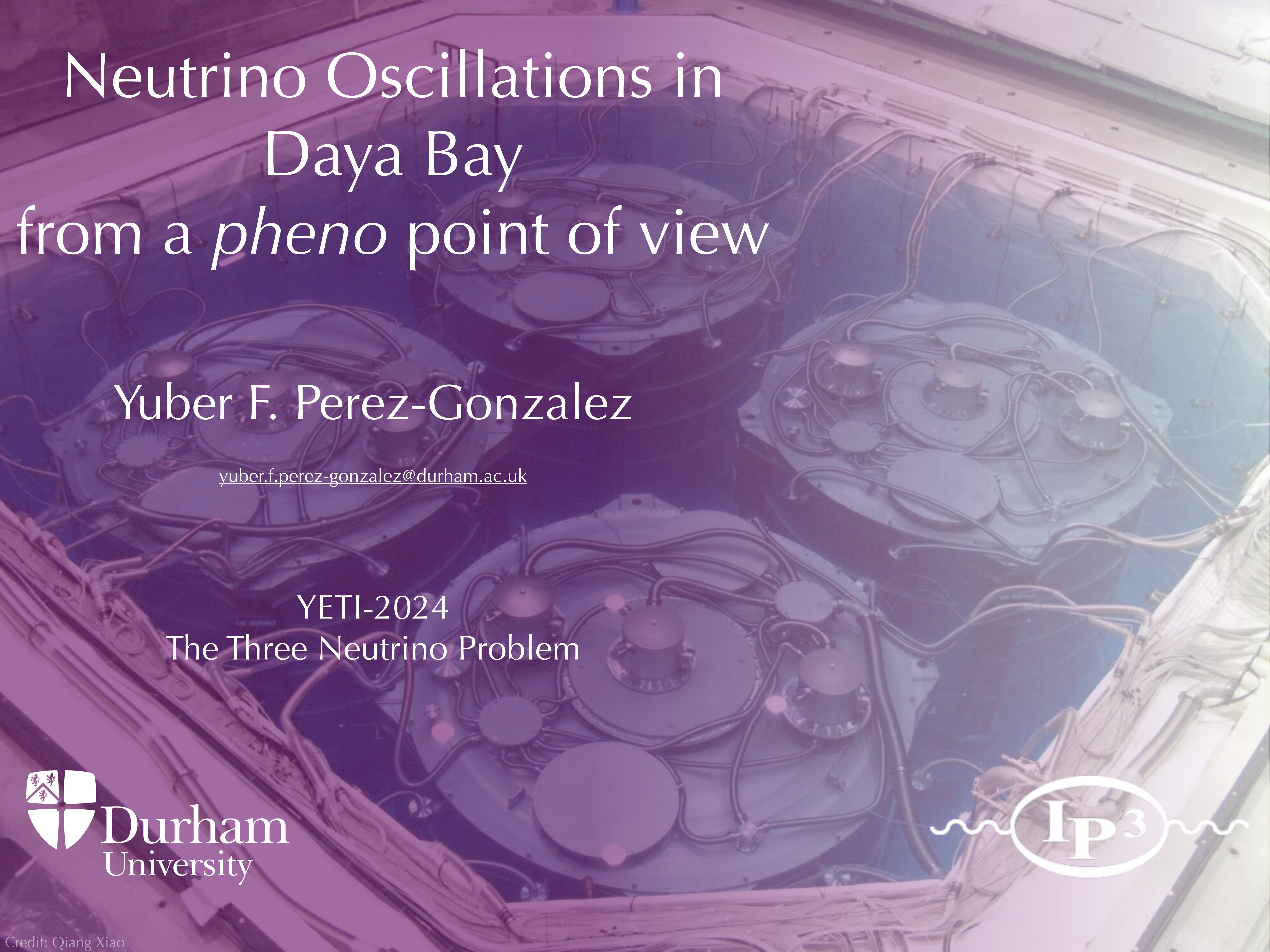


Neutrino Oscillations in Daya Bay from a *pheno* point of view

Yuber F. Perez-Gonzalez

yuber.f.perez-gonzalez@durham.ac.uk

YETI-2024
The Three Neutrino Problem

Credit: Qiang Xiao

The reason for the Daya Bay experiment

Looking back 20 years: The year 2004

Massive Neutrinos 2024

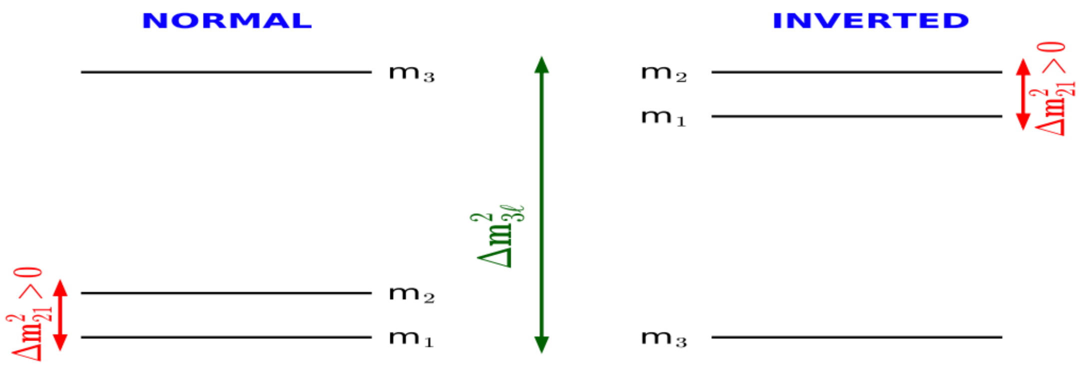
3ν Flavour Parameters

Concha Gonzalez-Garcia

- **For for 3 ν's :** 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \xcancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

- Convention: $0 \le \theta_{ij} \le 90°$ $\;0 \le \delta \le 360°$ $\;\Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

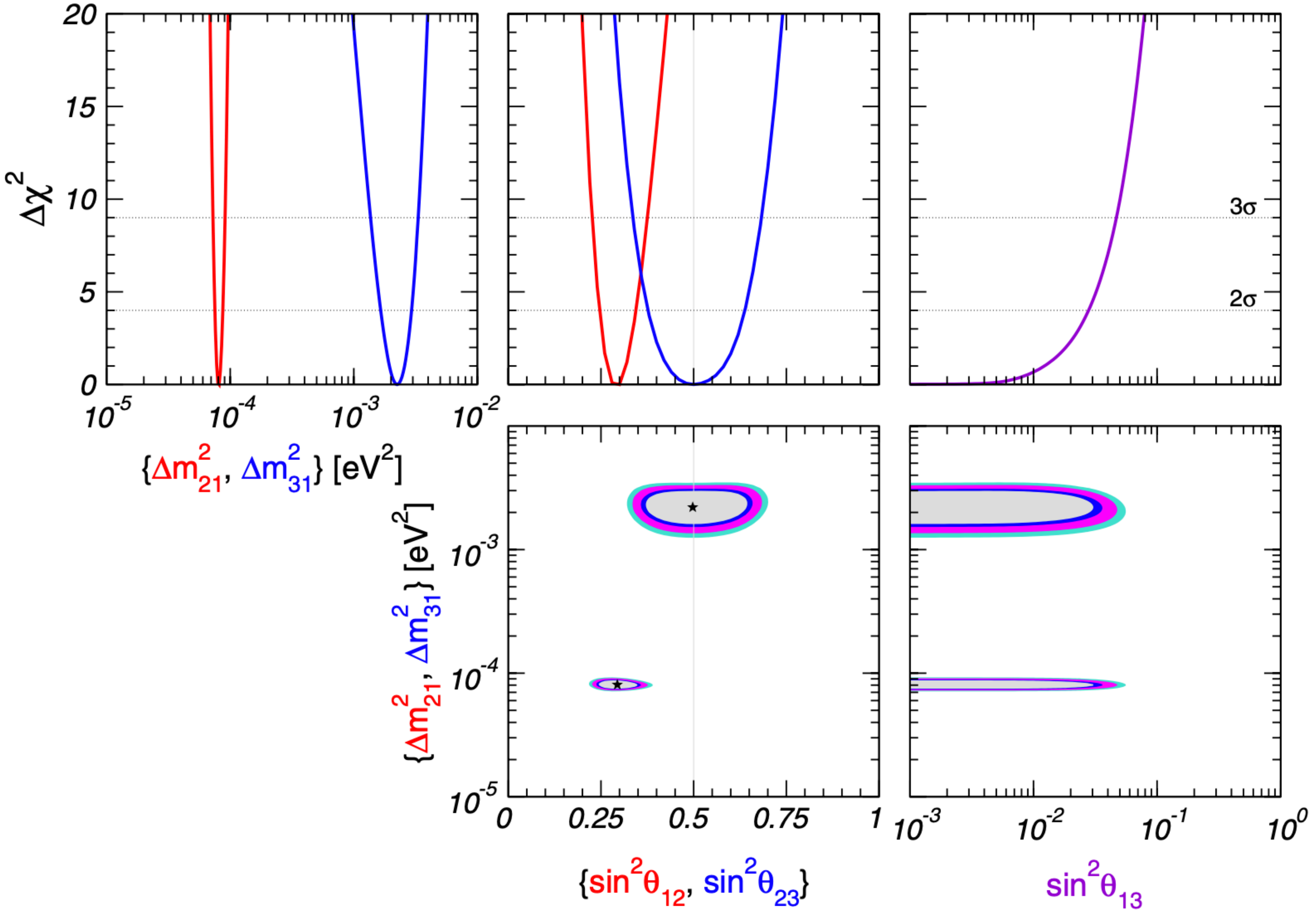
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

Experiment	Dominant	Important	Additional
Solar Experiments	θ_{12}	Δm^2_{21}	θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}	θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13}, $\Delta m^2_{3\ell}$		
Atmospheric Experiments (SK,IC)	θ_{23}	$\Delta m^2_{3\ell}$	θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$. θ_{23}		
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$		θ_{13}

Looking back 20 years: The year 2004

Rather interesting things were happening with neutrino oscillations!

