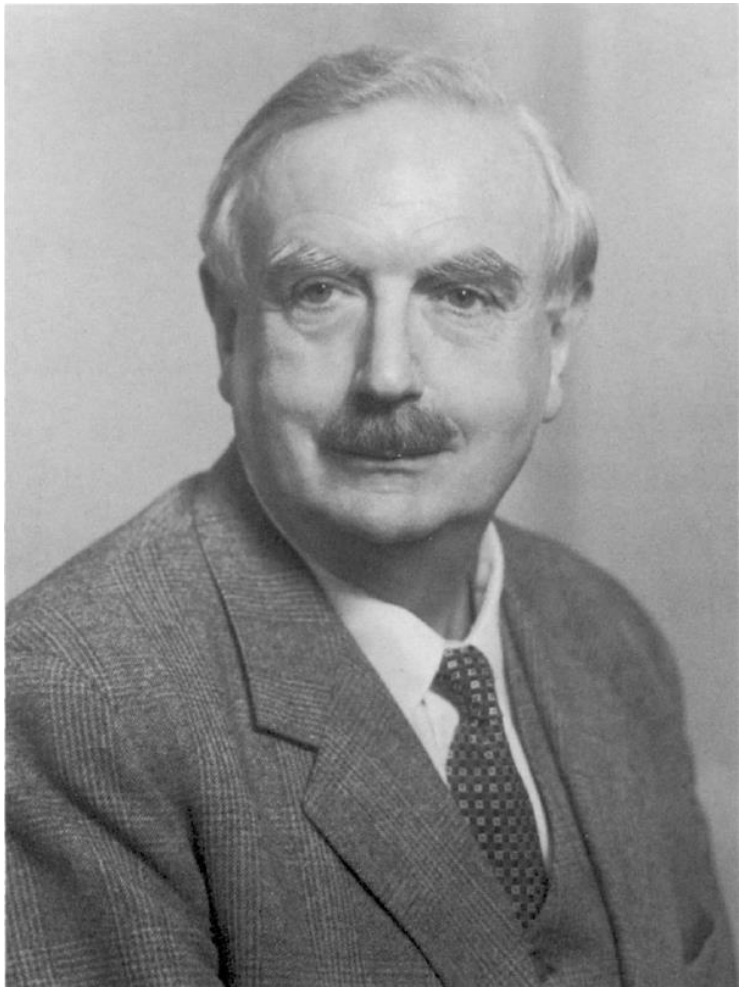
(Wolfgang Altmannshofer, Aspen Winter Conference on Particle Physics 2016)

What to do now ?

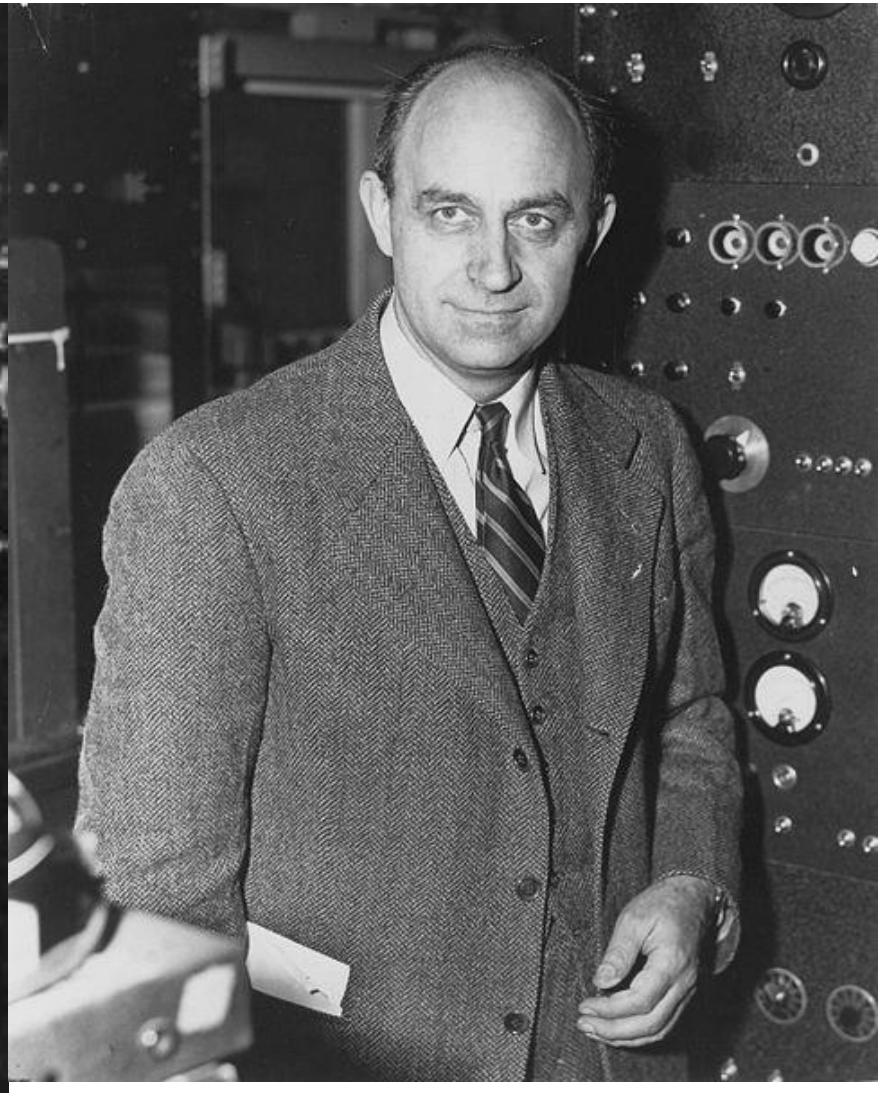
- 1. Continue the LHC.

- 2. But use widely all possibilities from neutrino physics, because neutrino are really particles BSM

Heroes -(ins) of beta decay drama



Great inventors



Attraction of neutrinos

- They are SM particles but behave like BSM particles.

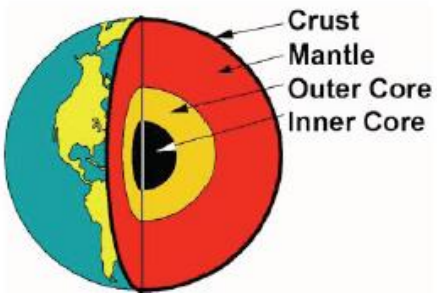
They are still mysterious: mass ordering, CP violation or not, Dirac or Majorana, mass absolute value, possibilities to find more than 3 neutrinos, probable tie the lamda term with small neutrino mass and so on.

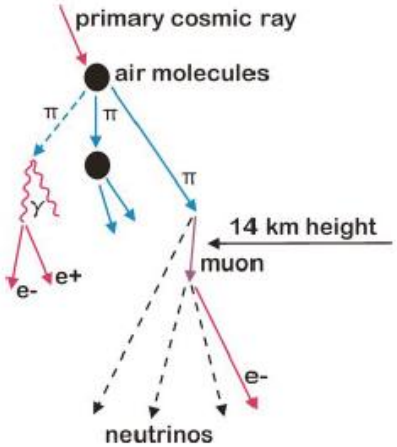
Ways to unveil the mysteries: natural resources, artificial resources, different techniques and collaborations.

- They are be becoming the work horse of high energy physics in searching a way beyond the SM.

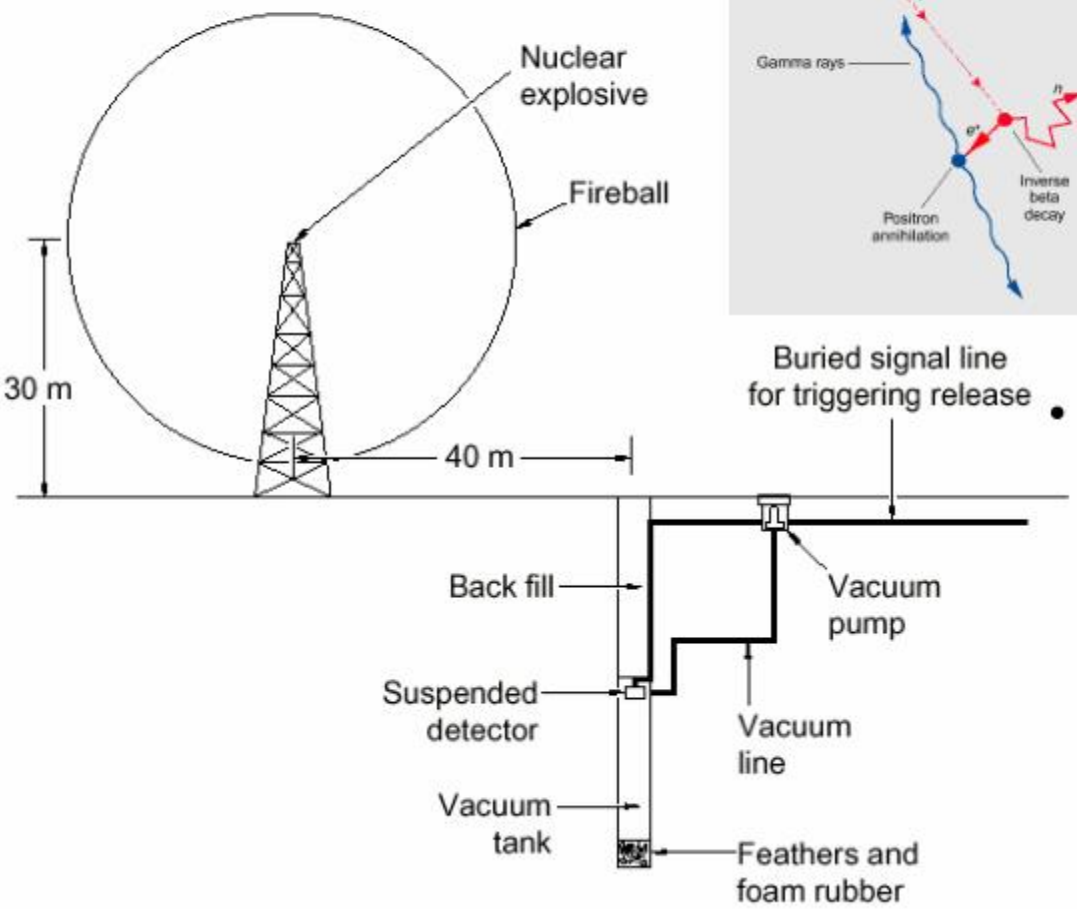
Where can one find neutino ?

