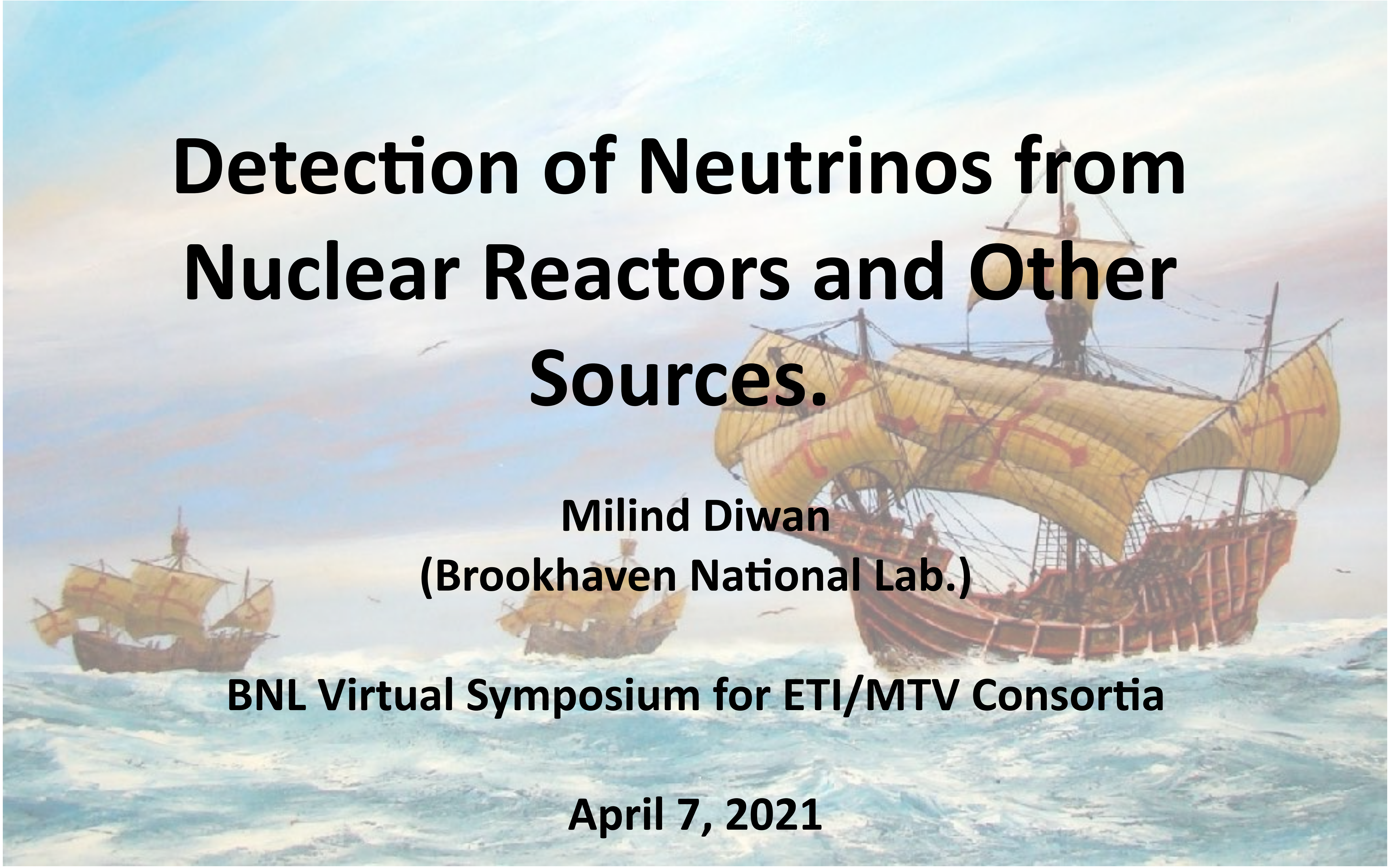

Detection of Neutrinos from Nuclear Reactors and Other Sources.

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BNL Virtual Symposium for ETI/MTV Consortia

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BROOKHAVEN
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Outline

- **Neutrino Characteristics**
- **Sources of Neutrinos**
- **Detector Requirements for reactor neutrinos**
- **Examples of Reactor Neutrino Detectors**
- **Technologies of the future.**

Reading material:

Light: https://kids.frontiersin.org/article/10.3389/frym.2020.00045

Heavy: https://www.annualreviews.org/doi/full/10.1146/annurev-nucl-102014-021939

What’s a neutrino ?

The world is made of two types of particles: ones that stick together and form ordinary items such as people, children, planets, or food, and ones that do not stick together and float in space. The non-stick particles also penetrate ordinary matter and occupy all available space as they diffuse from their origin. Neutrinos are such particles. They were found to exist because ordinary matter has the ability to both emit and absorb such particles on rare occasions. We learn about this process as radioactivity. It is lucky for us that radioactivity is a rare process which keeps the Sun burning slowly for billions of years and allows life to evolve. It also causes the stars to burst when they reach a certain stage when all the matter is so compressed that it decays in a huge radioactive decay. The universe is full of these neutrinos from both the big bang and the stars. They are nearly as common as light itself.