Status circa 05/2004



Maltoni et al,
New. J. Phys. 6, 122 (2004)

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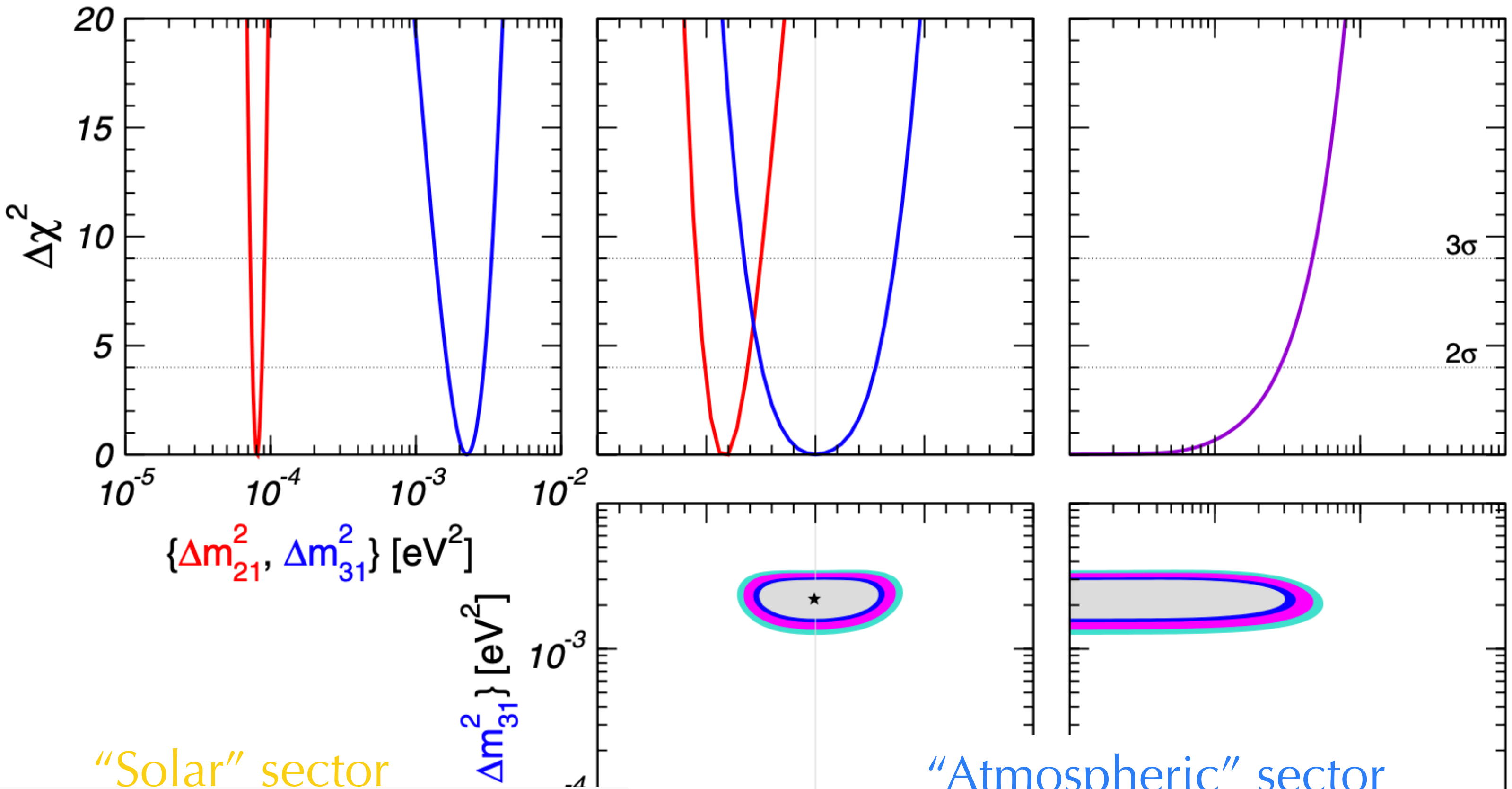
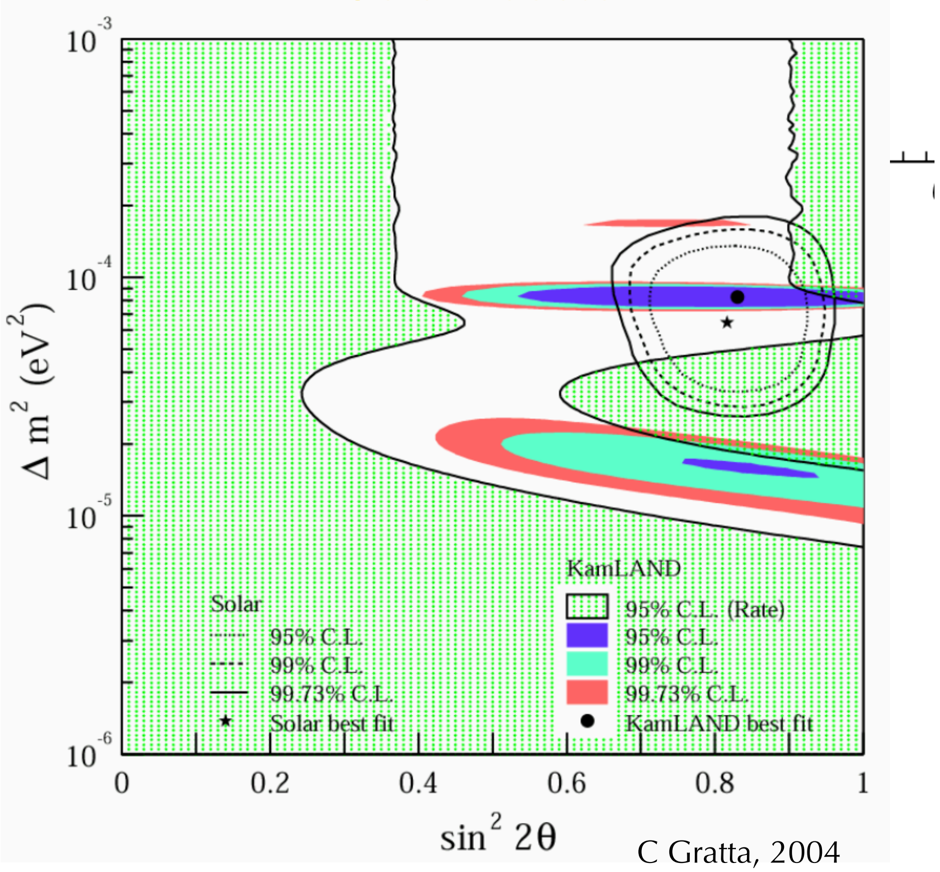


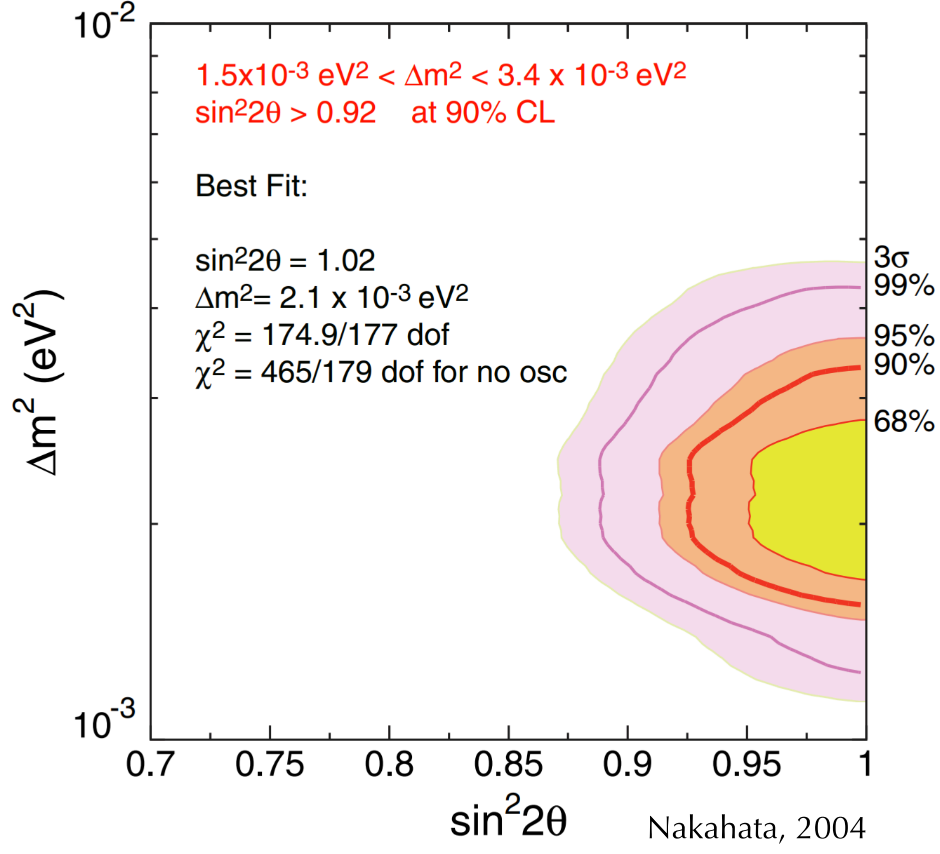
"Solar" sector

"Atmospheric" sector

Neutrino 2004
Paris



C Gratta, 2004



$1.5\text{x}10^{-3}$ eV^2 < Δm^2 < $3.4 \text{ x } 10^{-3}$ eV^2
$\sin^2 2\theta > 0.92$ at 90% CL