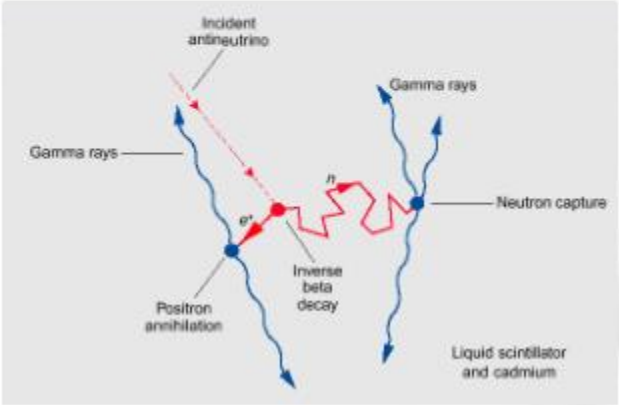
- Use natural resources
- Use artificial resources





Extreme Measures to Overcome Weakness *(Reines and Cowan, 1946)*



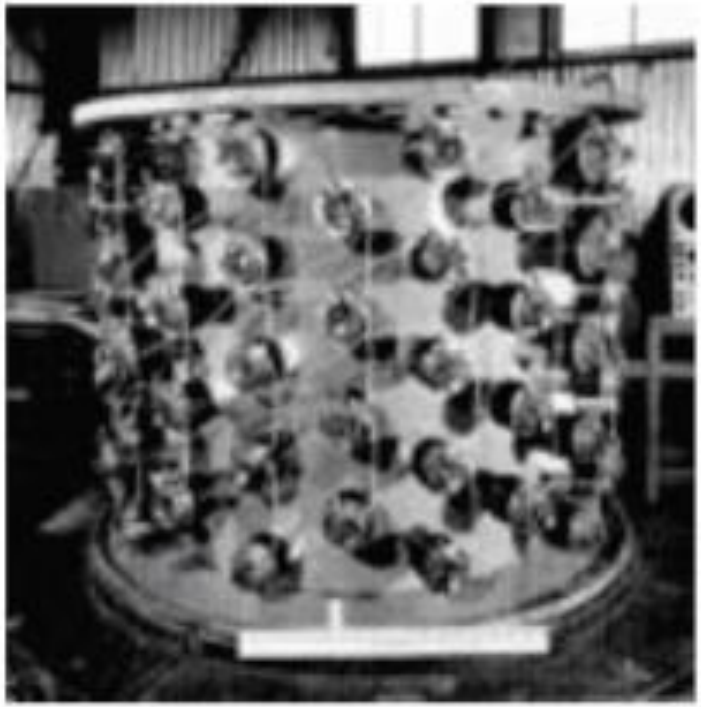


$$\bar{\nu}\, p \rightarrow e^{+} n$$

- Why inverse neutron beta decay?
  - clean prediction of Fermi weak theory
  - clean signature of prompt gammas from e^{+} plus delayed neutron signal.
    - Latter not as useful with bomb source.

First appearance of neutrino

In **1956** @Savannah river, S. Carolina
By Reines and Cowan

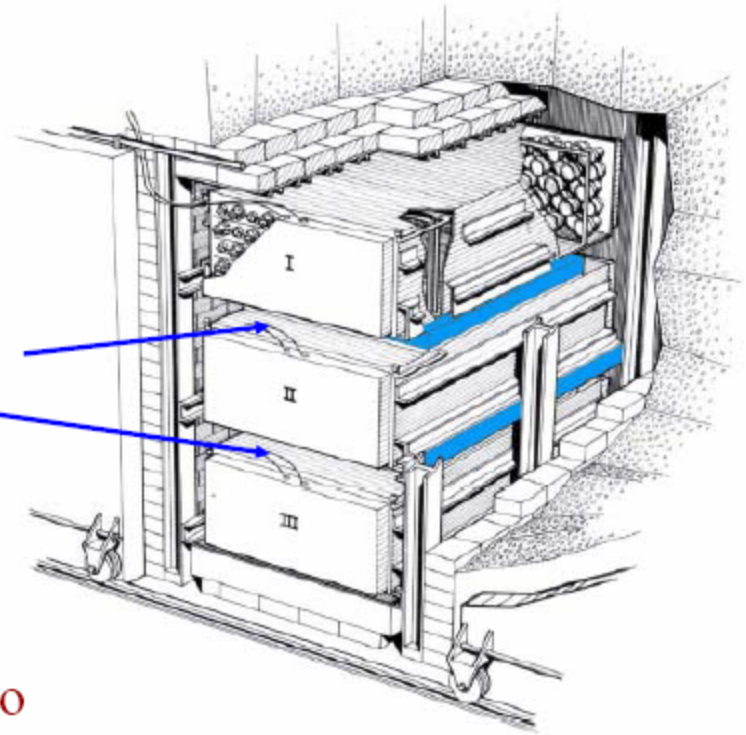


1953 Experiment at Hanford

1956: Savannah River Experiment

Tanks I, II, and III were filled with liquid scintillator and instrumented with 5" PMTs.

Target tanks (blue) were filled with water+cadmium chloride.



Inverse β decay would produce two signals in neighboring tanks (I,II or II,III):

- prompt signal from e+ annihilation producing two 0.511 MeV γs
- delayed signal from n capture on cadmium producing 9 MeV in γs

Nobel prizes for neutrino

- 1988 L.Lederman,M.Schwartz,
- J.Steinberger, neutrino from accelerator.
- 1995 F.Reines, neutrino from reactor.
- 2002 R.Davis Jr,M.Koshiba,cosmic neu.
- 2015 T.Kajita,A.McDonalds, oscillations.

In dete

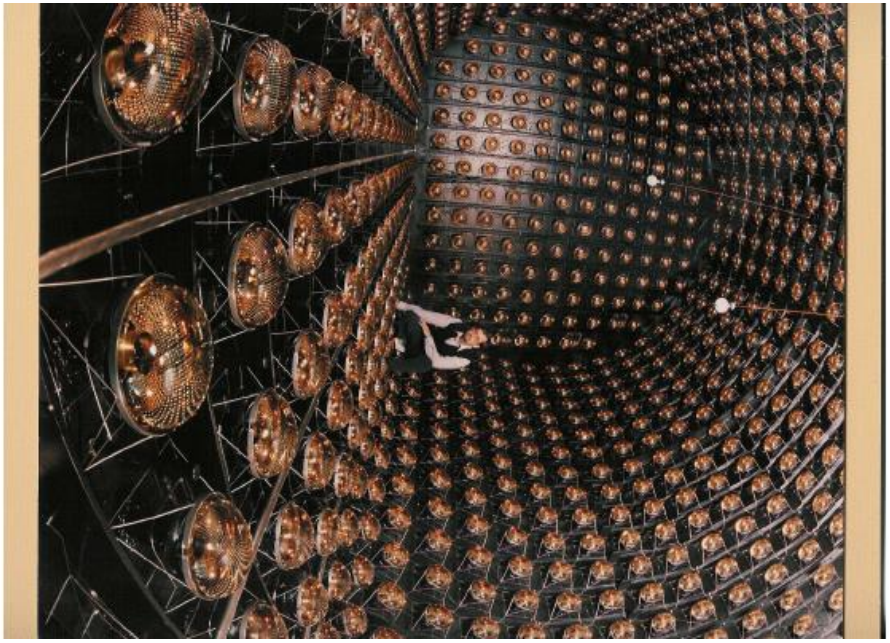


Figure 11. A photograph of the inside of the LSND detector tank.

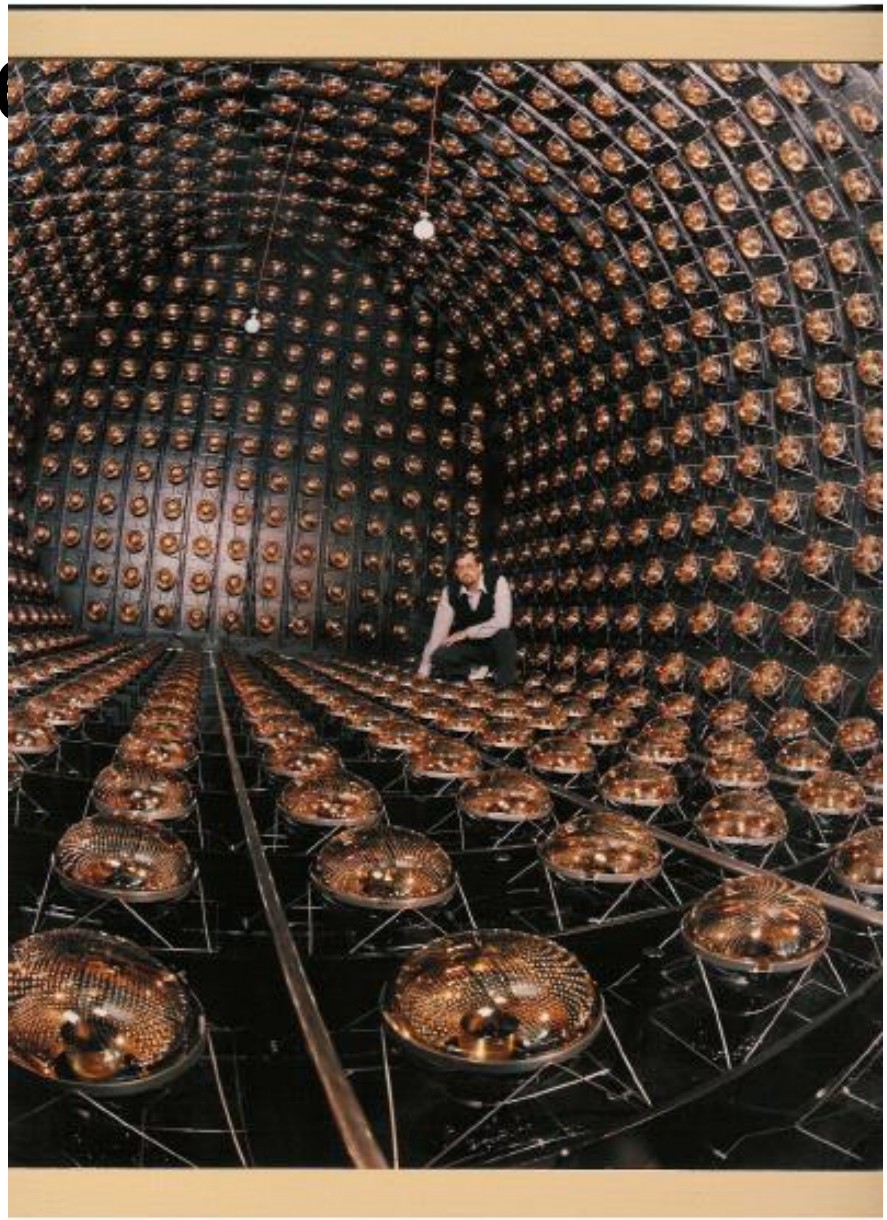
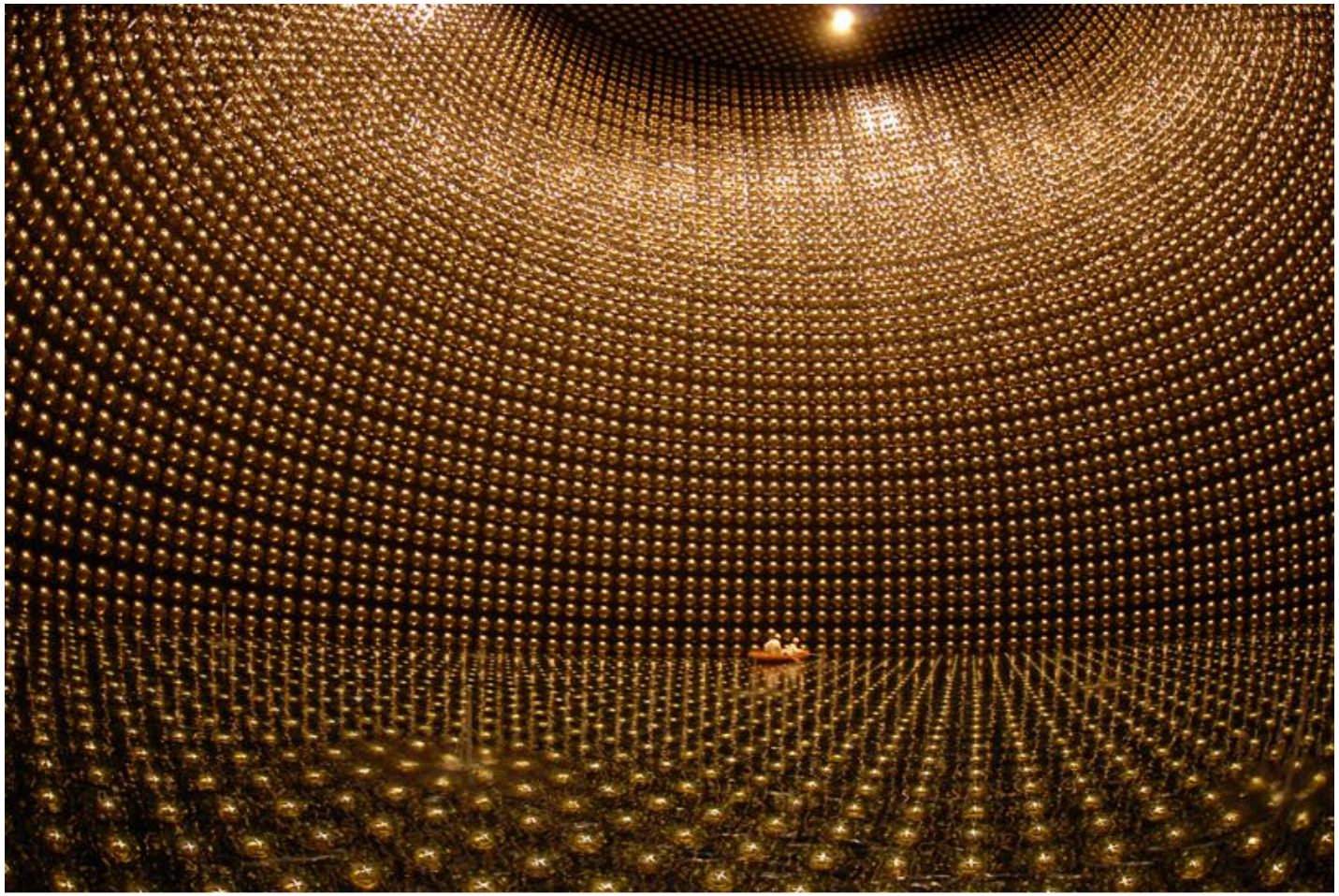