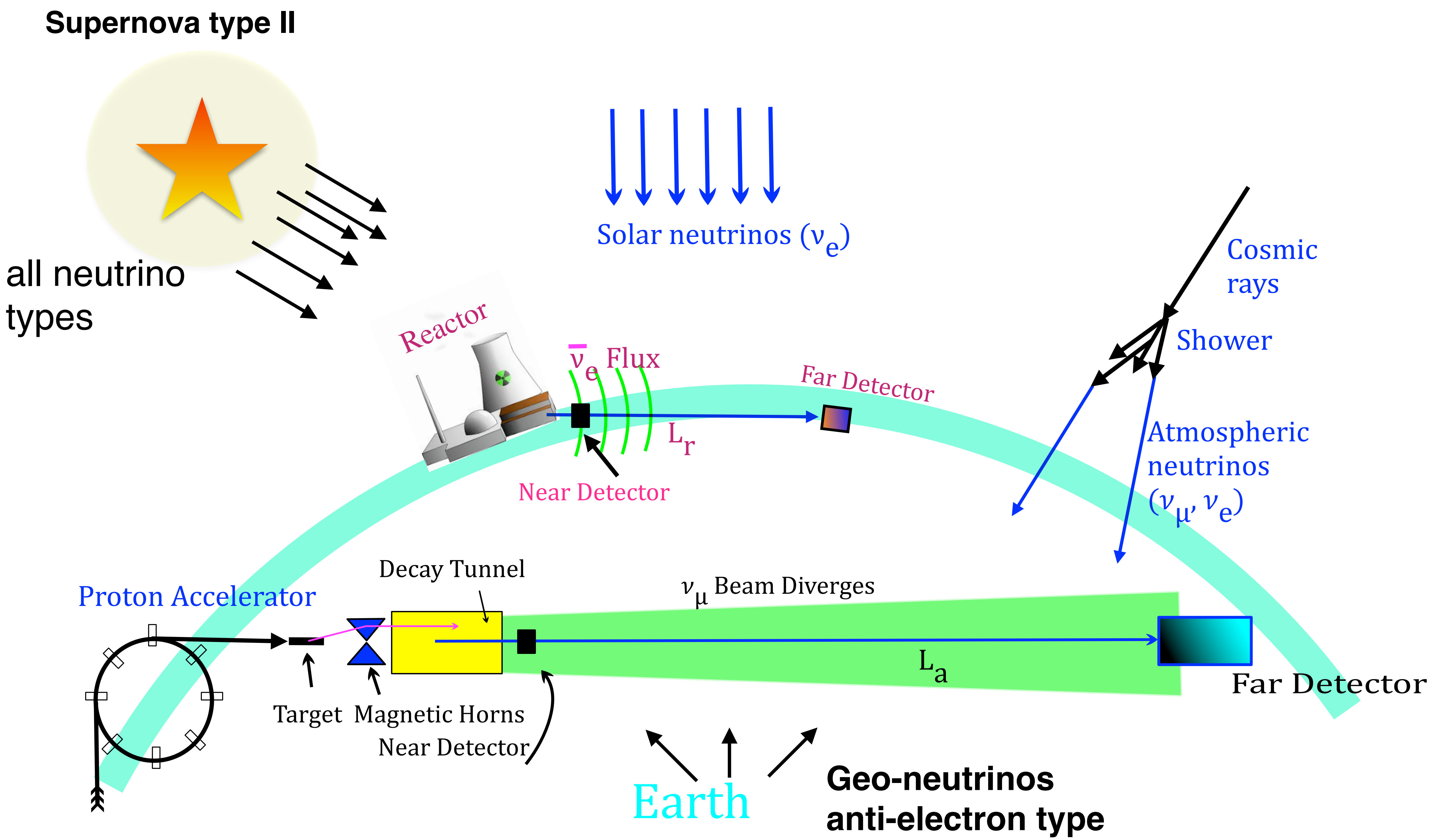
Three types of Neutrinos. We can only detect these. They are grouped together with charged partners.

Particles in this table are called leptons (Greek root: leptos)

Particle	**Symbol**	**Mass**	**Associated Neutrino**	**Also Anti-neutrino**
Electron	**e**	**1**	ν_e	$\bar{\nu}_e$
Muon	μ	**200**	ν_μ	$\bar{\nu}_\mu$
Tau	τ	**3500**	ν_τ	$\bar{\nu}_\tau$
	Negative Electrical Charged		**Neutral**	

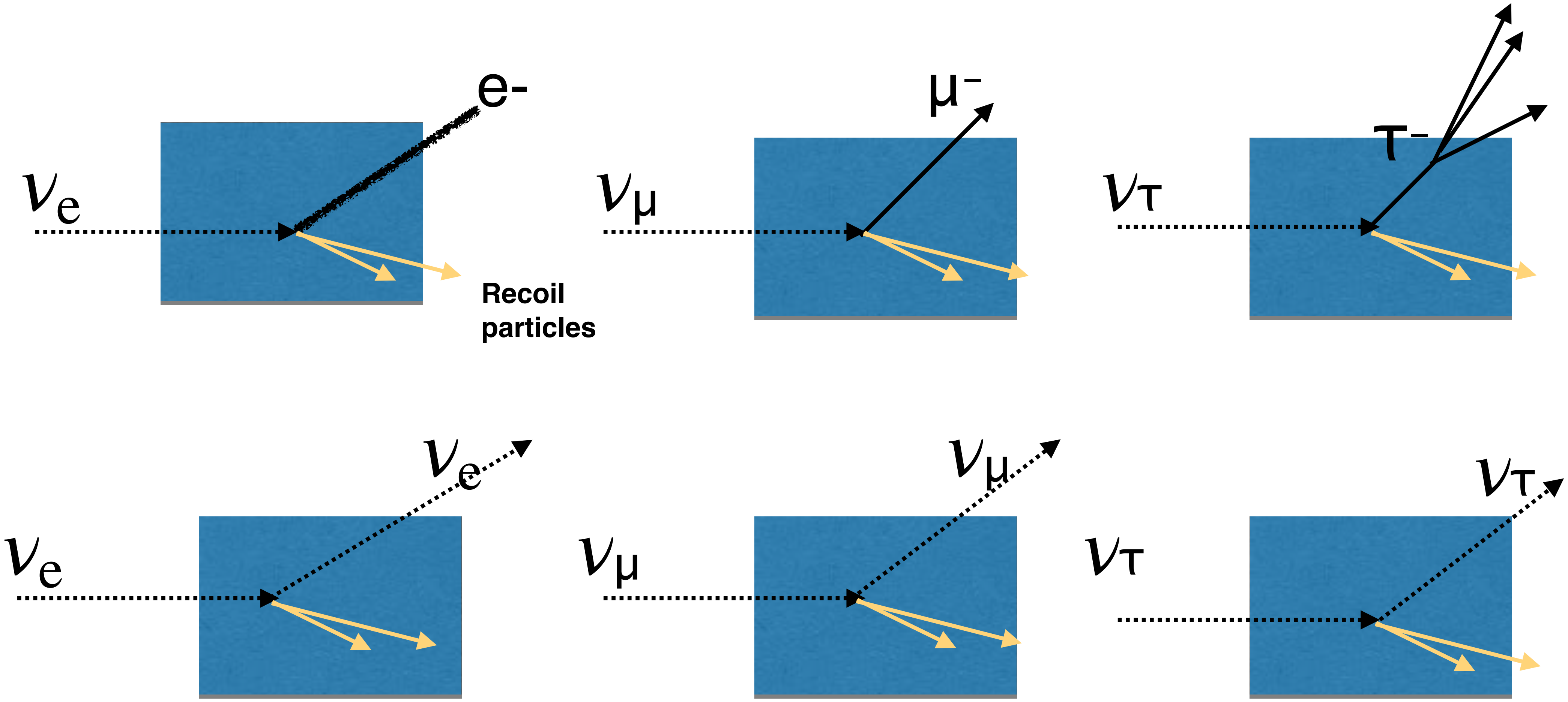
In any given weak interaction the leptons always appear in pairs. (e+ e-) or (e+ v_e), etc. (opposite charged particles are called anti-particles)