Best Fit:

$\sin^2 2\theta = 1.02$
$\Delta m^2 = 2.1 \text{ x } 10^{-3}$ eV^2
$\chi^2 = 174.9/177$ dof
$\chi^2 = 465/179$ dof for no osc

Nakahata, 2004

Maltoni et al,
New. J. Phys. 6, 122 (2004)

Looking back 20 years: The year 2004

What about θ_{13}?

Looking back 20 years: The year 2004

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Reactor $\overline{\nu}_e$ disappearance
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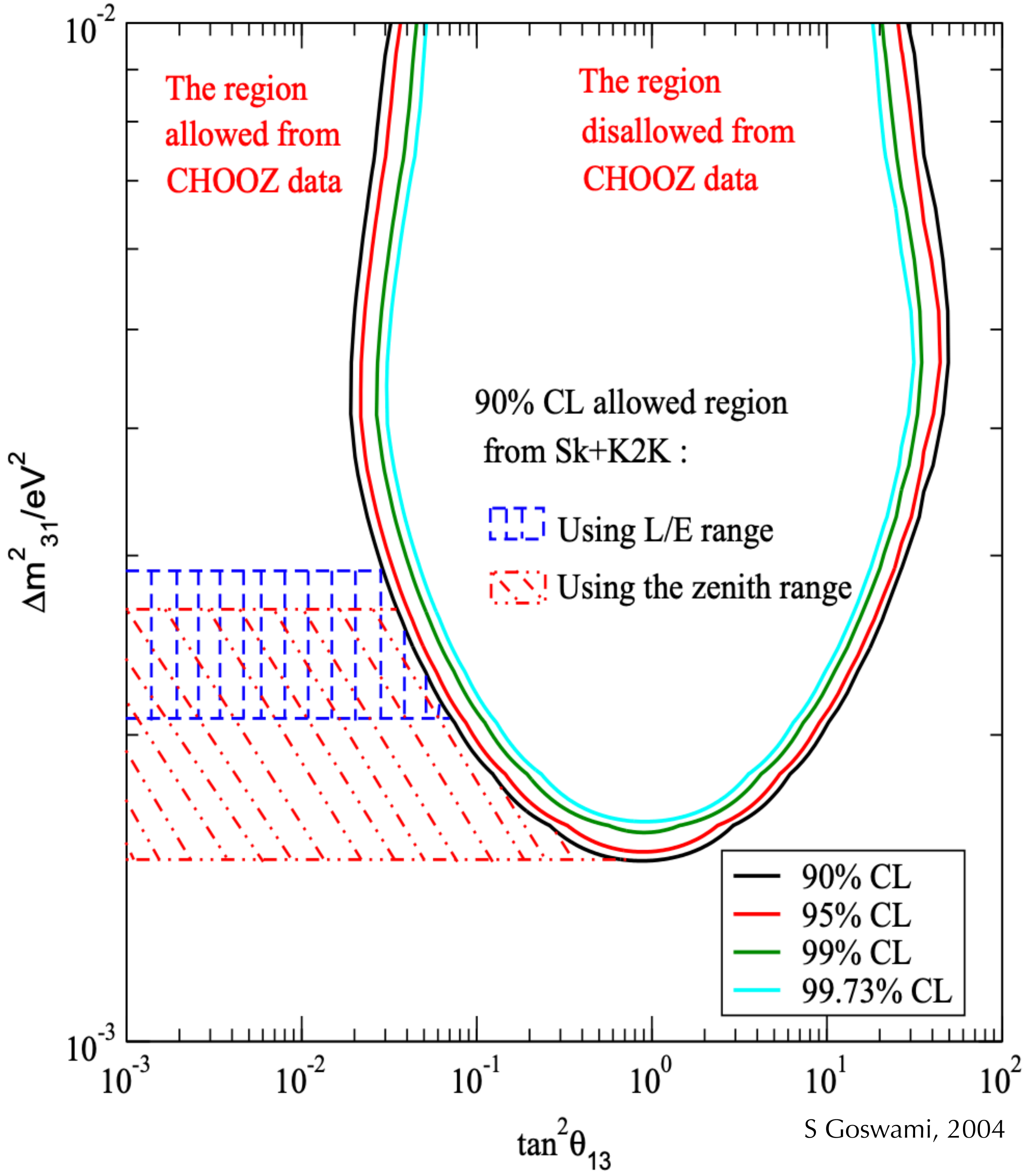


S Goswami, 2004

How to detect $\bar{\nu}_e$?

Inverse Beta Decay

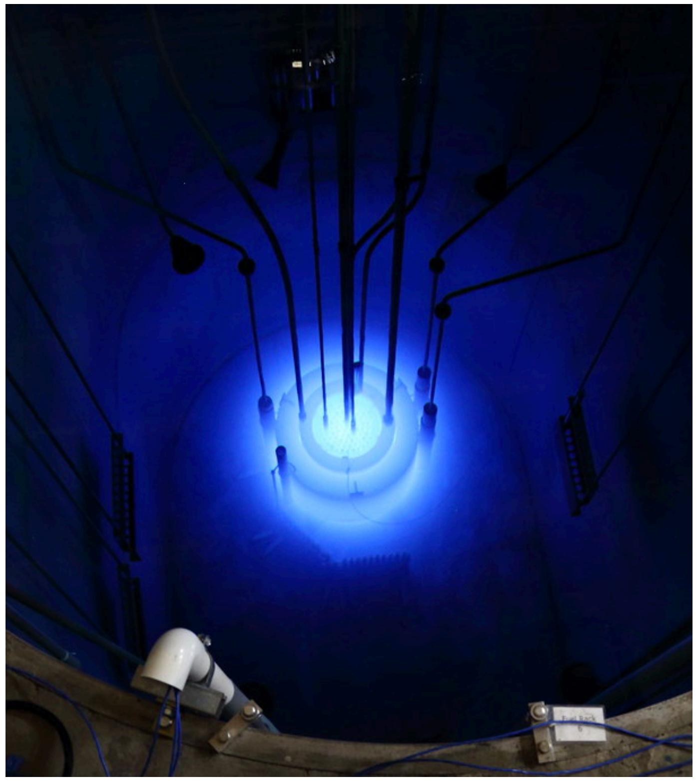
$n \to p^+ + e^- + \bar{\nu}_e$ → $\bar{\nu}_e + p^+ \to n + e^+$

How to detect $\overline{\nu}_e$?

Inverse Beta Decay

$$n \to p^+ + e^- + \bar{\nu}_e \quad \Longrightarrow \quad \bar{\nu}_e + p^+ \to n + e^+$$

$\Phi_{\bar{\nu}} \sim 2 \times 10^{20}\ \mathrm{s}^{-1}/\mathrm{GW}$



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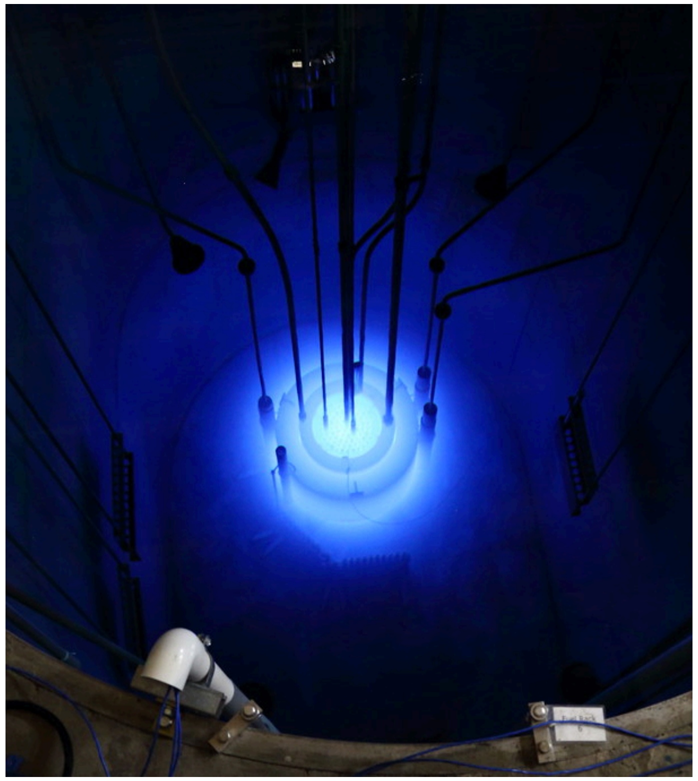