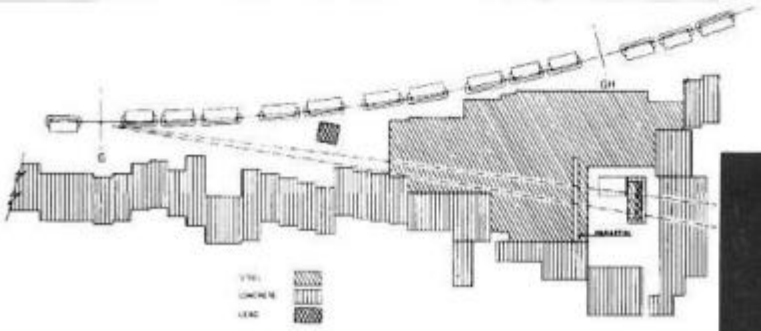
Figure 11. A photograph of the inside of the LSND detector tank.

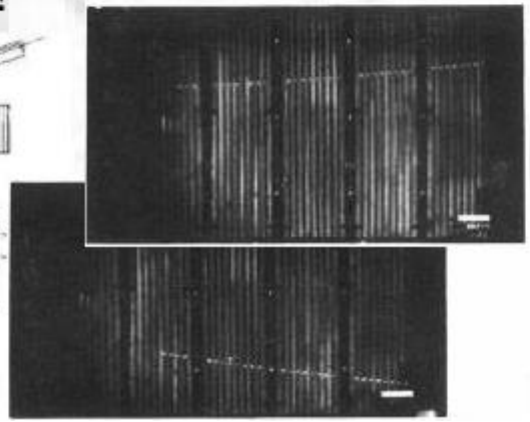
Inside detector



Interactions and Flavor

- 1962 Lederman, Schwartz, Steinberger at Brookhaven Nat'l Lab
- One neutrino was known (beta decay)
  - Question: if $\mu^+ \rightarrow e^+ \nu \bar{\nu}$, why not $\mu^+ \rightarrow e^+ \gamma$?
- First accelerator neutrino beam
  - 5 GeV protons on Be Target (3.5×10^{17} of them)
  - $\pi^+ \rightarrow \mu^+ \nu_\mu$ in a 21m decay region
  - Found 34 single-μ events, 5 background, but NO e-like events!



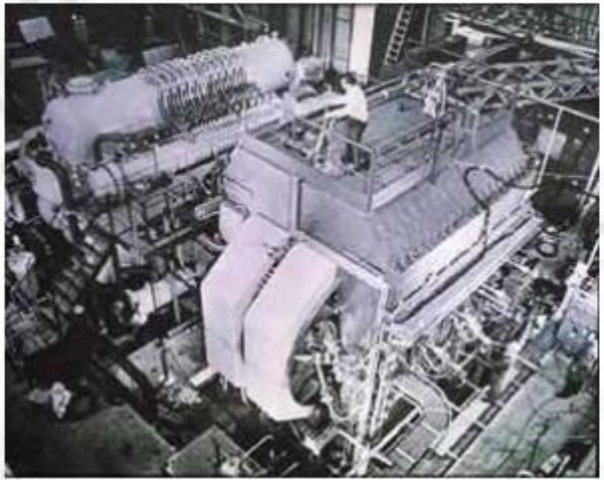


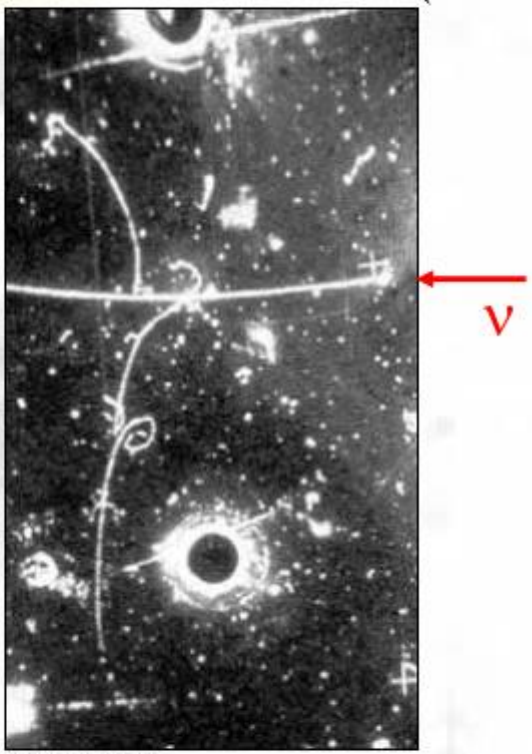
1988 Nobel citation: "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino"

Another Neutrino Interaction Discovery

- Neutrinos only feel the weak force
  - a great way to study the weak force!
- Search for neutral current
  - arguably the most famous neutrino interaction ever observed is shown at right

$$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$$





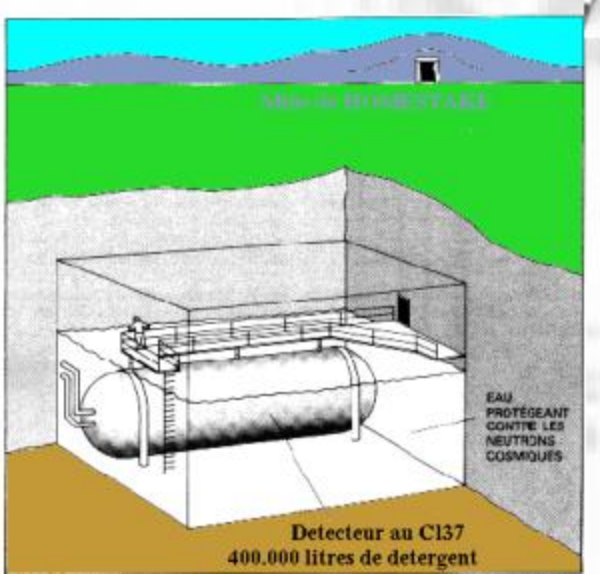
Gargamelle, event from neutral weak force

Another Flavor Example

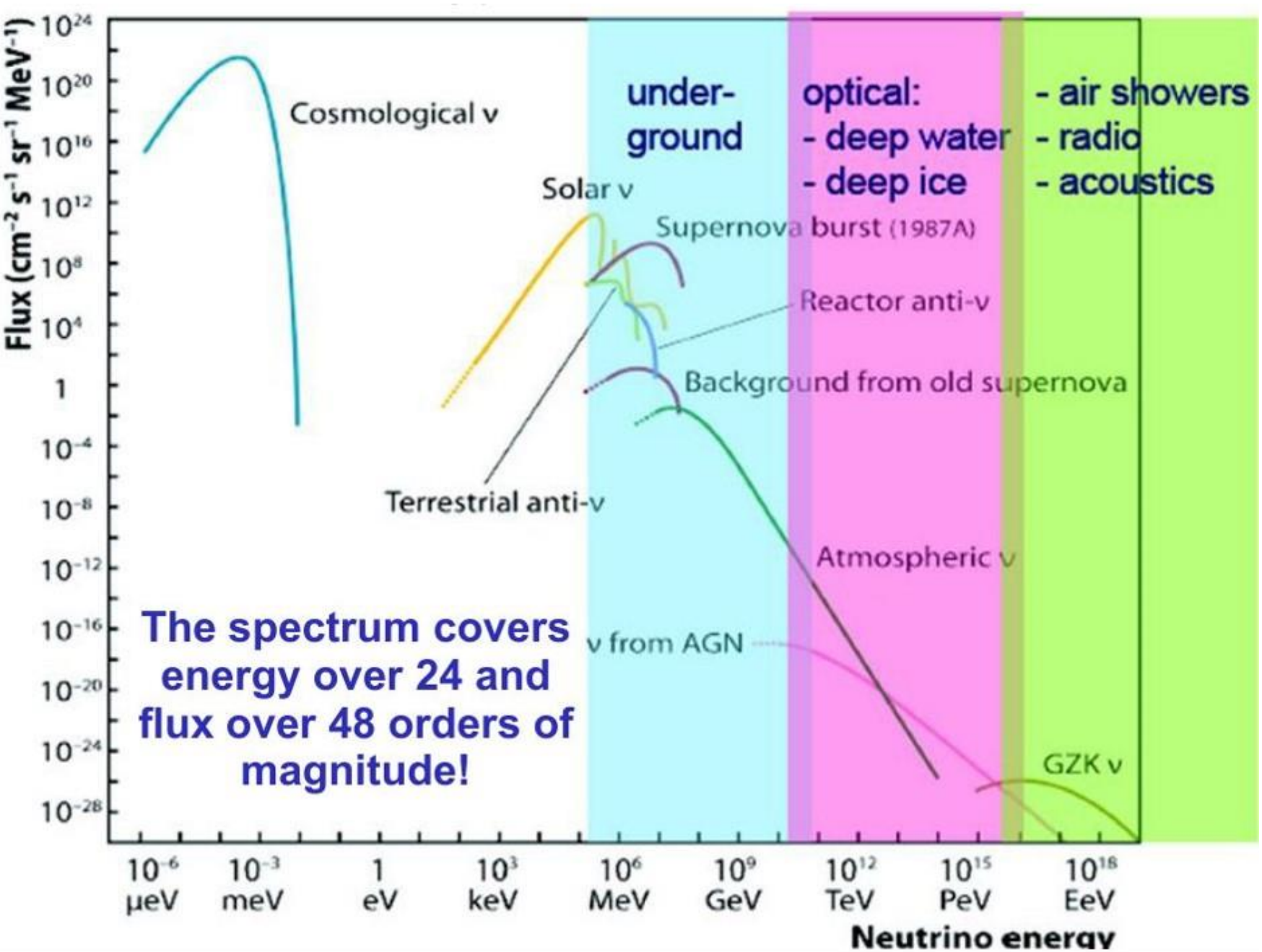
- Radiochemical Solar Neutrino Detector

  Ray Davis (Nobel prize, 2002)

  - $\nu + n \rightarrow p + e^-$ (stimulated β-decay)
  - Use this to produce an unstable isotope, $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$, which has 35 day half-life
  - Put 615 tons of Perchloroethylene in a gold mine
    - o expect one ^{37}Ar atom every 17 hours.