Neutrino Sources



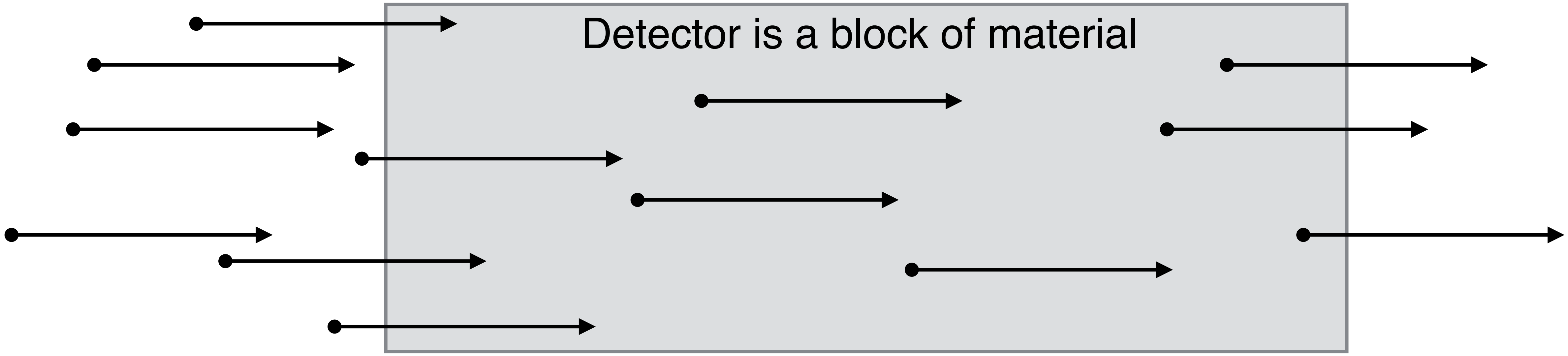
Natural and manmade sources of led us to understand the properties of neutrinos in much greater detail. Annual Rev. 66, 2016.

Neutrino Detection



- **The neutrino has no charge and so it is invisible as it enters a detector. Only very rarely it interacts and leaves charged particles that can be detected.**
- **Neutrino collision on atoms in detectors produces a charged lepton. (Charged Current)**
- **The electron, muon, tau have very different signatures in a detector.**
- **Neutrino can also collide and scatter away leaving observable energy.(Neutral Current)**

How often does a neutrino interact depend on the “cross section” of an atom that a neutrino sees. An atom and a neutrino do not meet very often ! ~10^{-38} cm^2/GeV



As particles penetrate material, there is a reduction in the flux (particle/area/sec)

$$F(x) = F(0)e^{-\sigma\rho x}$$

$$\lambda = 1/(\sigma\rho)$$

λ is the mean free path

σ is the cross section

ρ is the density of targets

(In water $\rho \sim 6\times10^{23} cm^{-3}$)

For 1 GeV neutrino interactions $\sigma \sim 10^{-38}$ and

$$\lambda = \frac{1}{10^{-38} \bullet 6\times10^{23}} \approx 10^{12}\,meters!$$

1 AU = 1.5 10^{11} m

In ordinary matter neutrinos just penetrate through with very rare interactions.

How to calculate neutrino event rate ?

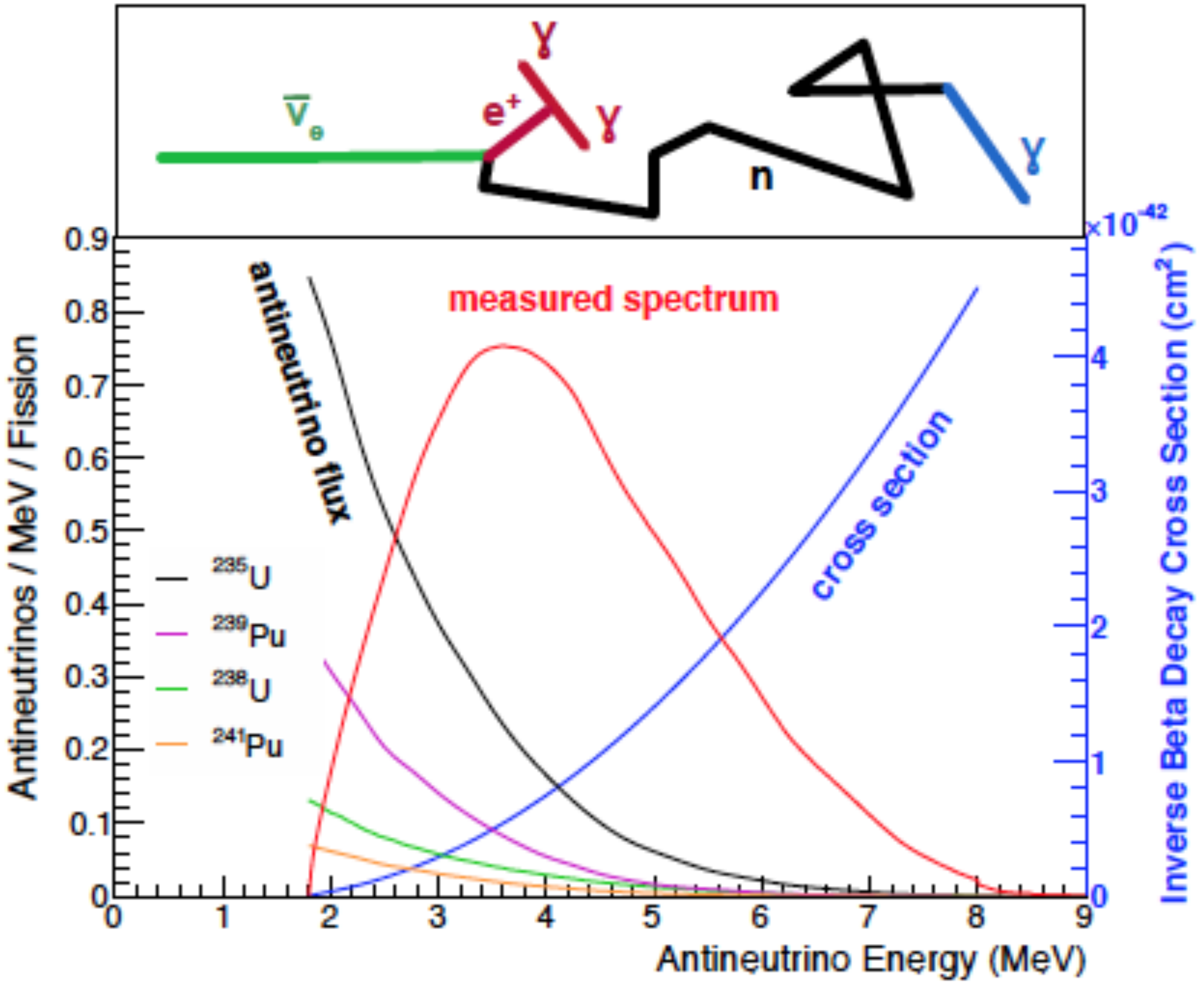
- *Two methods -*
  1. *Events = Flux (/cm^2/sec)*Cross-section(cm^2)*Targets*
  2. *Events = Length-of-path(cm)*cross-sec(cm^2)*Target density (/cm^3)/sec (think of this as a tube around a trajectory)*