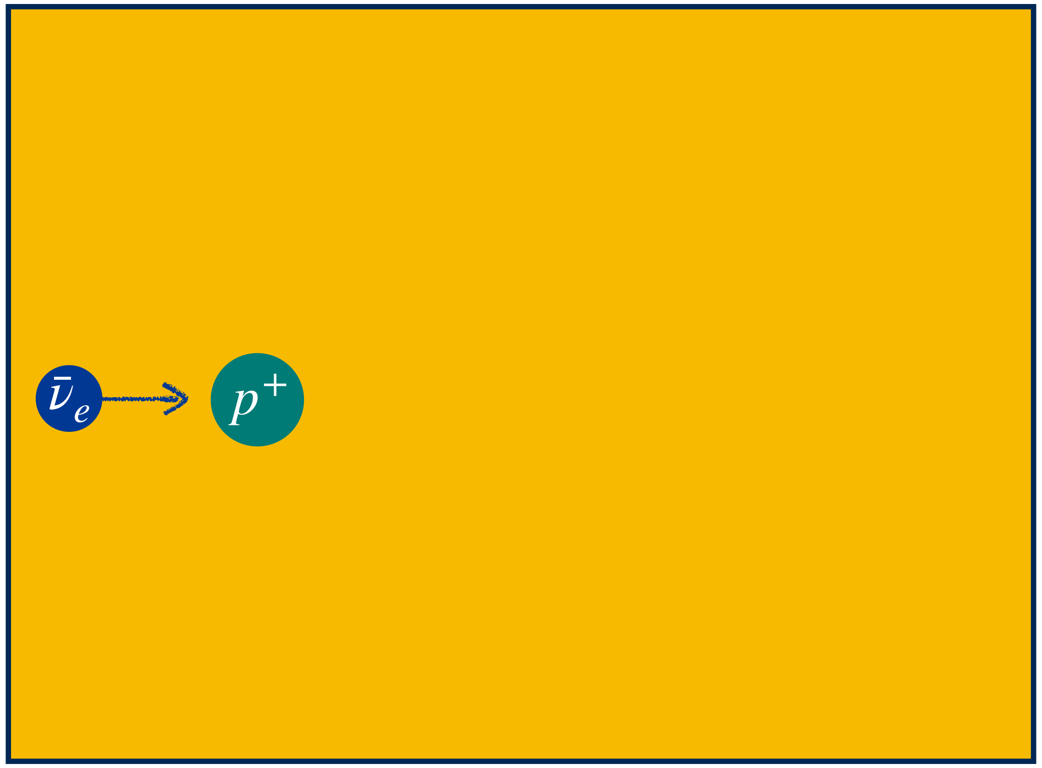

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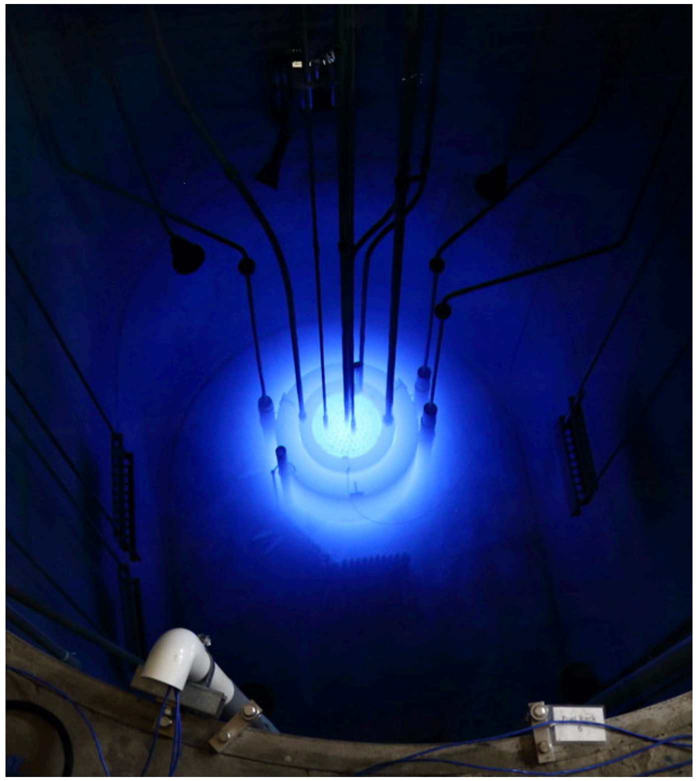

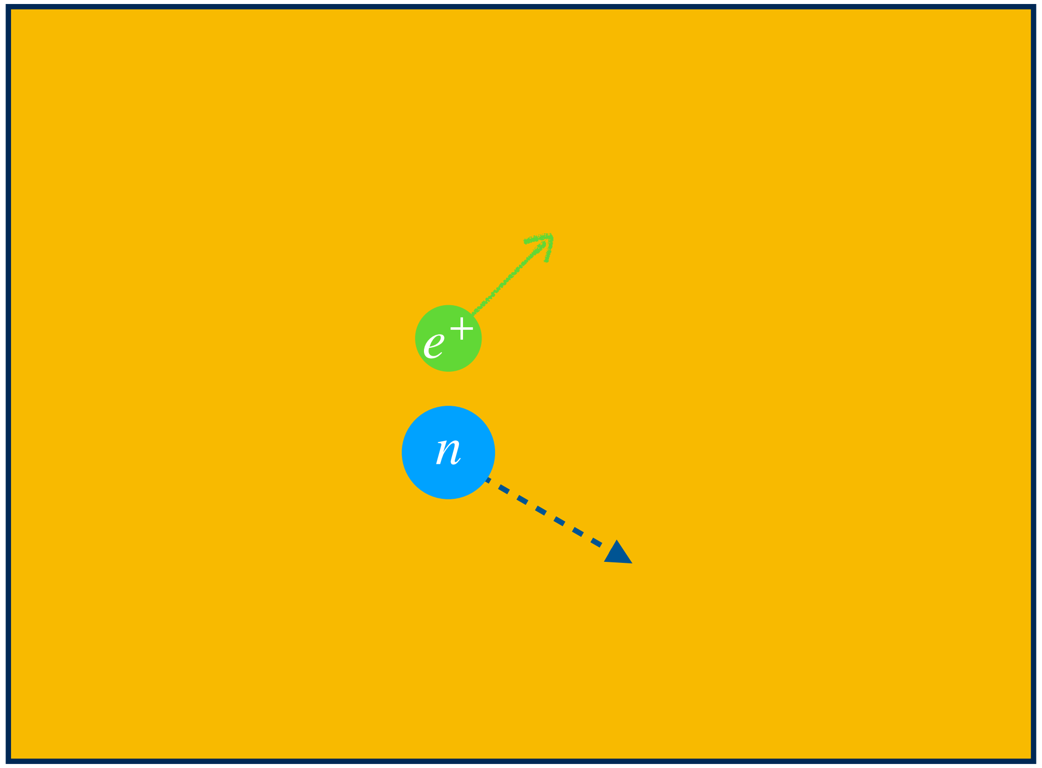

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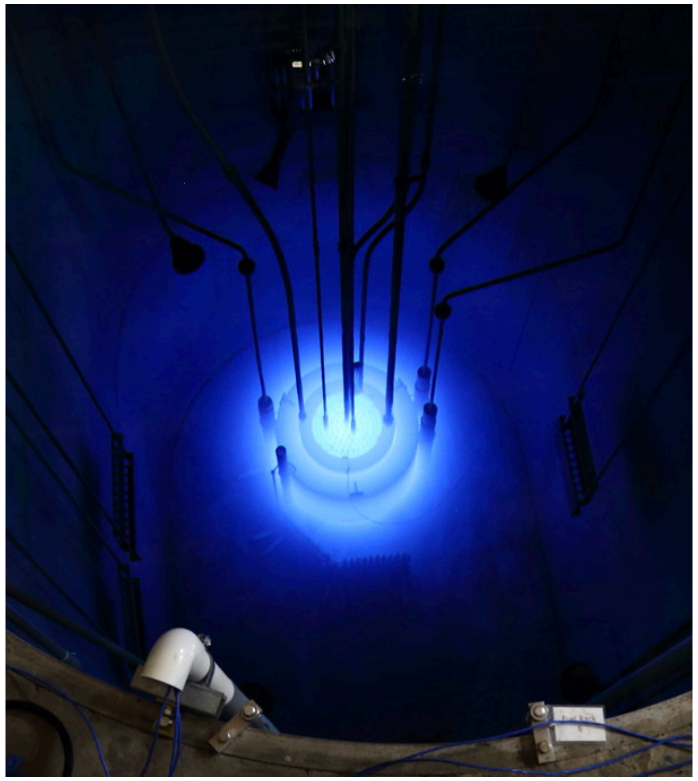