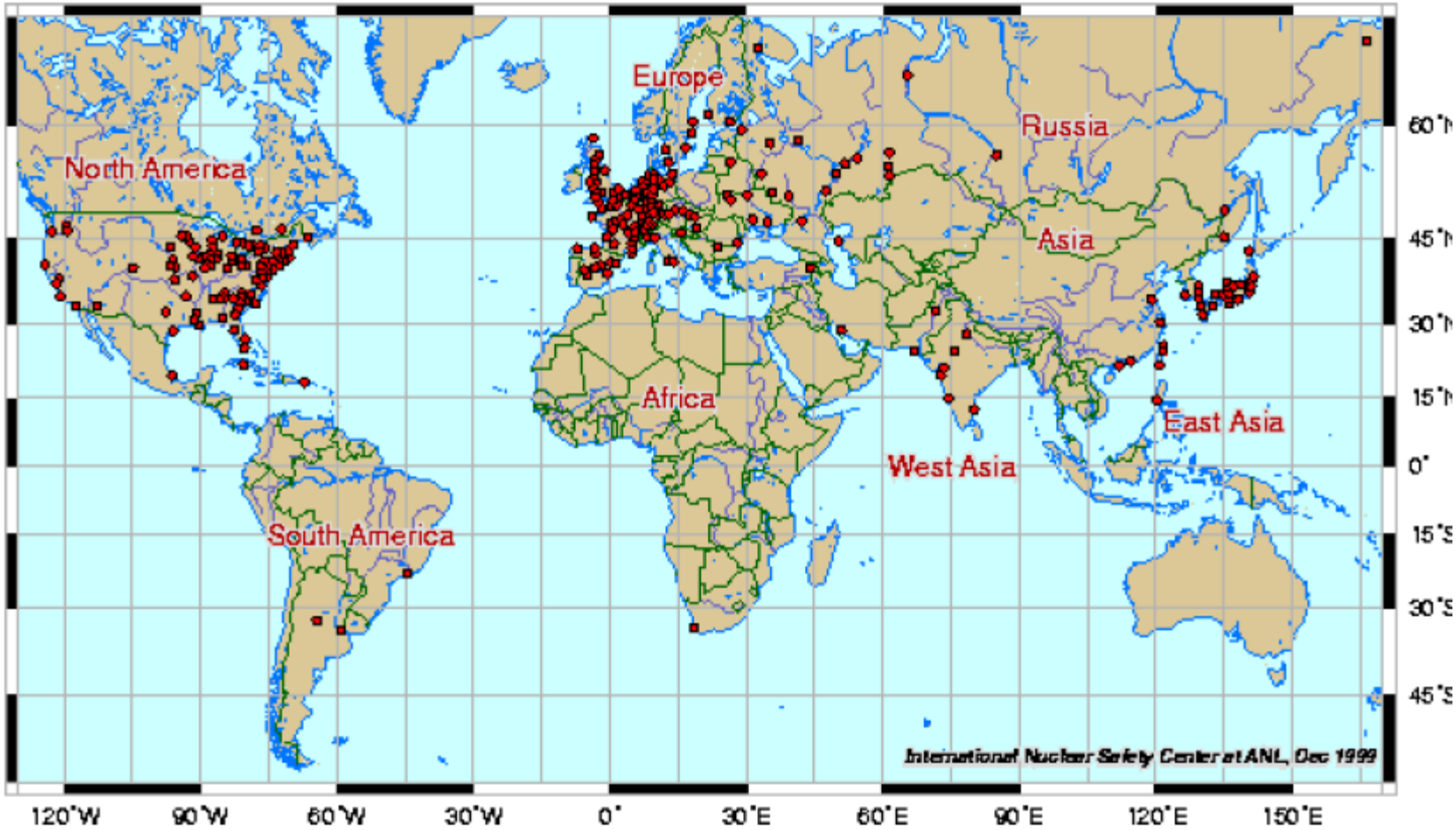


Neutrino fluxes

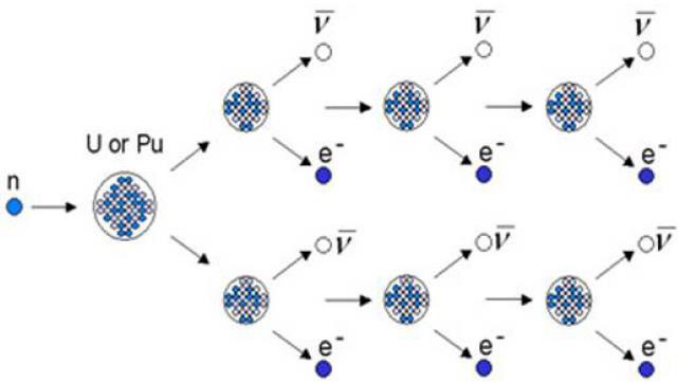


~100 km baseline requires very large detector and very large ν source (and very deep experimental site).

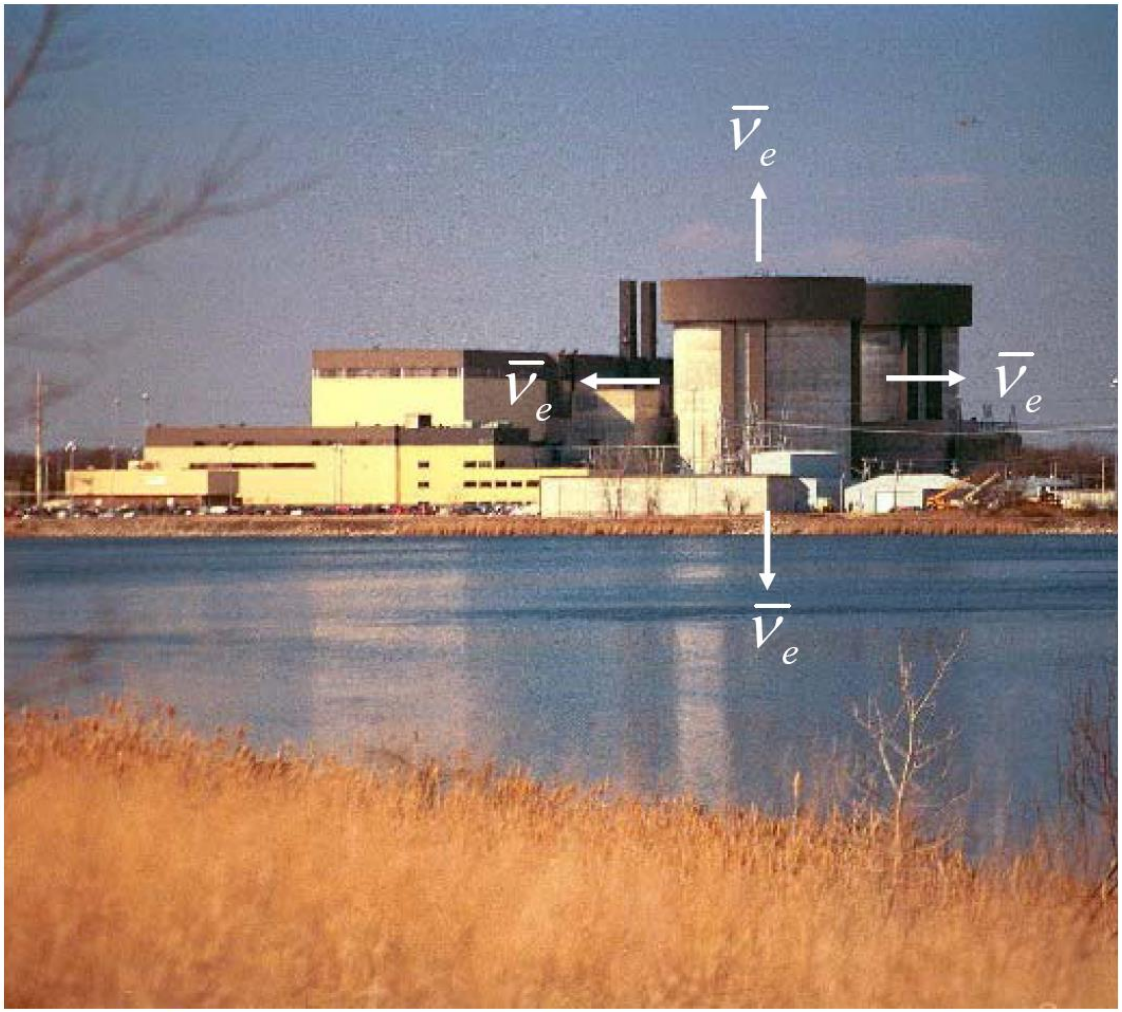
Large concentrations of reactors in U.S., Europe, and Japan.