- **Targets are the number of particle targets in a detector volume. Detector itself serves as the target for interactions.**

- **1 ton of anything has ~ 6 x 10^{29} protons and neutrons and**
- **1 ton of anything has ~3x10^{29} electrons**
- **Typical cross section is 10^{-38} cm^2 x Energy (in billion eV)**
- **Neutrinos have huge energy range: eV to 10^{15} eV.**
- **Cross sections for low energies can be extremely small.**

- **1 eV = Energy to move 1 electron through 1V=1.6 10^{-19}Joule**
- **Proton mass is ~1 billion eV = 1 GeV. Electron mass ~ 0.511 MeV**

Nuclear Reactor Events and spectrum



Typical Power reactors produce 3 GW of thermal energy.

Each fission has ~200 MeV.

Each fission leads to 6 beta decays.

Beta decays produce electron antineutrinos.

These anti-neutrinos have inverse beta decay reactions on protons in a detector.

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

$$Neutrinos/\sec = 6\frac{3\times10^{9}\,J/\sec}{1.6\times10^{-13}\,J/MeV\bullet 200\,MeV} = 6\times10^{20}/sec$$

for 3 GW Thermal power.

Find how to calculate the spectrum from literature. (P. Vogel et al.)

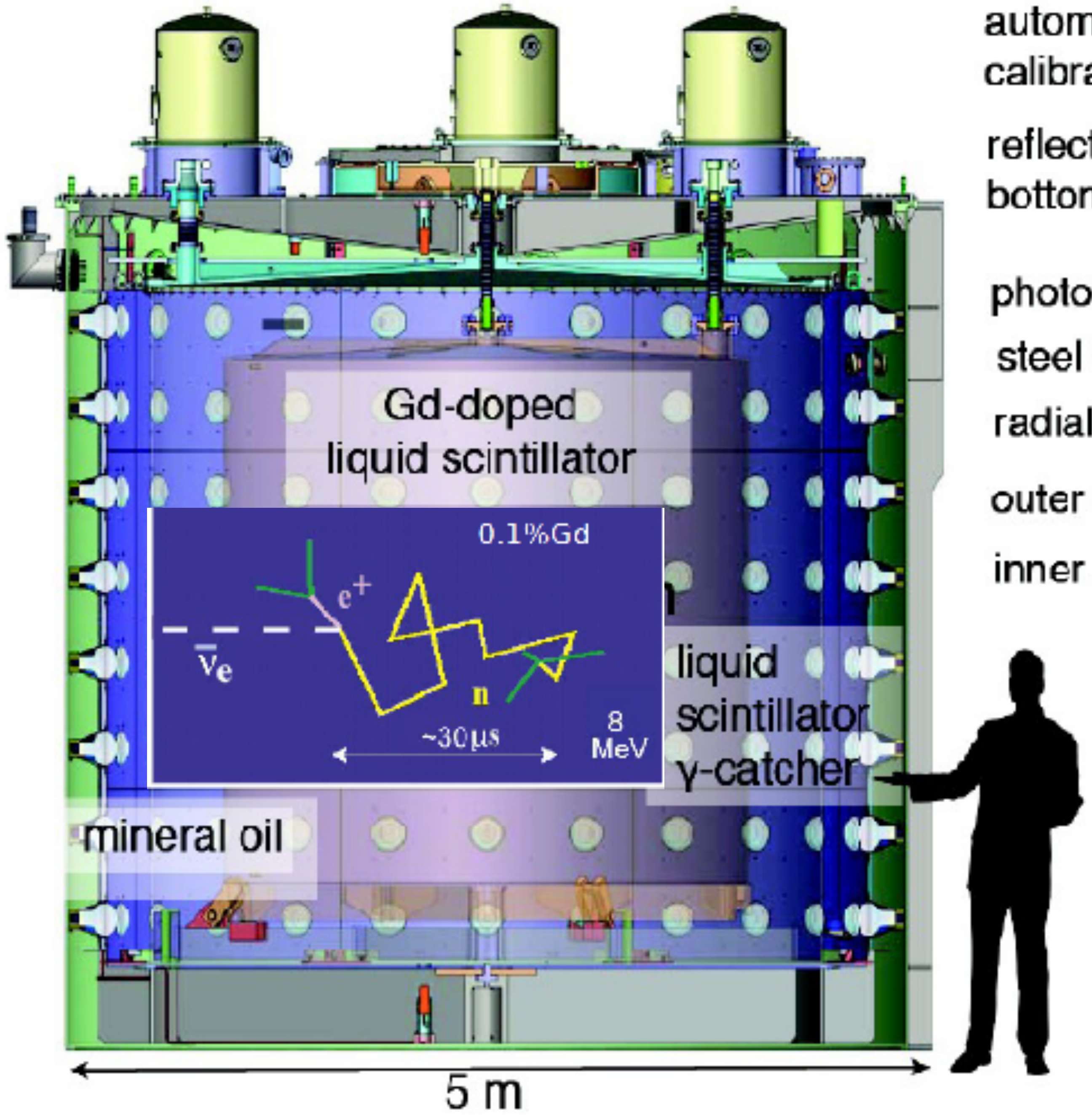
Detector mass needed for 1000 reactor evts/yr ?