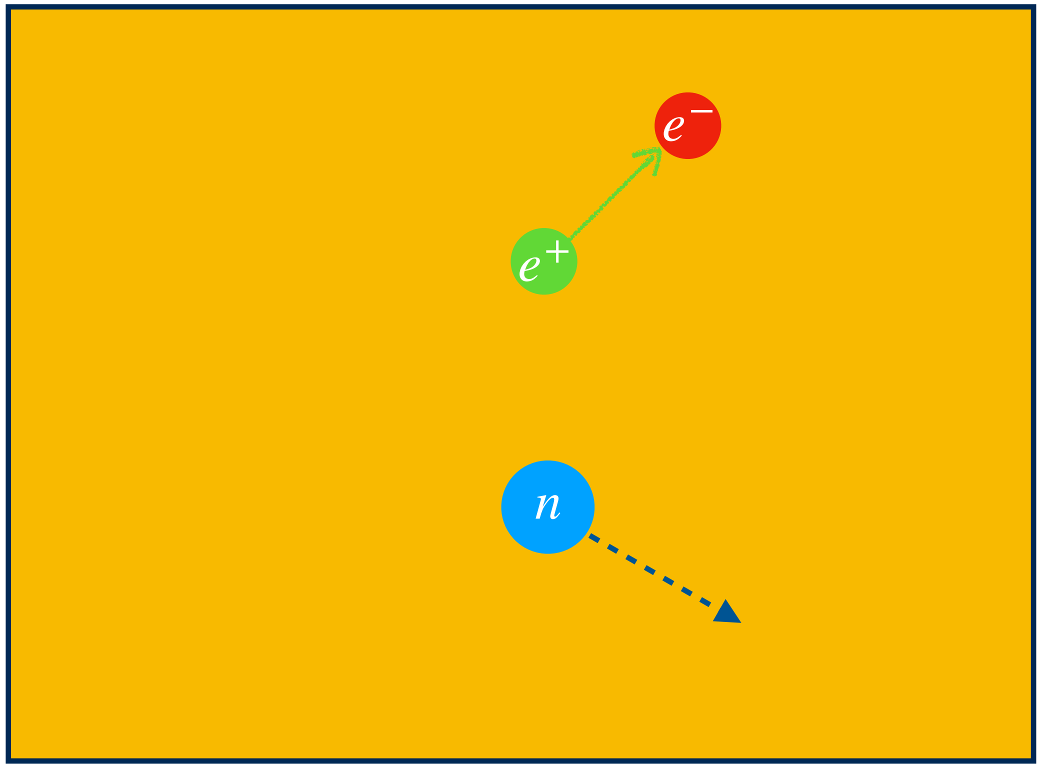

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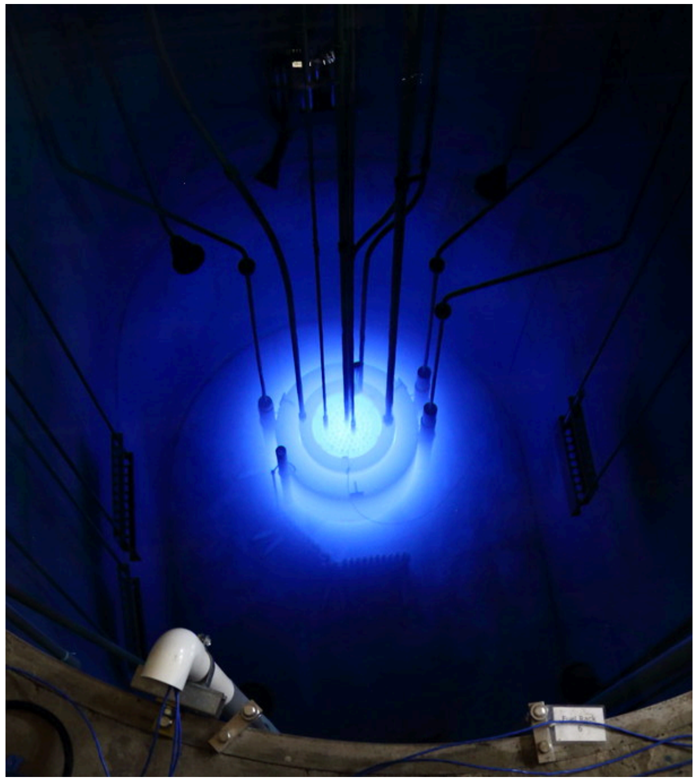

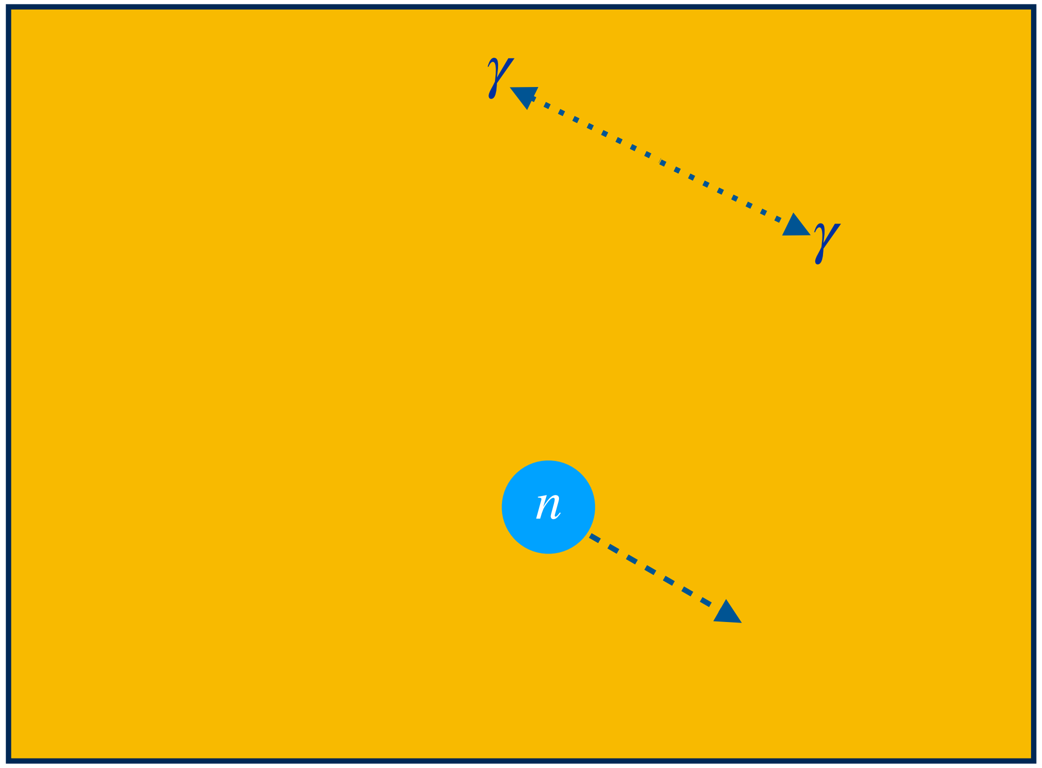

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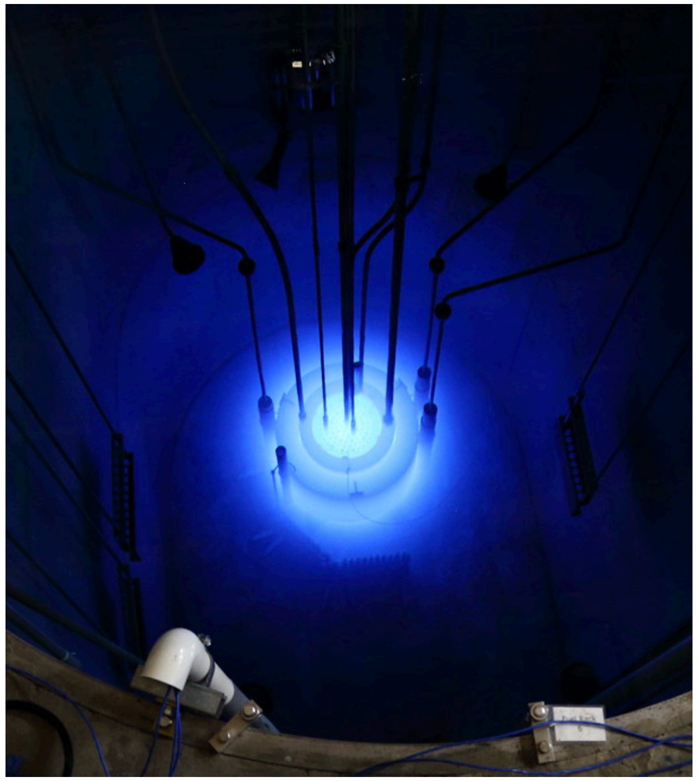