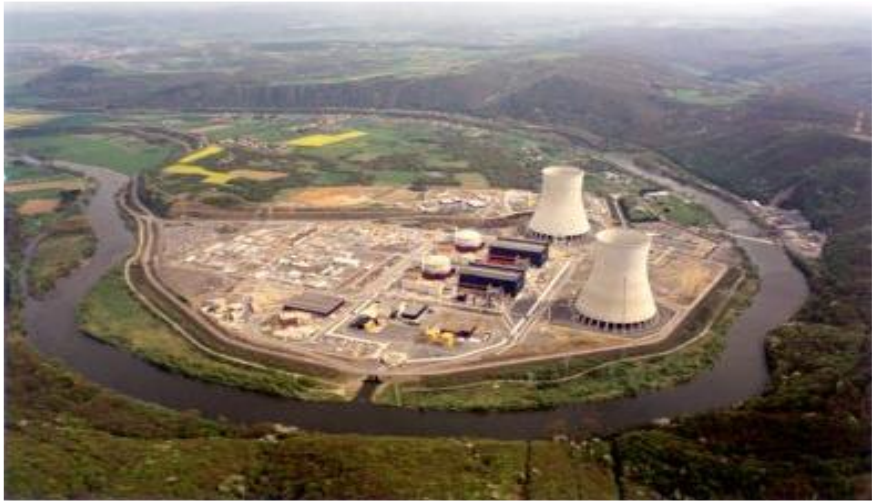
Antineutrino from reactor



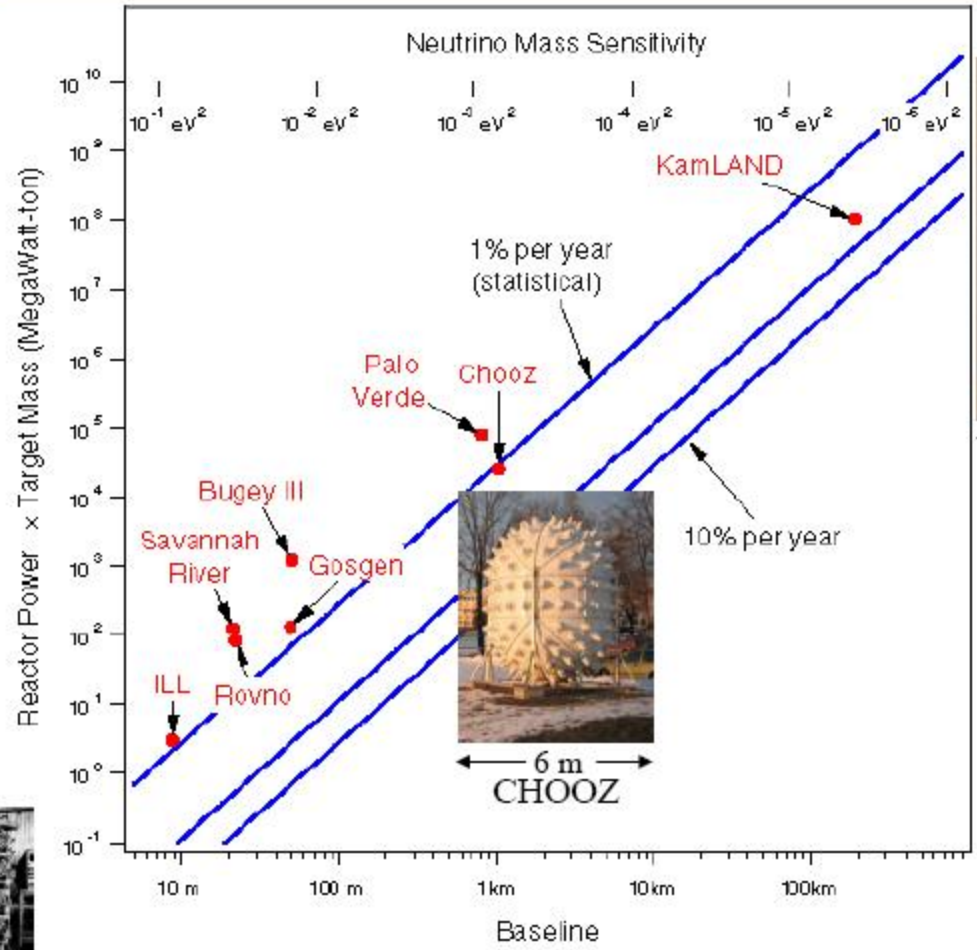
β⁻ decay of neutron rich fission fragments and U and Pu fission

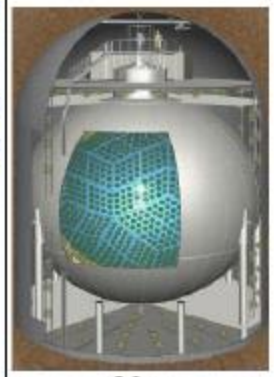


3 Herculeses



Long history of neutrino experiments at reactors





20 m
KamLAND

6 m
CHOOZ

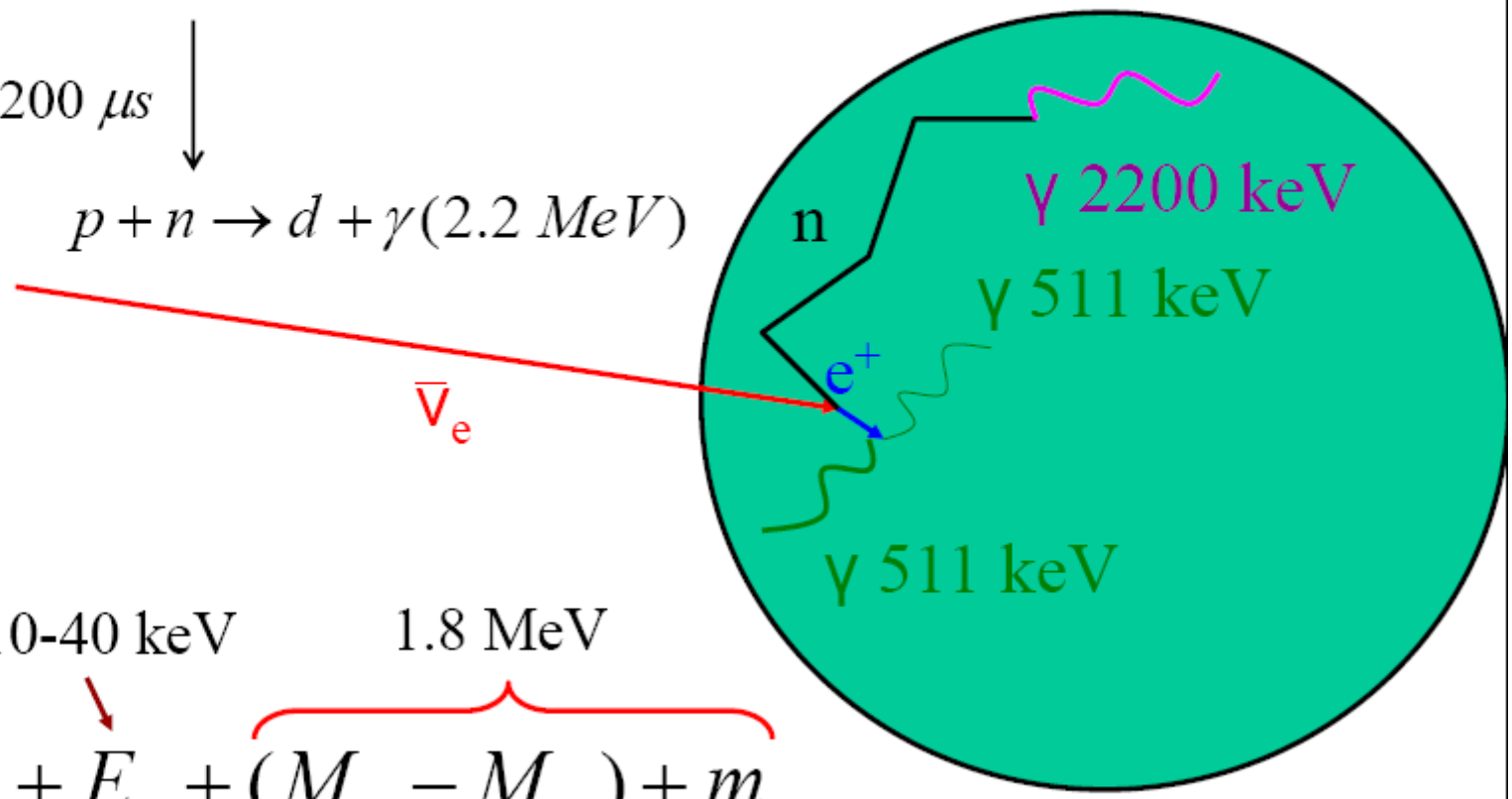
1m
Poltergeist

Experiments detect coincidence between prompt e^+ and delayed neutron capture on hydrogen (or Cd, Gd, etc.)

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

$$\tau \approx 200\ \mu s \downarrow$$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$



$$E_{\bar{\nu}} \cong E_{e^+} + \overset{10\text{-}40\ \text{keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{1.8\ \text{MeV}}$$

Including E from e^+ annihilation, $E_{prompt}=E_\nu-0.8$ MeV

Example: ^{235}U fission

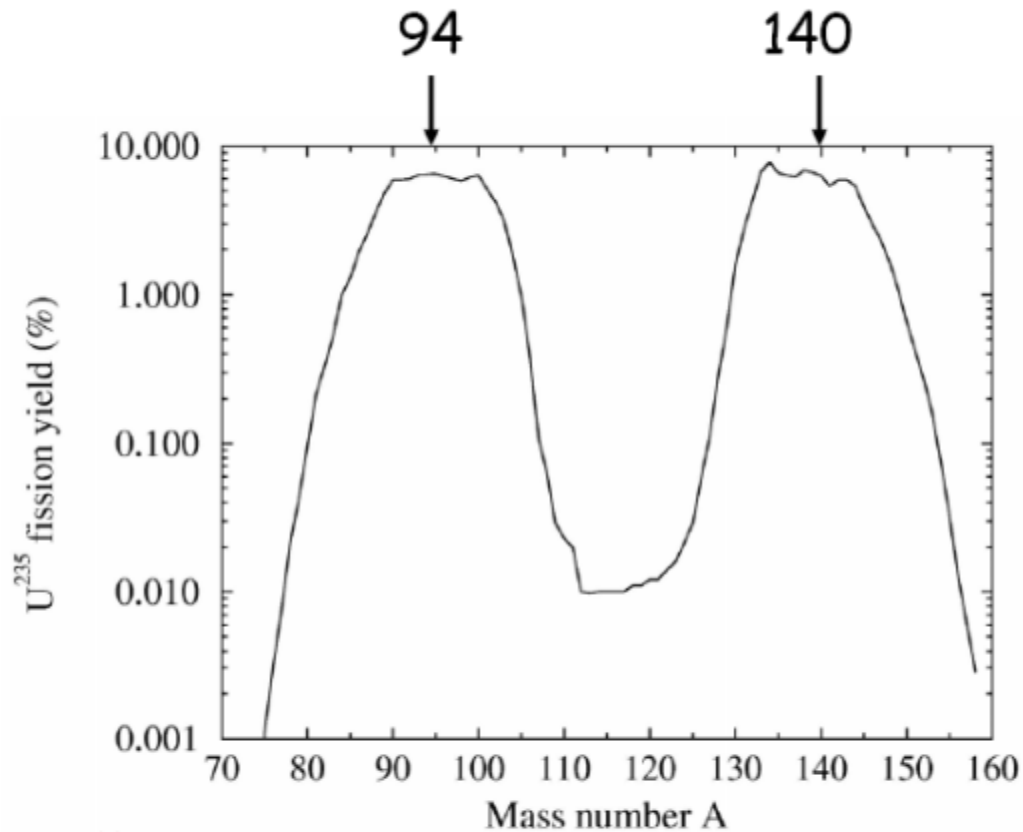
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

Stable nuclei with most likely A from ^{235}U fission:

$^{94}_{40}Zr$ $^{140}_{58}Ce$

Together, these have 98 p and 136 n, while fission fragments (X_1+X_2) have 92 p and 144 n

On average, 6 n have to decay to 6 p to reach stable matter



→ ~ 200 MeV/fission and ~6 $\bar{\nu}_e$ / fission implies that 3GW$_{th}$ reactor produces $\sim 6\times10^{20}$ $\bar{\nu}_e$ / sec.