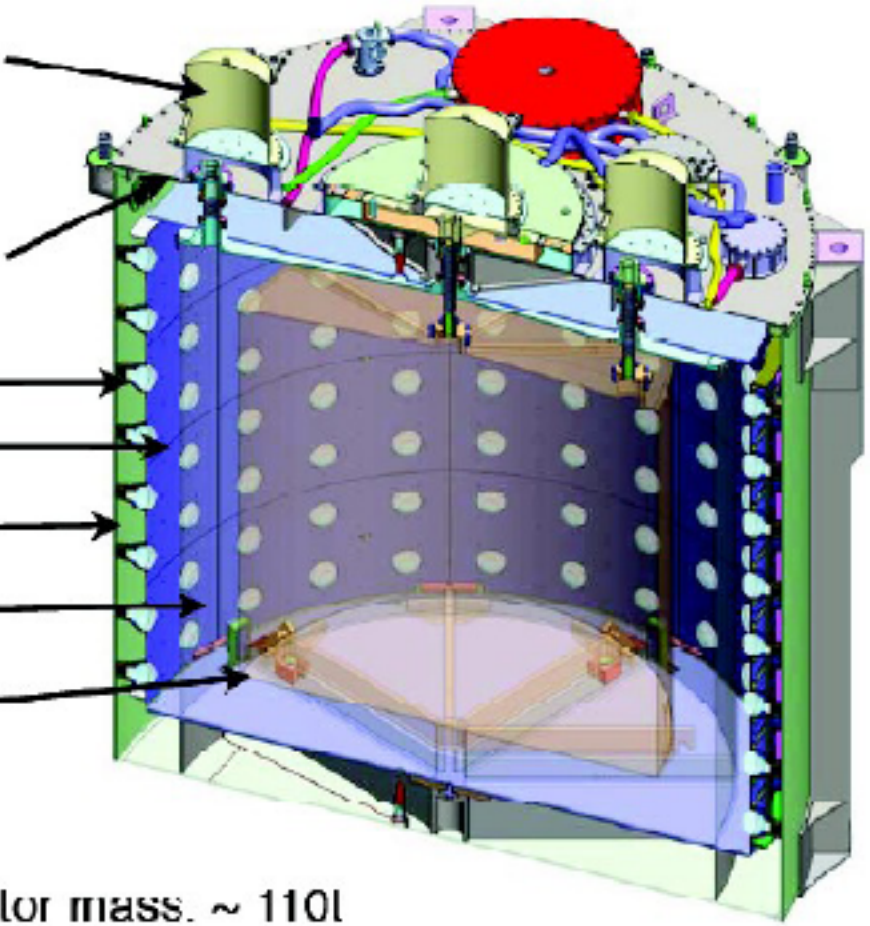
- Detector distance d = 100000 cm. (1 km)
- Yield = 2×10^{20} /sec for GW
- Flux = 1.6×10^{9} /cm^2/sec (assuming 4 pi)
- Protons = (2/3) x 10^{29} /ton
- Fraction above 2 MeV ~ 0.1
- Cross section ~ 0.9×10^{-42} cm^2
- 1 year = 3×10^{7} sec
- N = Flux* Fraction*cross section*Protons/ton*1 year
- N = 290 per ton per year for 1 GW reactor. at 1 km.

Daya Bay Experimental Method

- **Daya Bay has 6 cores each 2.9 GW ➜ 17.4 GW total**
- **The geography is ideal with hills rising away from the bay.**
- **We placed several detectors close to the reactors and several far away to understand neutrino physics called oscillations.**
- **Location is northeast of Hong Kong**

Daya Bay Antineutrino Detectors (AD)





Total detector mass: ~ 110t

inner: 20 tons Gd-doped LS (d=3m)
mid: : 22 tons LS (d=4m)
outer: 40 tons mineral oil buffer (d=5m)