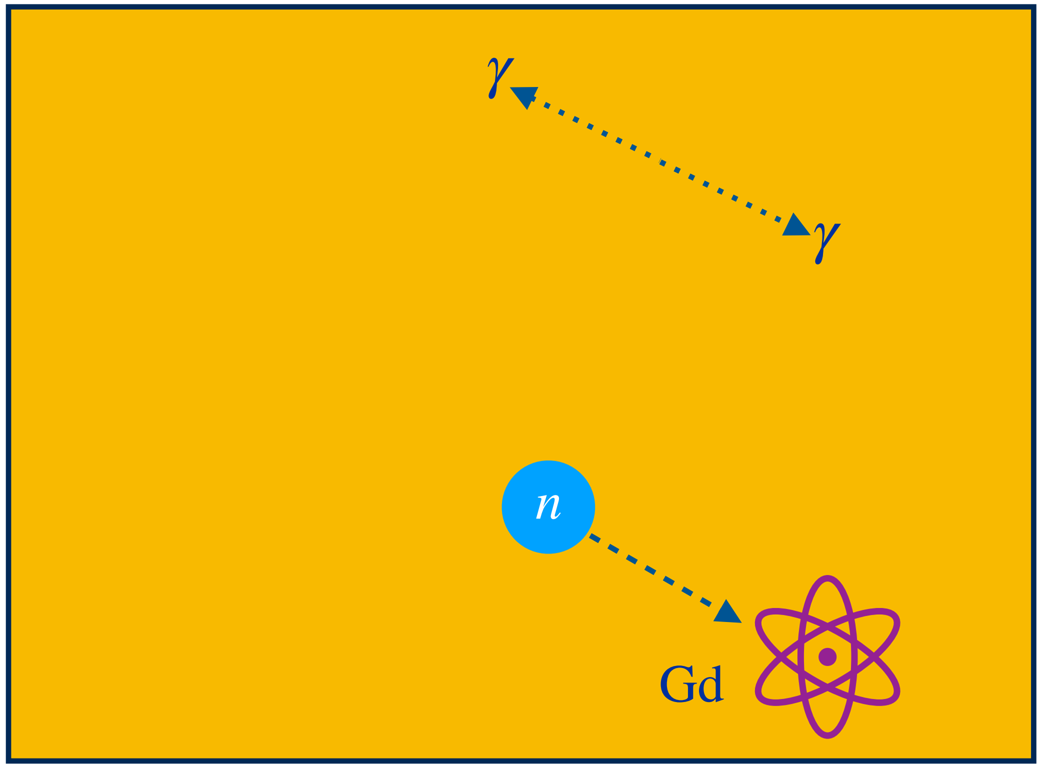

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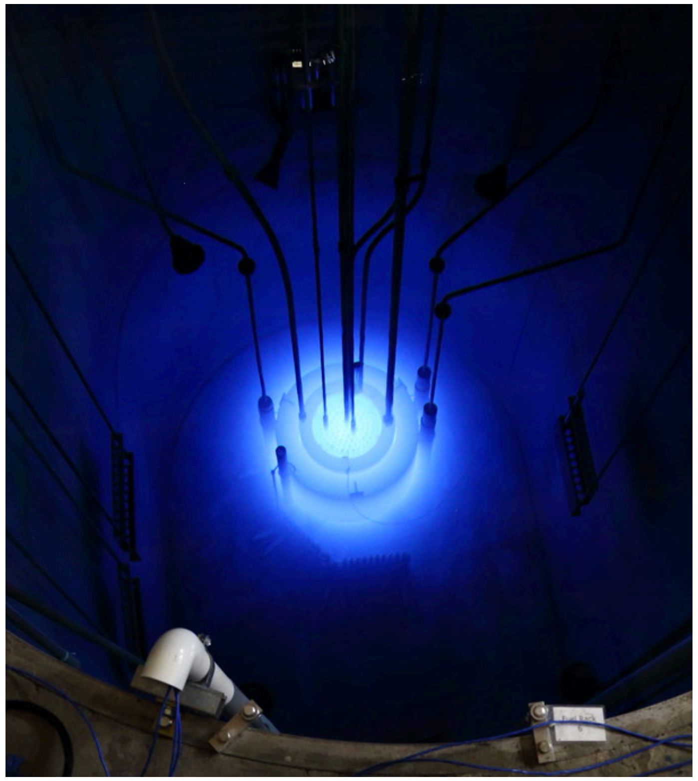
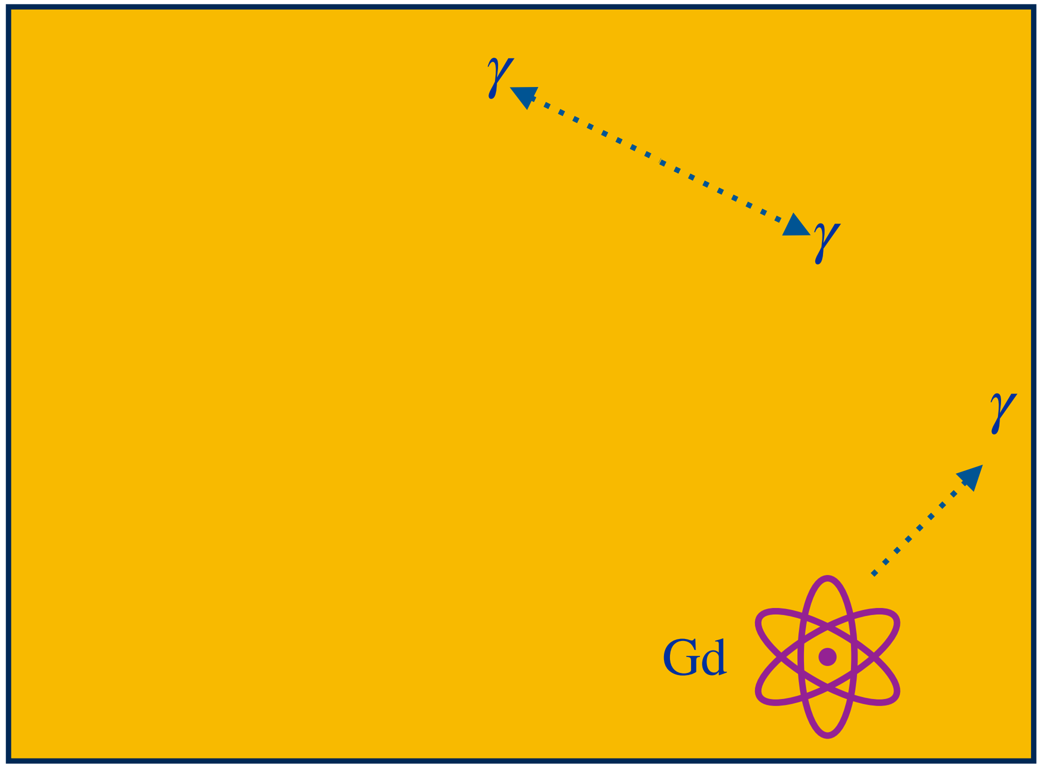




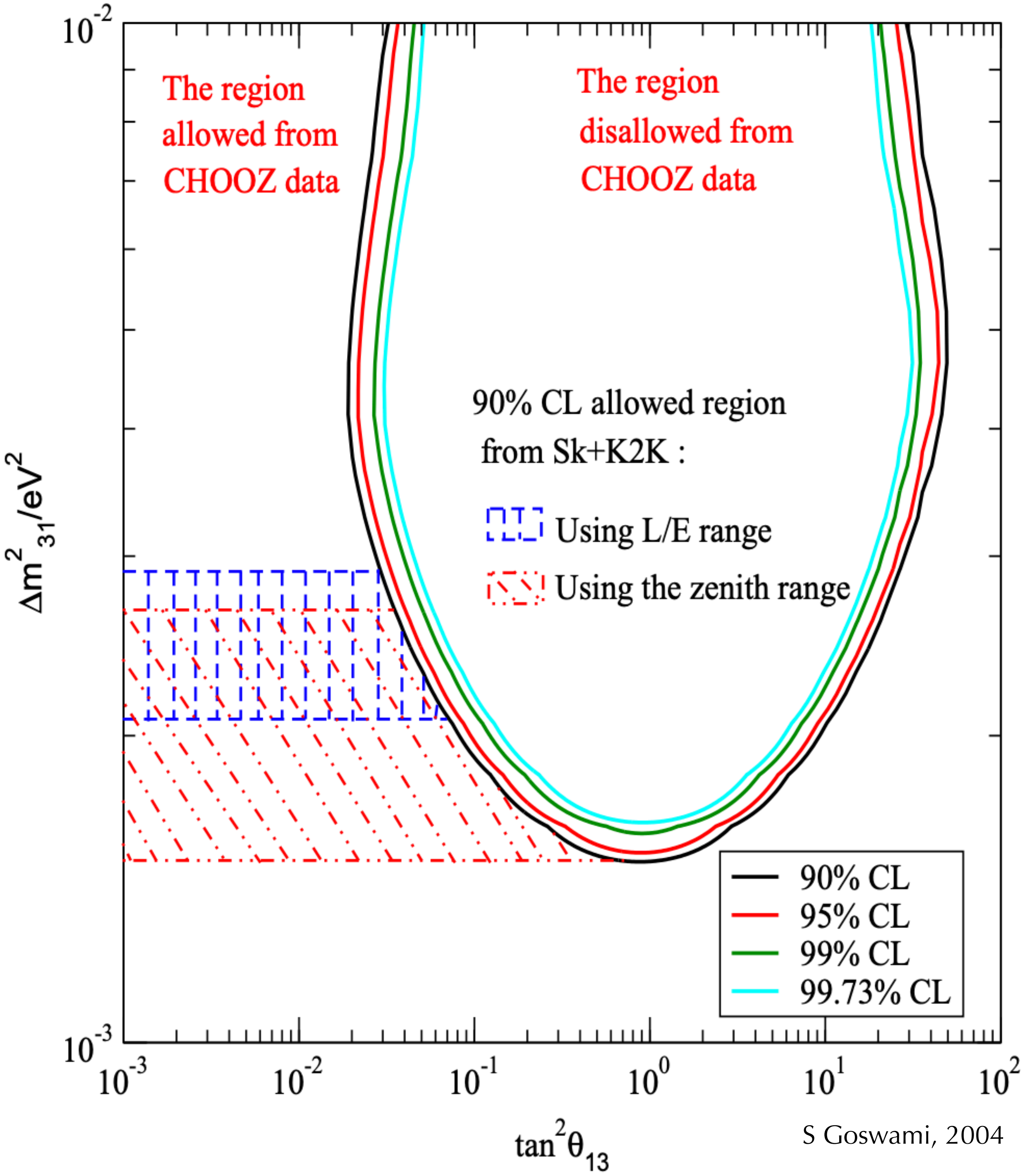
$\Delta t \sim 30\ \mu\mathrm{s}$

Looking back 20 years

What about θ_{13}?