How to receive of reactor antineutrino spectra

Experimental determination of the source spectrum

Measurements of $N_{ß}$ in 1981-1989 at ILL with ’BILL’ (K.Schreckenbach et al.), at Rovno AP (A.Borovoi, L.Mikaelyan), in 2013 at Munchen (KS et al)

Conversion into correlated N_{v}

A new conversion procedure (TH. Mueller et al,,P.Huber 2011)

New experiments now: Daya Bay, Double Chooz, RENO

Spectral anomalies

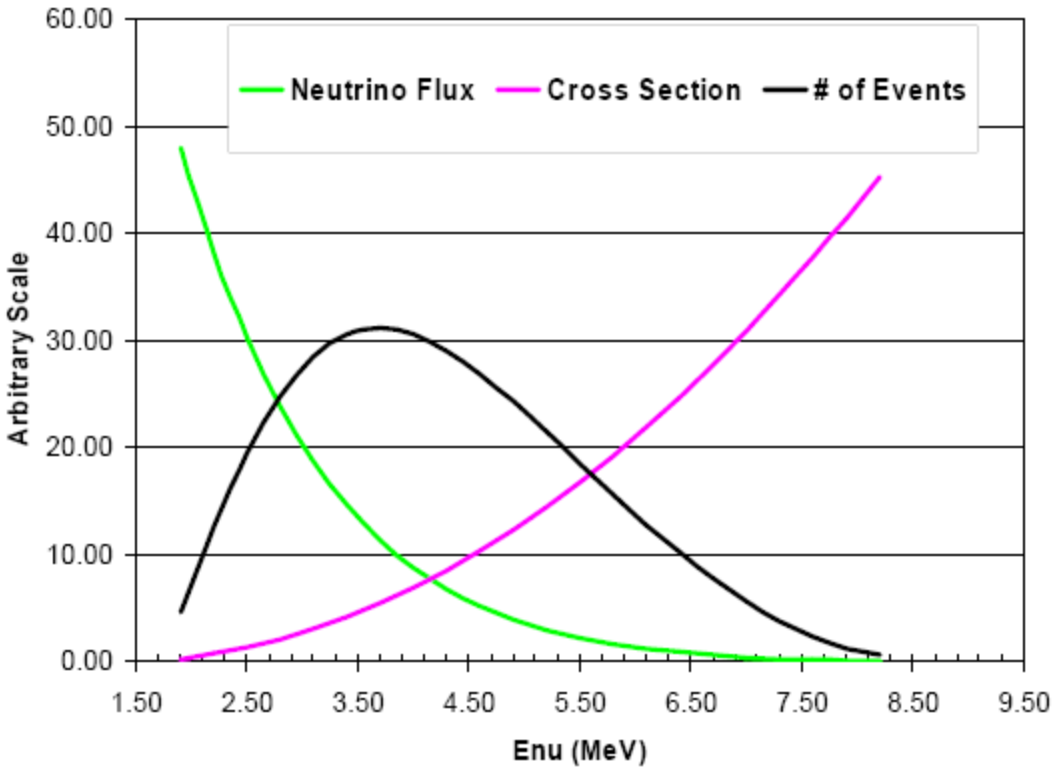
Detection of $\bar{\nu}_e$

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

Also possible:

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

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



$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2/m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

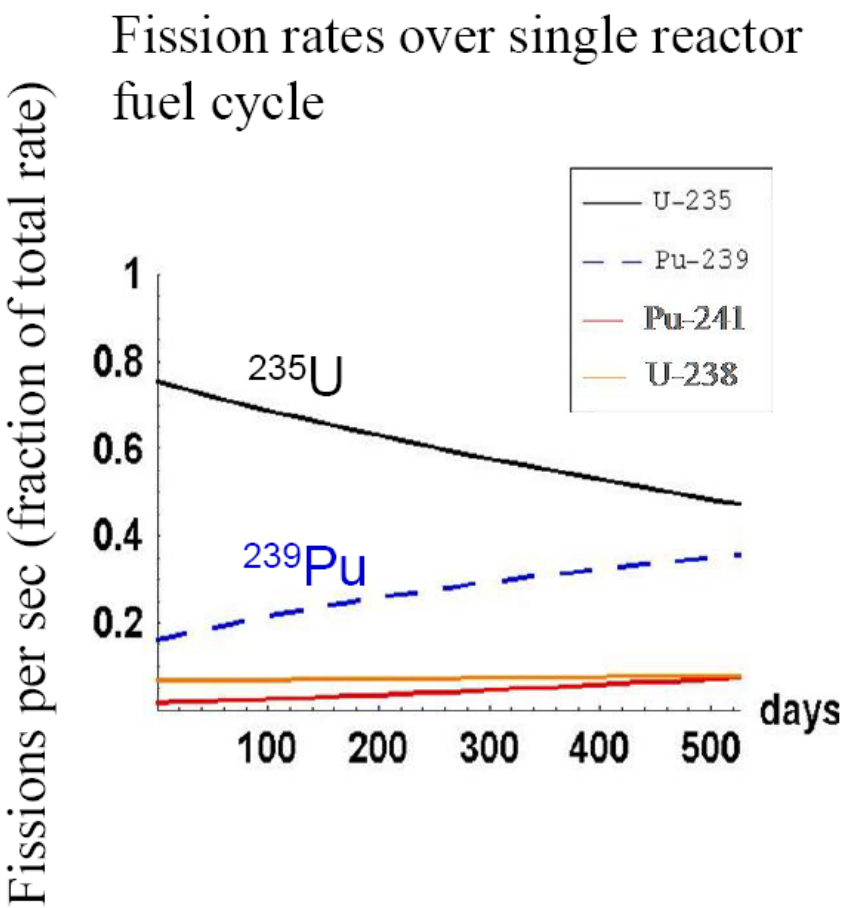
$$E_{th} \sim M_n + m_{e+} - M_p$$

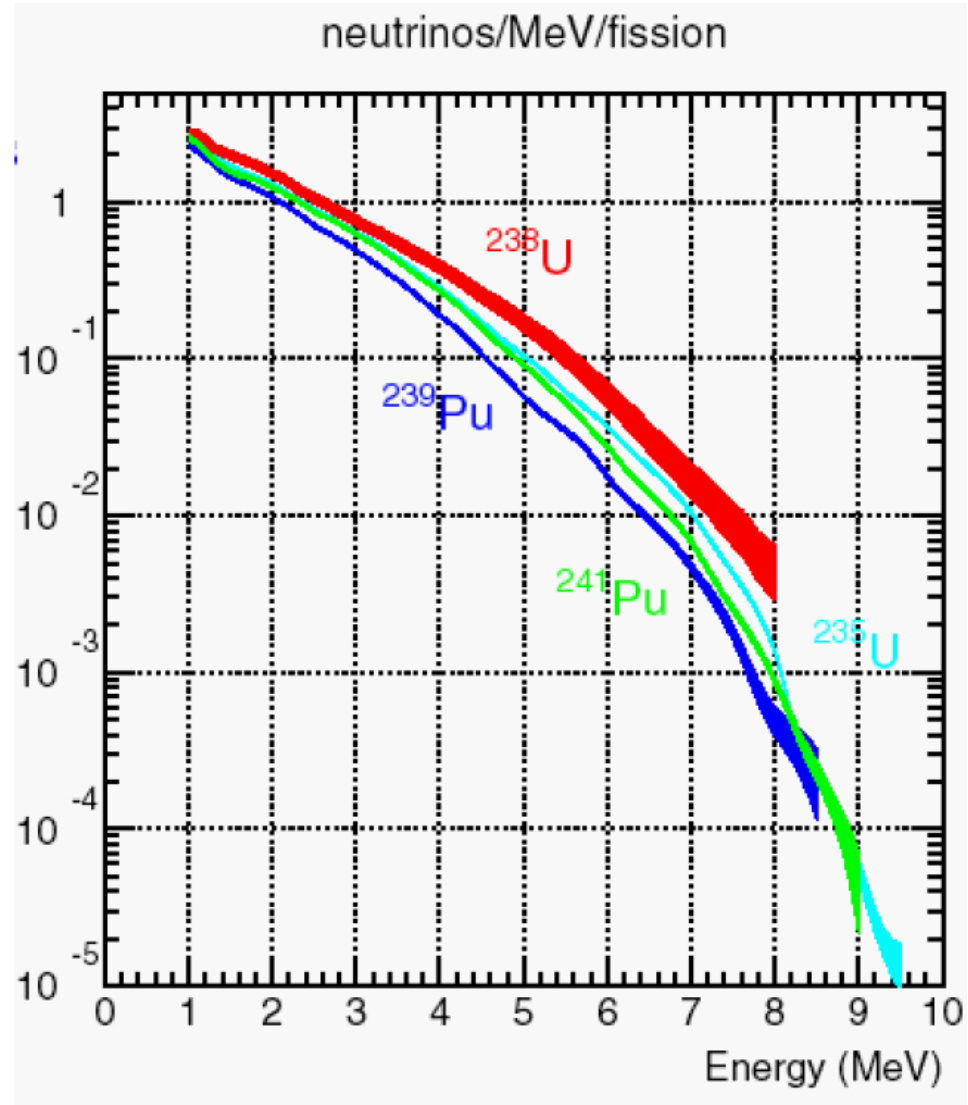
$$= 1.804 \text{ MeV},$$

so only ~1.5 $\bar{\nu}_e$ / fission can be detected.

~1 event per day per ton of LS per GW thermal at 1 km

> 99.9% of ν are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu





Plutonium breeding over fuel cycle(~250 kg over fuel cycle) changes antineutrino rate (by 5-10%) and energy spectrum