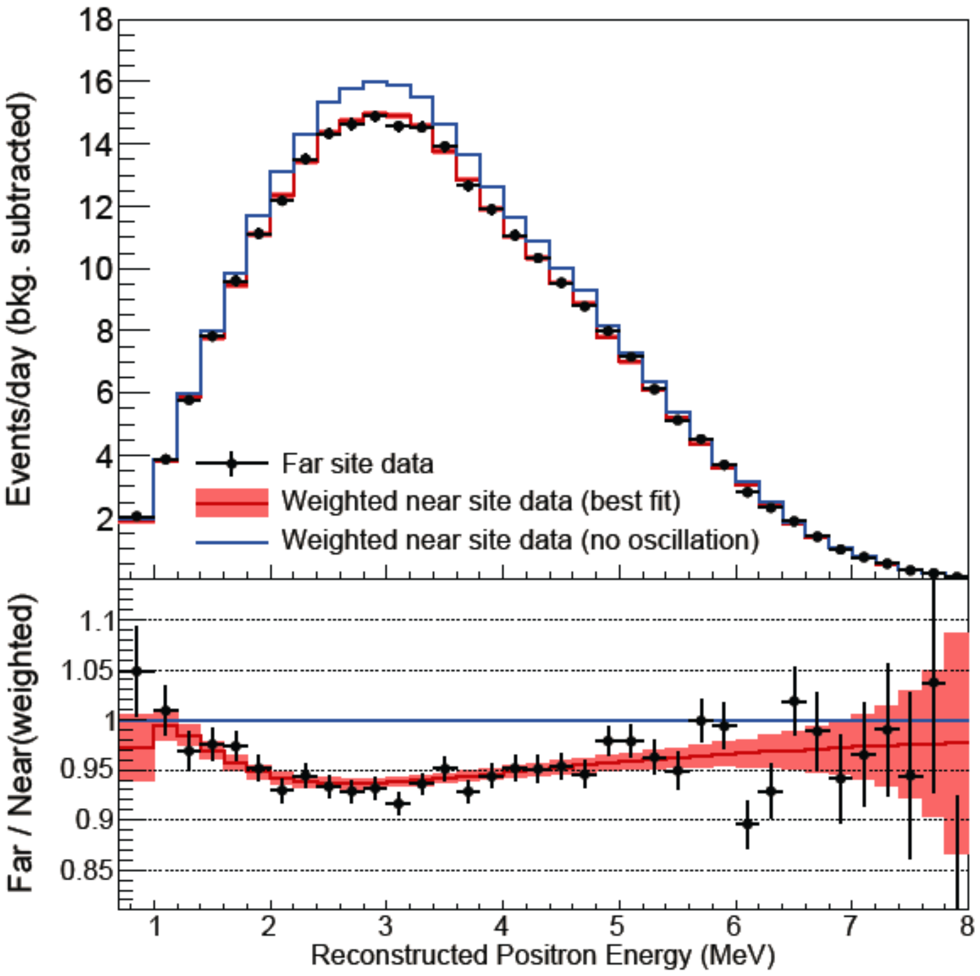
photosensors: 192 8"-PMTs

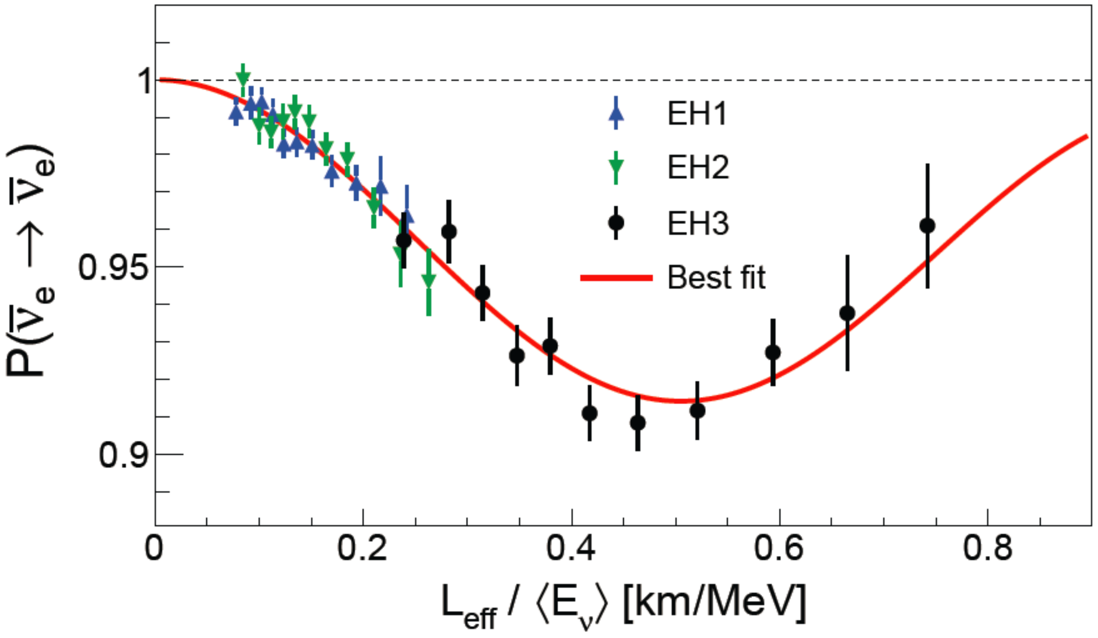
$$Yield = 10^4\, MeV^{-1} \times Coverage \times QE$$
$$= 10^4 \times 0.08 \times 0.2 \sim 160\ pe/MeV$$

8 "functionally identical", 3-zone detectors reduce systematic uncertainties.

Very well defined target region

Result From Daya Bay with data up to Nov 2013.



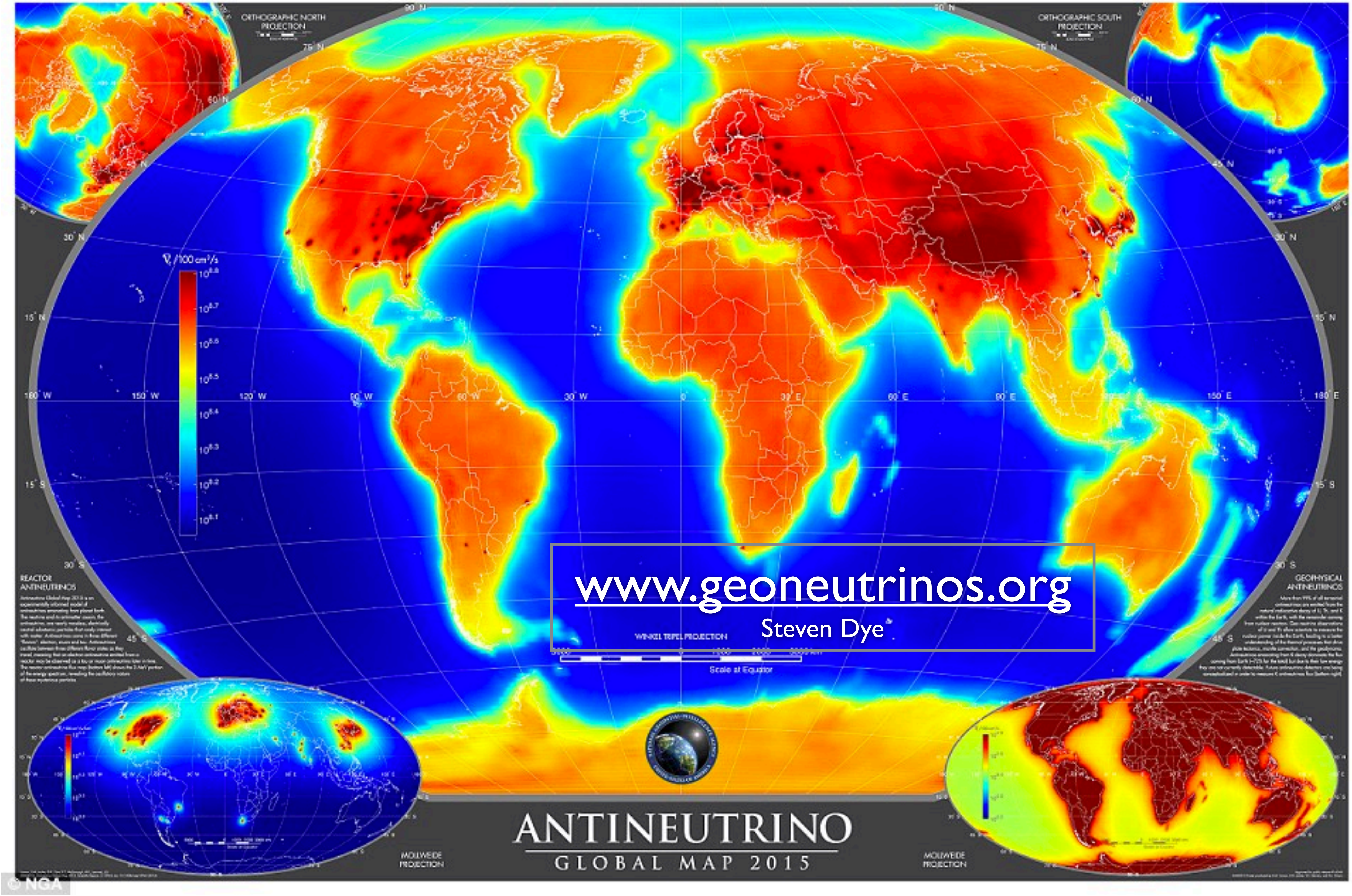


$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$

- Using 217 days of 6 AD data and 404 days of 8 AD data.
- Total of 1.2 M events

Can we use neutrinos to see/monitor reactors ? Yes, need to develop inexpensive and effective technologies. Please see Minfang Yeh’s lecture.