Reactor $\overline{\nu}_e$ disappearance offer a window to $\Delta m^2 \sim 10^{-2} - 10^{-3}\ \mathrm{eV}^2$ for distances of $\mathcal{O}(\mathrm{km})$

Null results from CHOOZ



S Goswami, 2004

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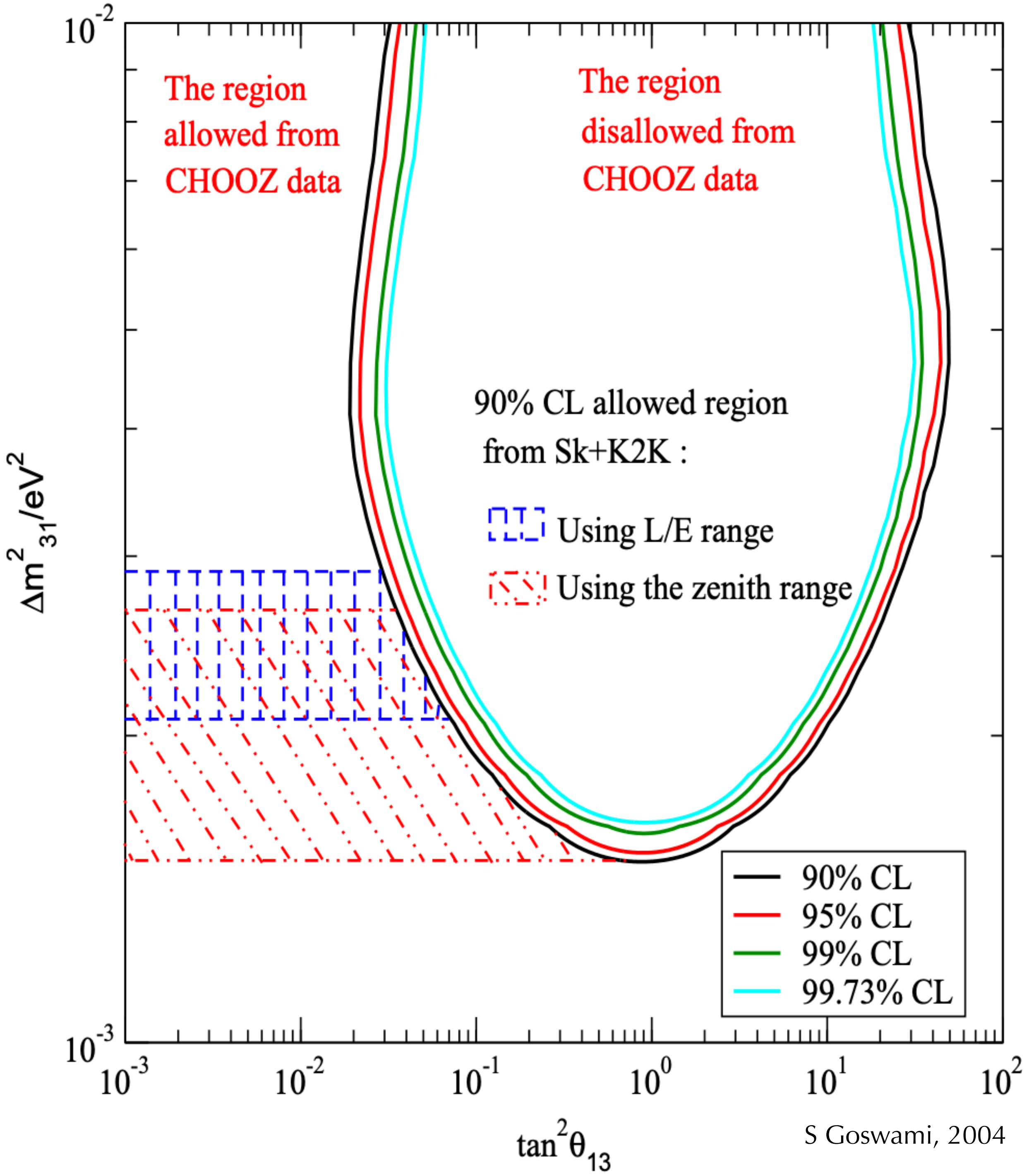
Main issue: Large systematic uncertainties

- Total flux
- Cross sections
- Efficiencies
- Time dependence



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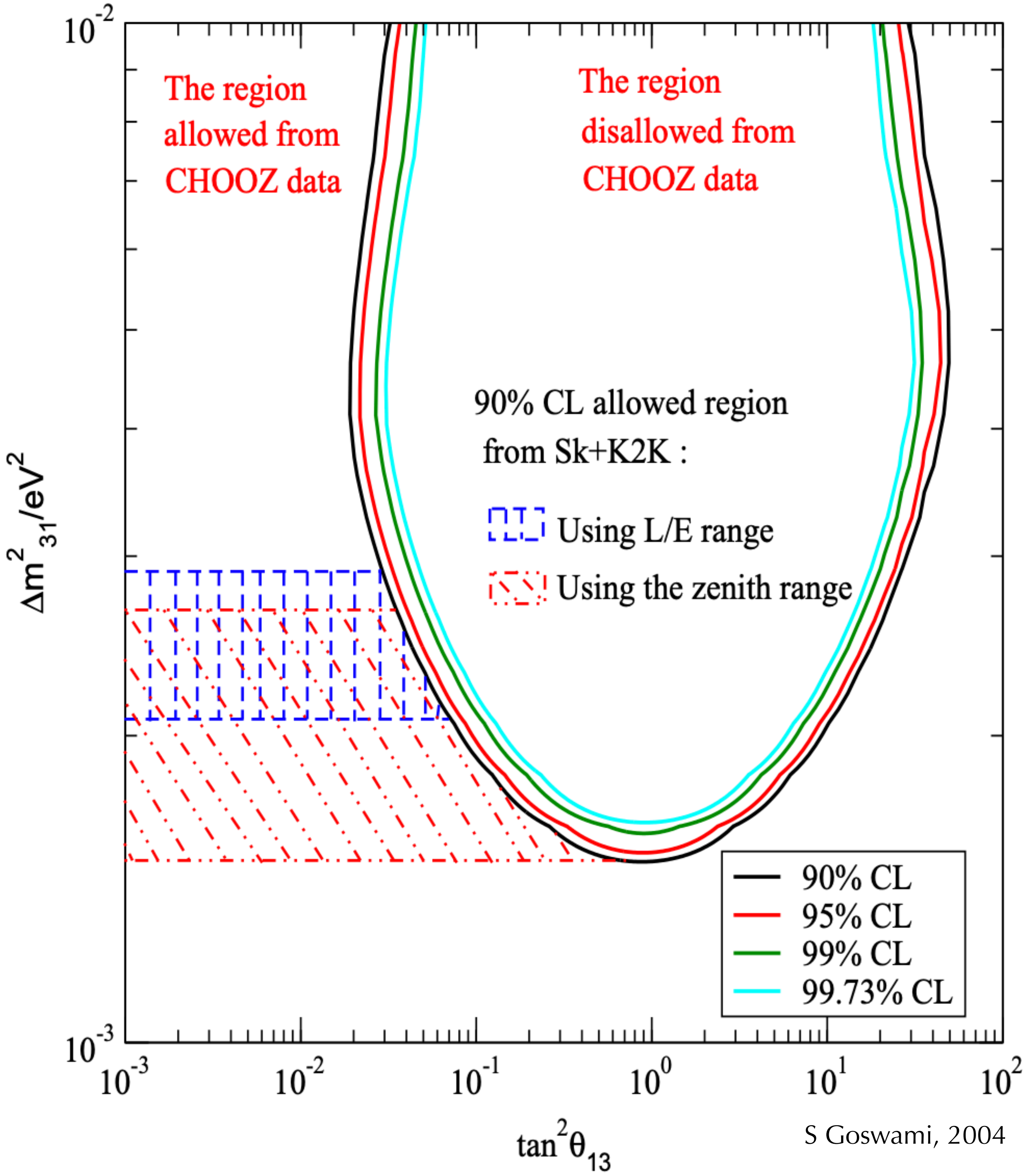

S Goswami, 2004

Neutrino oscillations with Reactor $\bar{\nu}_e$

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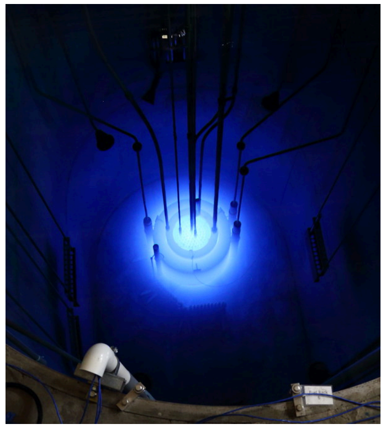