Neutrino - observer

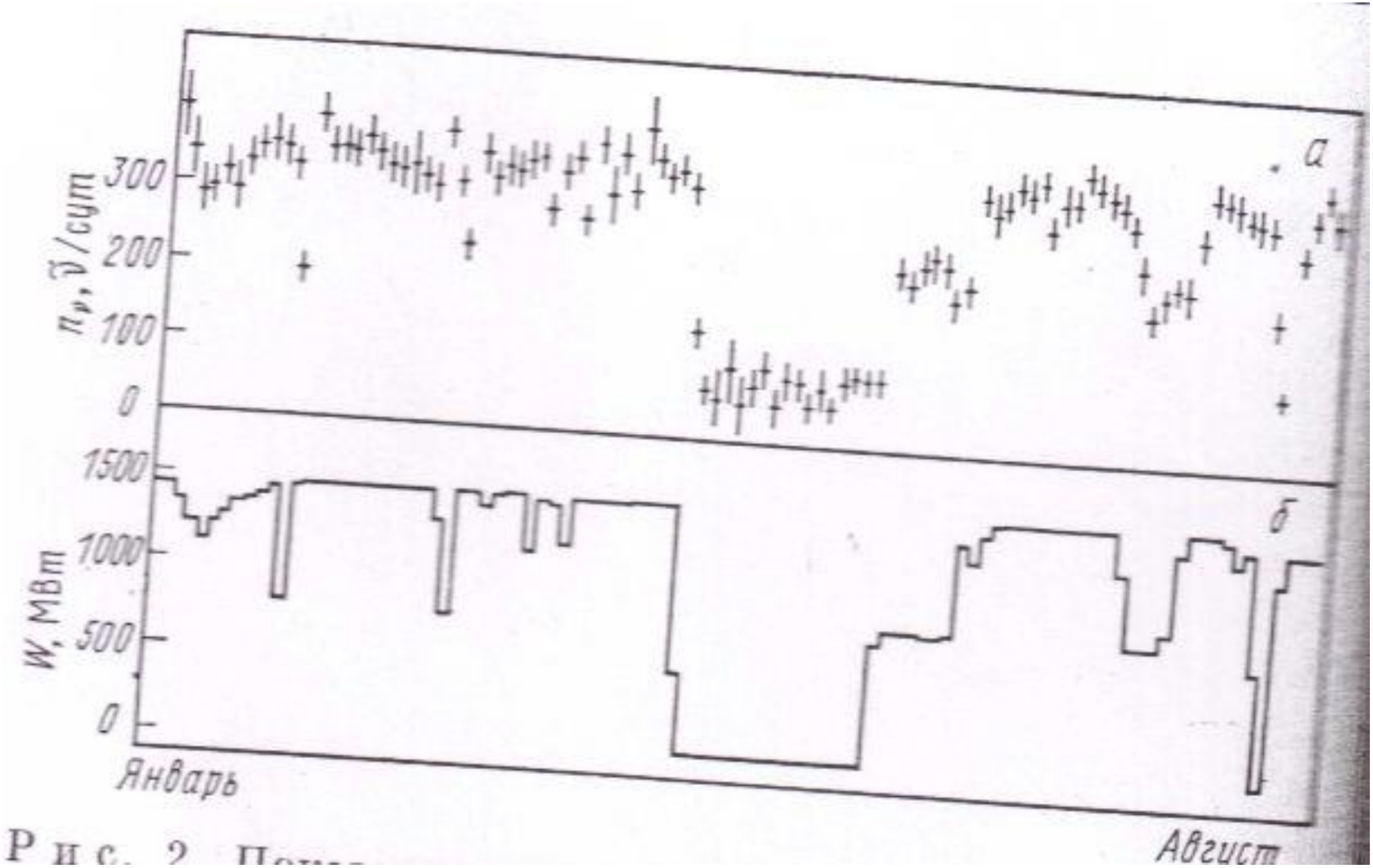
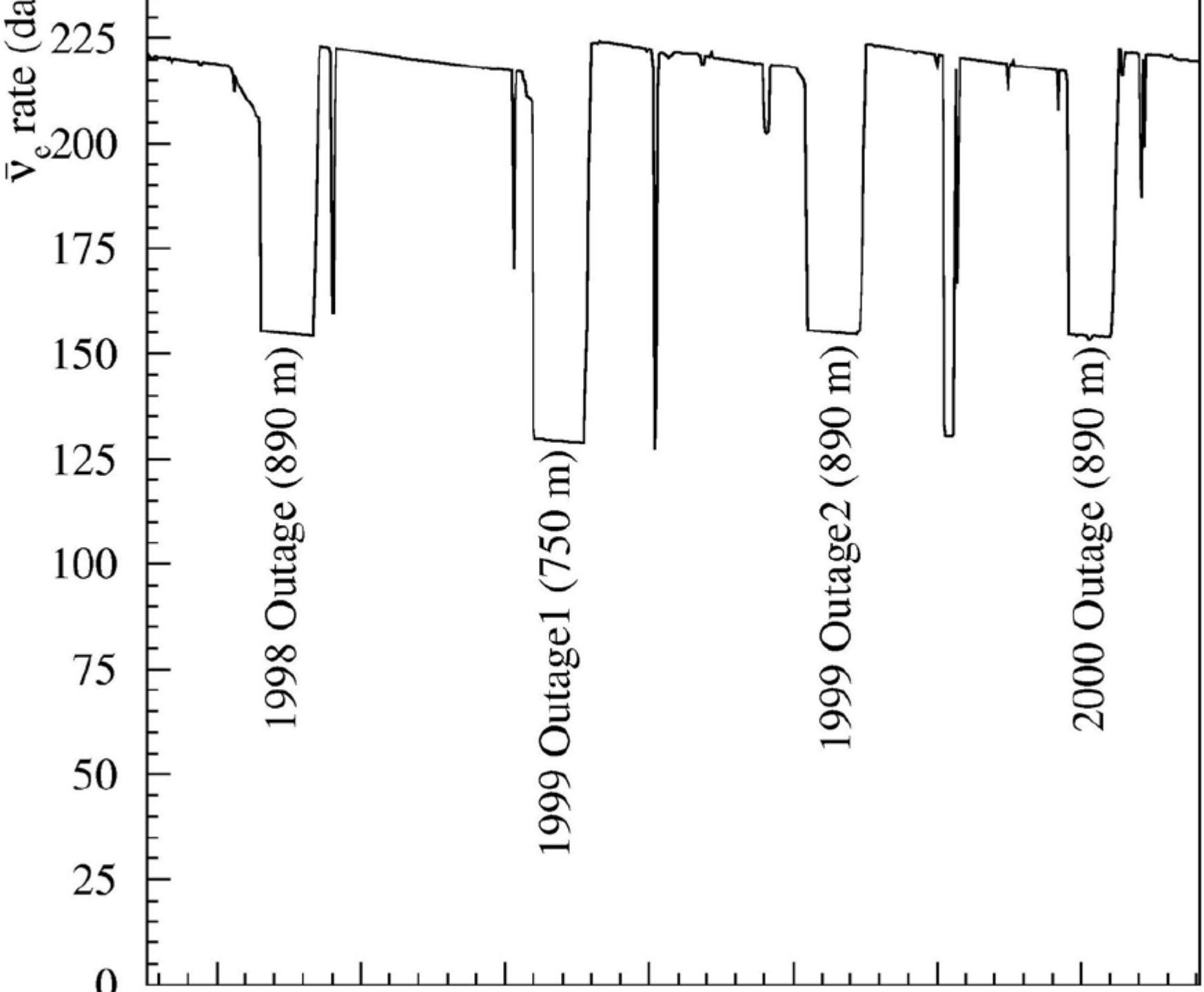


Рис. 2. Пост...


$\bar{\nu}_e$ rate (da
225
200
175
150
125
100
75
50
25
0
1998 Outage (890 m)
1999 Outage1 (750 m)
1999 Outage2 (890 m)
2000 Outage (890 m)

NEUTRINO OSCILLATIONS

oscillation formula

$$P_{ee} = 1 - \sin^2(2\theta_{new}) \sin^2\left(\frac{\Delta m^2_{new} L}{4E_{\bar{\nu}_e}}\right) \tag{110}$$

is adopted, where active neutrino oscillation effects are neglected at these short baselines. In such a framework the mixing angle is related to the U matrix element by the relation:

$$\sin^2(2\theta_{new}) = 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right). \tag{111}$$

One can us now fit the sterile neutrino hypothesis to the data (baselines below 100 m) by minimizing the least-squares function

$$\left(P_{ee} - \vec{\mathrm{R}}\right)^T W^{-1}\left(P_{ee} - \vec{\mathrm{R}}\right), \tag{112}$$

assuming $\sin^2(2\theta_{13}) = 0$. Figure 58 provides the results of the fit in the $\sin^2(2\theta_{new}) - \Delta m^2_{new}$ plane, including only the reactor experiment rate information. The fit to the data indicates that $|\Delta m^2_{new,R}| > 0.2$ eV^2 (99%) and $\sin^2(2\theta_{new,R}) \sim 0.14$. The best fit point is at $|\Delta m^2_{new,R}| = 0.5$ eV^2 and $\sin^2(2\theta_{new,R}) \sim 0.14$. The no-oscillation analysis is excluded at 99.8%, corresponding roughly to 3σ.

Neutrino oscillation

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1.40}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1.41}$$

Oscillation Experiments with Reactors

Antineutrinos from reactors can be used to study neutrino oscillations with "solar" $\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 and "atmospheric" $\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2

→ Mean antineutrino energy is 3.6 MeV. Therefore, only disappearance experiments are possible.

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E},$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$.

Experiments look for non-$1/r^2$ behavior of antineutrino rate.

Oscillation maxima for E_ν=3.6 MeV:

$\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 → L ~ 1.8 km

$\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2 → L ~ 60 km

Neutrino Oscillation Milestones

Atmos. Neutrino Oscillation — θ_{23} — ~45° (1998) **Super-K;** K2K

↓ 3 years

Solar Neutrino Oscillation — θ_{12} — 34° (2001) **SNO, Super-K;** KamLAND

↓ 11 years

Reactor Neutrino Oscillation — θ_{13} — 9° (2012) **Daya Bay, RENO** Double Chooz

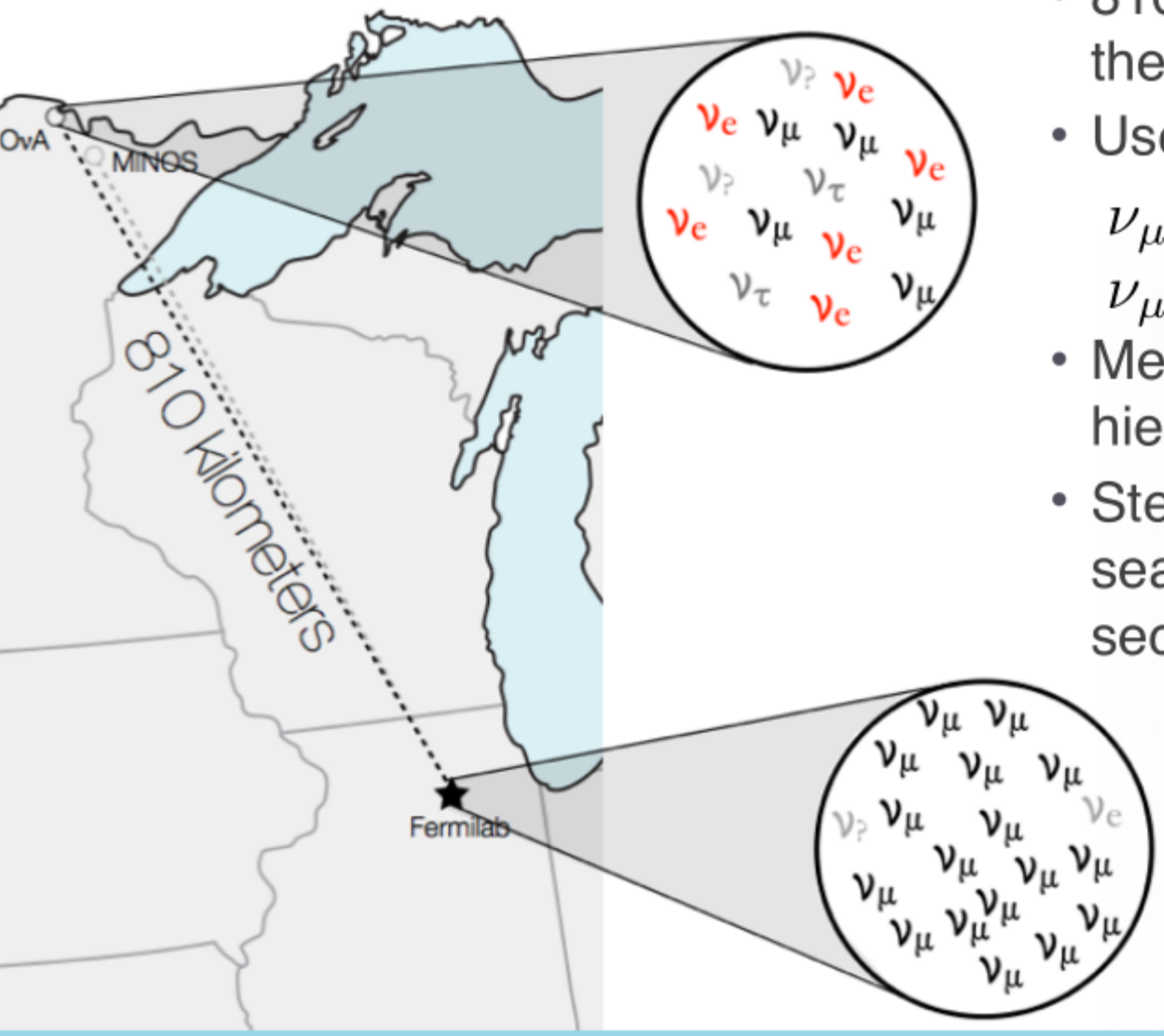
Neutrino Oscillation Results from the NOvA Experiment