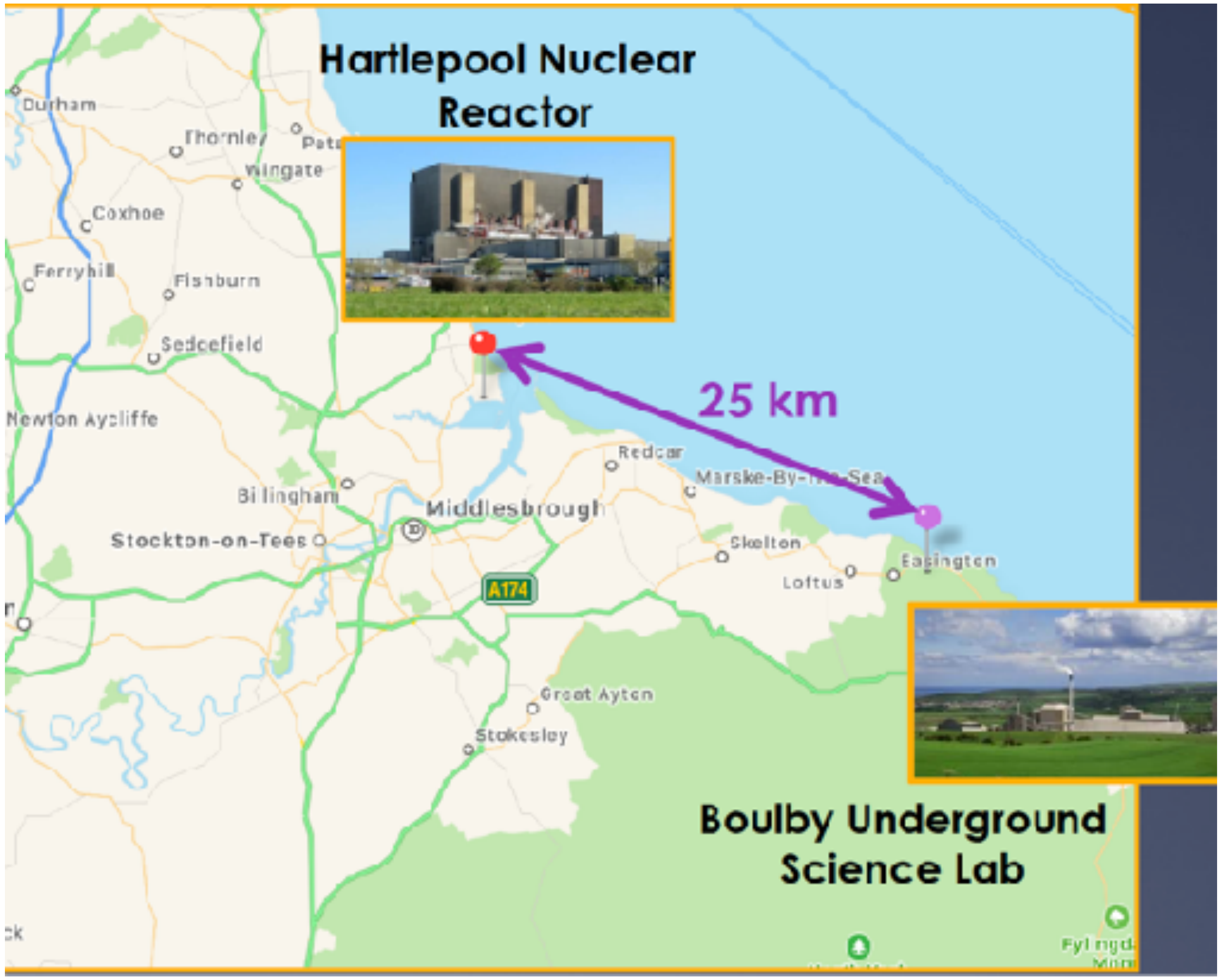


www.geoneutrinos.org

Steven Dye

AIT/NEO or Watchman project.

- Remote monitoring demonstration project for a single reactor for non-proliferation.
- Verify, to 3 sigma, the presence of a nuclear reactor within a reasonable period of time.
- Technology: 1 ton scale Gd-loaded water-based anti-neutrino detector located 20-30 km from a fission reactor.
- AIT - Advanced Instrumentation Testbed. NEO- Neutrino Experiment
- Test bench for R&D for detector materials, sensors, electronics, and backgrounds.
- Could include physics topics by additional requirements. Supernova, Solar neutrinos, etc.



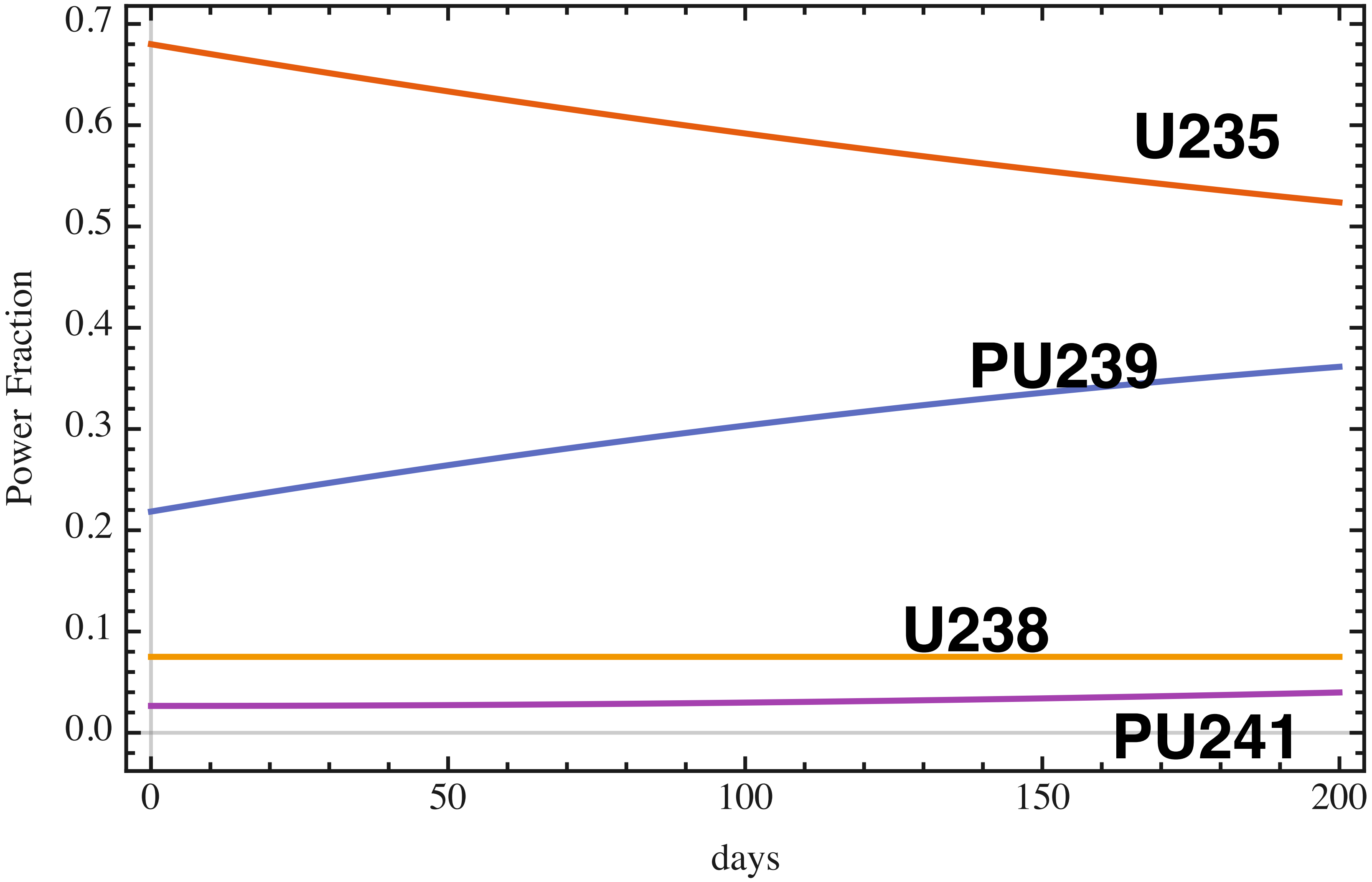
Being planned jointly by DOE and UK/STFC