Evan Niner, Fermilab

La Thuile 2017

6 March 2017

he NOvA Experiment

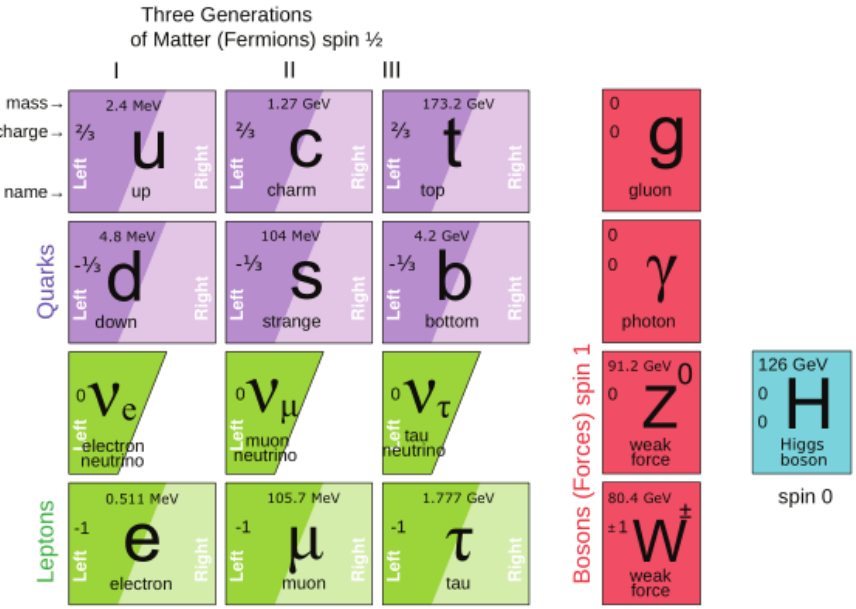


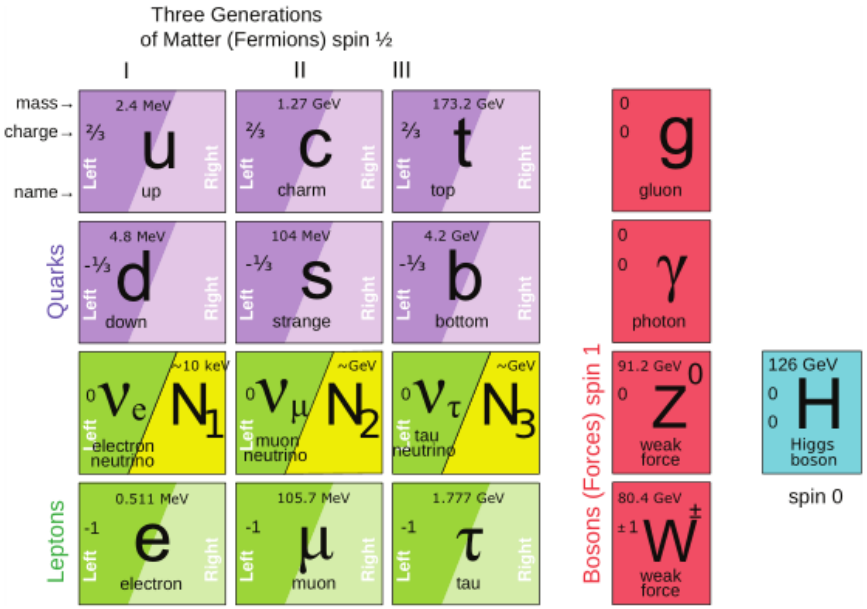
- Observe neutrinos from NuM
  neutrino beam line at Fermila
- Two functionally identical detectors
- 810 km baseline, the longest the world
- Uses four oscillation channel

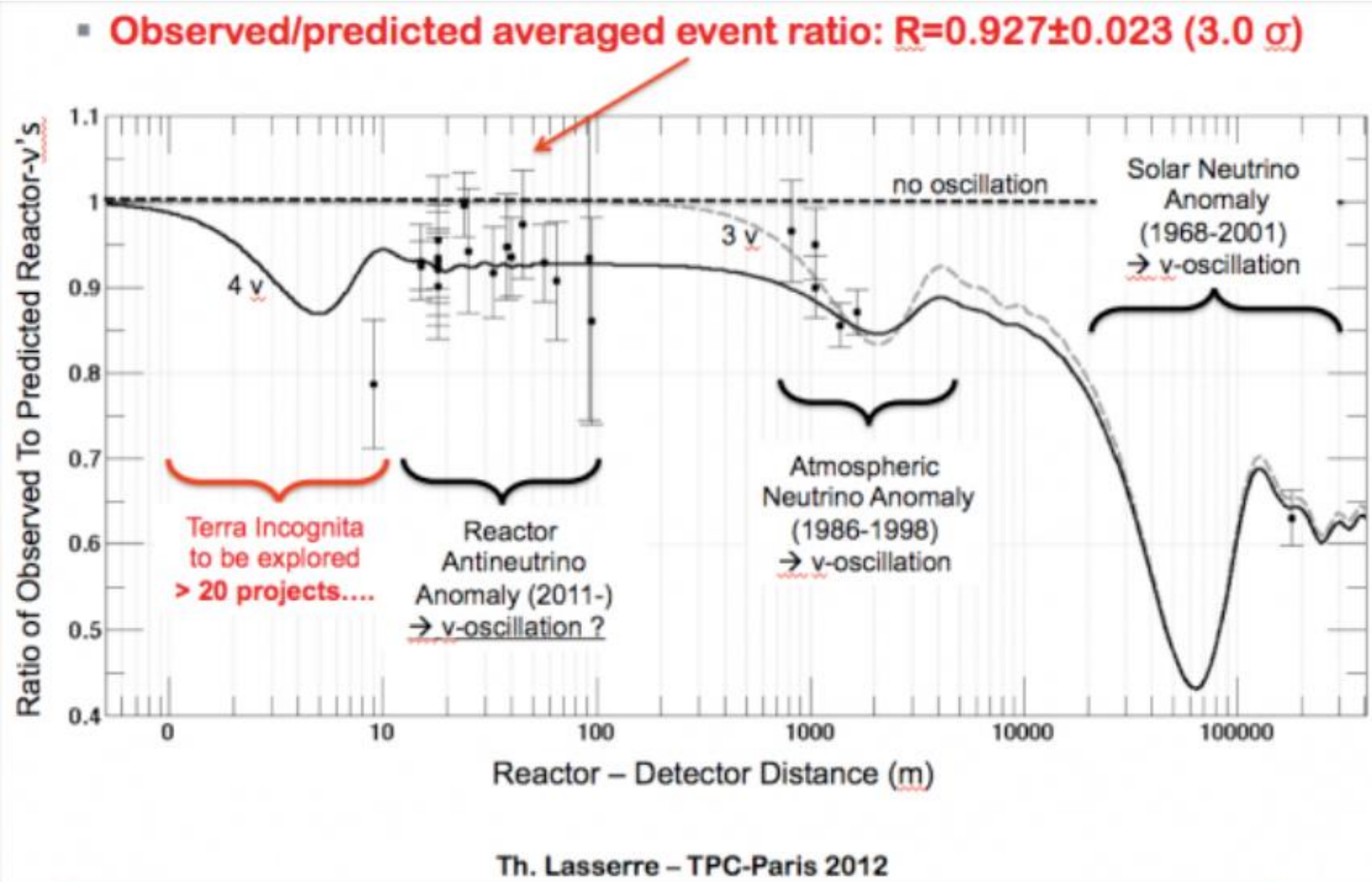
$$\nu_\mu \to \nu_\mu \qquad \overline{\nu}_\mu \to \overline{\nu}_\mu$$
$$\nu_\mu \to \nu_e \qquad \overline{\nu}_\mu \to \overline{\nu}_e$$

- Measure θ_{13}, θ_{23}, Δm^2_{32}, mas hierarchy, and δ_{cp}
- Sterile neutrino searches, ex searches, neutrino cross sections

New neutrinos

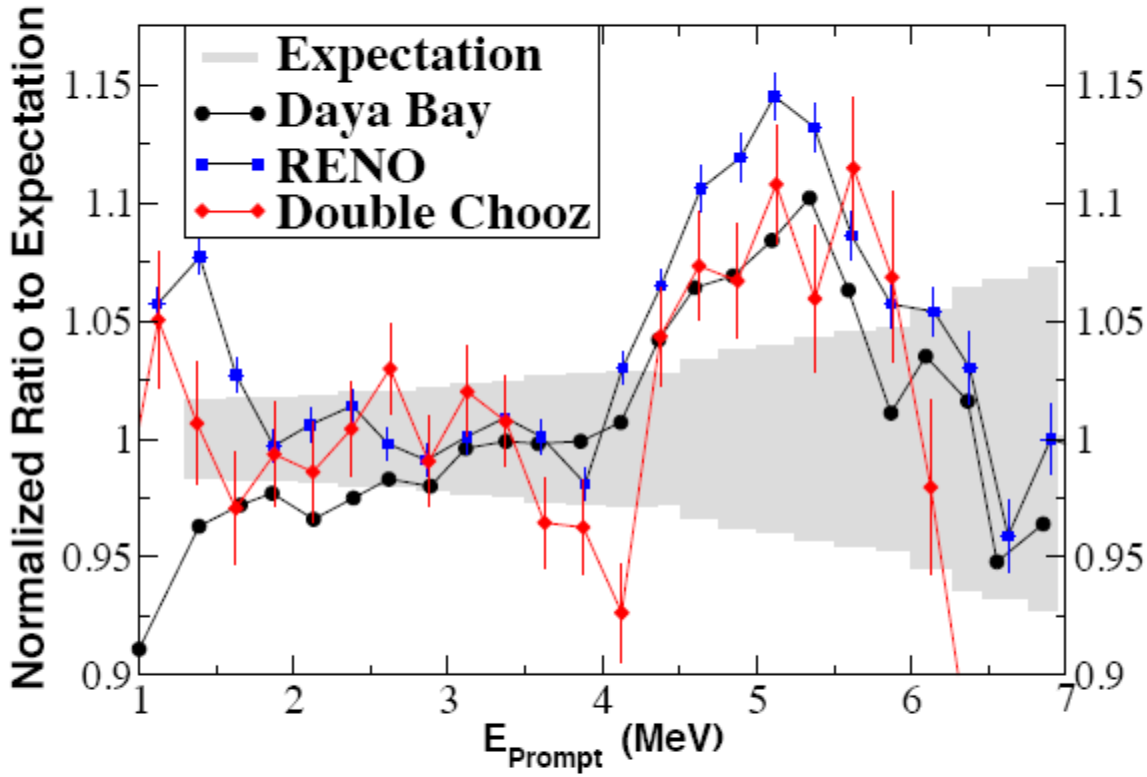






If this is an oscillation phenomenon, it requires a 1 eV sterile neutrino.

All three recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations –the 'Bump'



- The current expectations are Huber (^{235}U,$^{239,241}Pu$) and Mueller (^{238}U)
- RENO observed the largest bump
- Double-Chooz used Huber and Haag (^{238}U) for expected flux

P. Huber, Phys. Rev. C 84, 024617 (2011); Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011); N. Haag, Phys. Rev. Lett. 112, 122501 (2014).

Future small detectors

	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)	Data Taking
Nucifer (FRA)	70	0.8	7	13	**analyzing**
Poseidon (RU)	100	~ 3	5-8	~ 15	**?**
Stéréo (FRA)	57	1.75	8.8-11.2	18	**2015**
Neutrino 4 (RU)	100	1.5	6-12	~ 10	**2015**
Hanaro (KO)	30-2800	~ 1	6	few	**2015**
DANSS (RU)	3000	0.9	9.7-12.2	50	**2015**
Prospect (USA)	85	1 & 10	7-18	few	**?**
SoLid (UK)	45-80	2.9	6-8	10	**2016**

Future

- Neutrino oscillation is strong evidence for physics beyond the physics of the SM. So, the investigation of them are giving the right way for searching it at reactors, in cosmic and at not very big accelerators. Therefore, such experiments will be the good competitors with ones at LHC.

Thanks