Location: East Coast of UK.

Conclusion

- **This lecture was about the basics of neutrino detectors.**
- **Specifically we examined detection of anti-neutrinos from nuclear reactors. This could form the basis for remote monitoring of reactors if the technology could be scaled up at low cost.**
- **The most important feature is inexpensive mass.**
- **Detectors are designed to measure light emission from neutrino interactions.**
- **For each application additional considerations must be made**
    - **Background from cosmic rays and radioactivity.**
    - **reduction of background by using coincidence of prompt and delayed neutron.**
    - **Energy threshold and resolution**
    - **Time and location of events in the detector.**

How to calculate reactor spectra

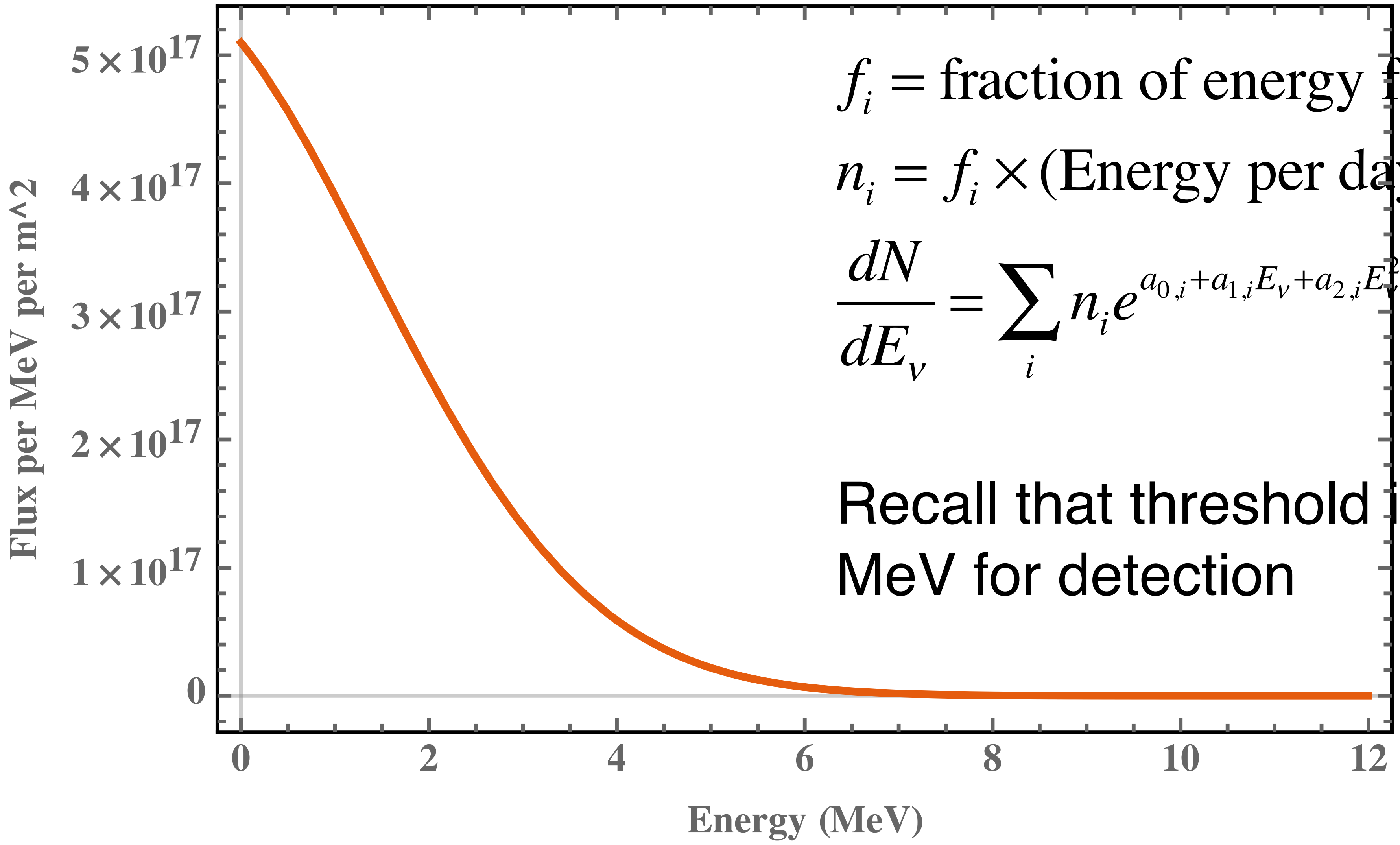


First calculate power produced by each isotope.

In a real experiment the power company will provide this information.

The reactor spectrum parameterization from Vogel and Engel based on data by Schreckenbach. New methods use tabulated beta decay spectra.

Reactor Spectrum



f_i = fraction of energy from isotope i

$n_i = f_i \times (\text{Energy per day})/(\text{Energy per fission})$

$$\frac{dN}{dE_\nu} = \sum_i n_i e^{a_{0,i}+a_{1,i}E_\nu+a_{2,i}E_\nu^2}$$

Recall that threshold is 1.8 MeV for detection

Isotope	U235	Pu239	U238	Pu241
Energy (MeV)	201.7	205.0	210.0	212.4
a0	0.870	0.896	0.976	0.793
a1	-0.160	-0.239	-0.162	-0.080
a2	-0.0910	-0.0981	-0.0790	-0.1085