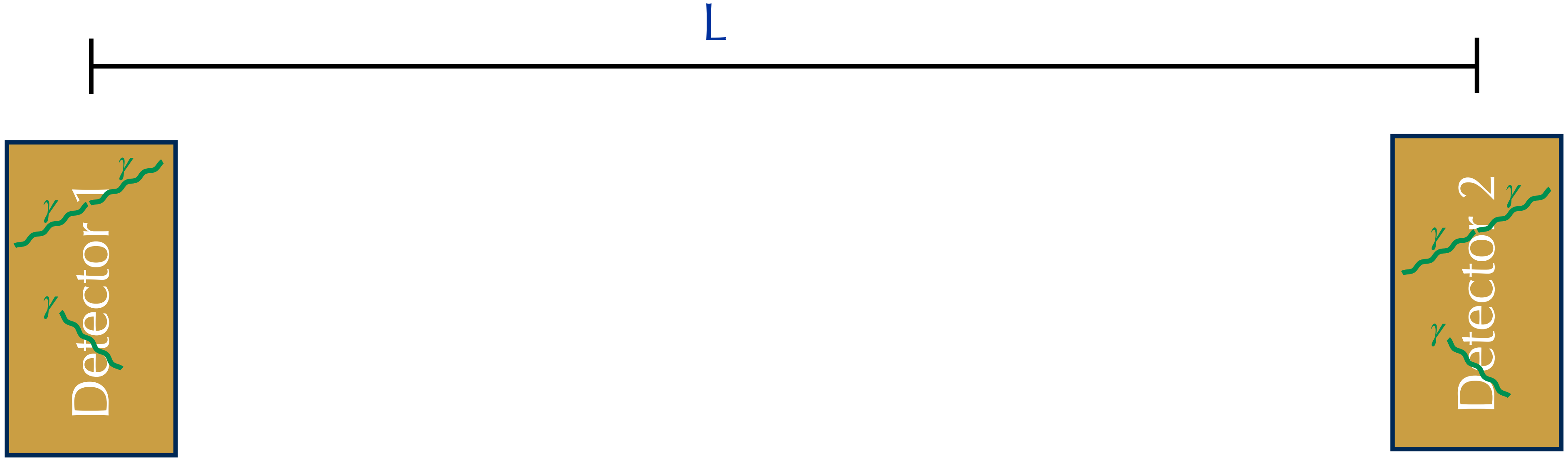

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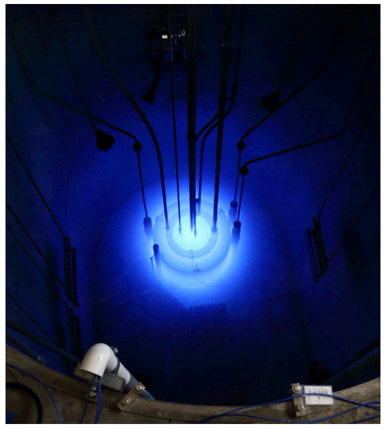
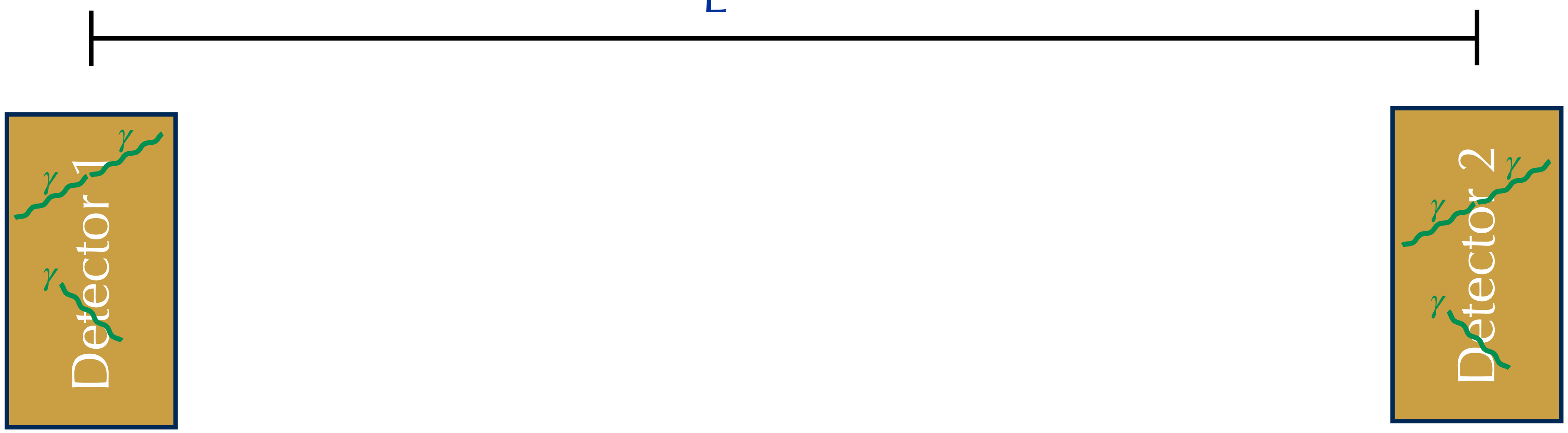




$$\frac{\Phi_{\overline{\nu}_e}(L)}{\Phi_{\overline{\nu}_e}(0)} \longrightarrow P(\overline{\nu}_e \to \overline{\nu}_e)$$

Disappearance Probability

Neutrino oscillations with Reactor $\overline{\nu}_e$

$$\frac{\Phi_{\overline{\nu}_e}(L)}{\Phi_{\overline{\nu}_e}(0)} \longrightarrow P(\overline{\nu}_e \to \overline{\nu}_e)$$

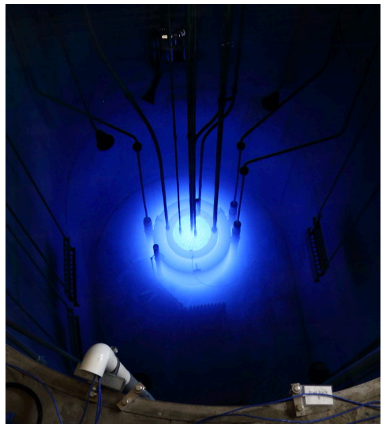
Disappearance Probability

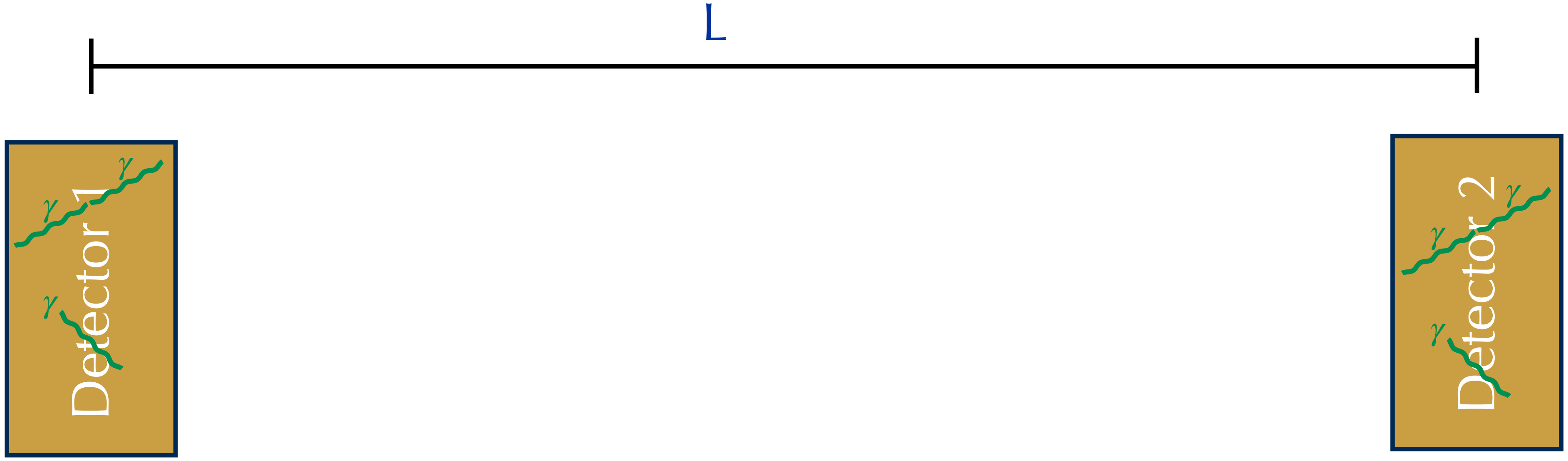
In the 3-ν framework

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\Delta_{ij} = 1.267\left(\frac{\Delta m_{ij}^2}{1\ \mathrm{eV}^2}\right)\left(\frac{L}{1\ \mathrm{m}}\right)\left(\frac{1\ \mathrm{MeV}}{E_\nu}\right)$$

Neutrino oscillations with Reactor $\overline{\nu}_e$





$$\frac{\Phi_{\overline{\nu}_e}(L)}{\Phi_{\overline{\nu}_e}(0)} \longrightarrow P(\overline{\nu}_e \to \overline{\nu}_e)$$

Disappearance Probability

In the 3-ν framework

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

Valid for $L/E \lesssim 1\ \mathrm{km/MeV}$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

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Nunokawa et al,
PRD 72, 013009 (2005)

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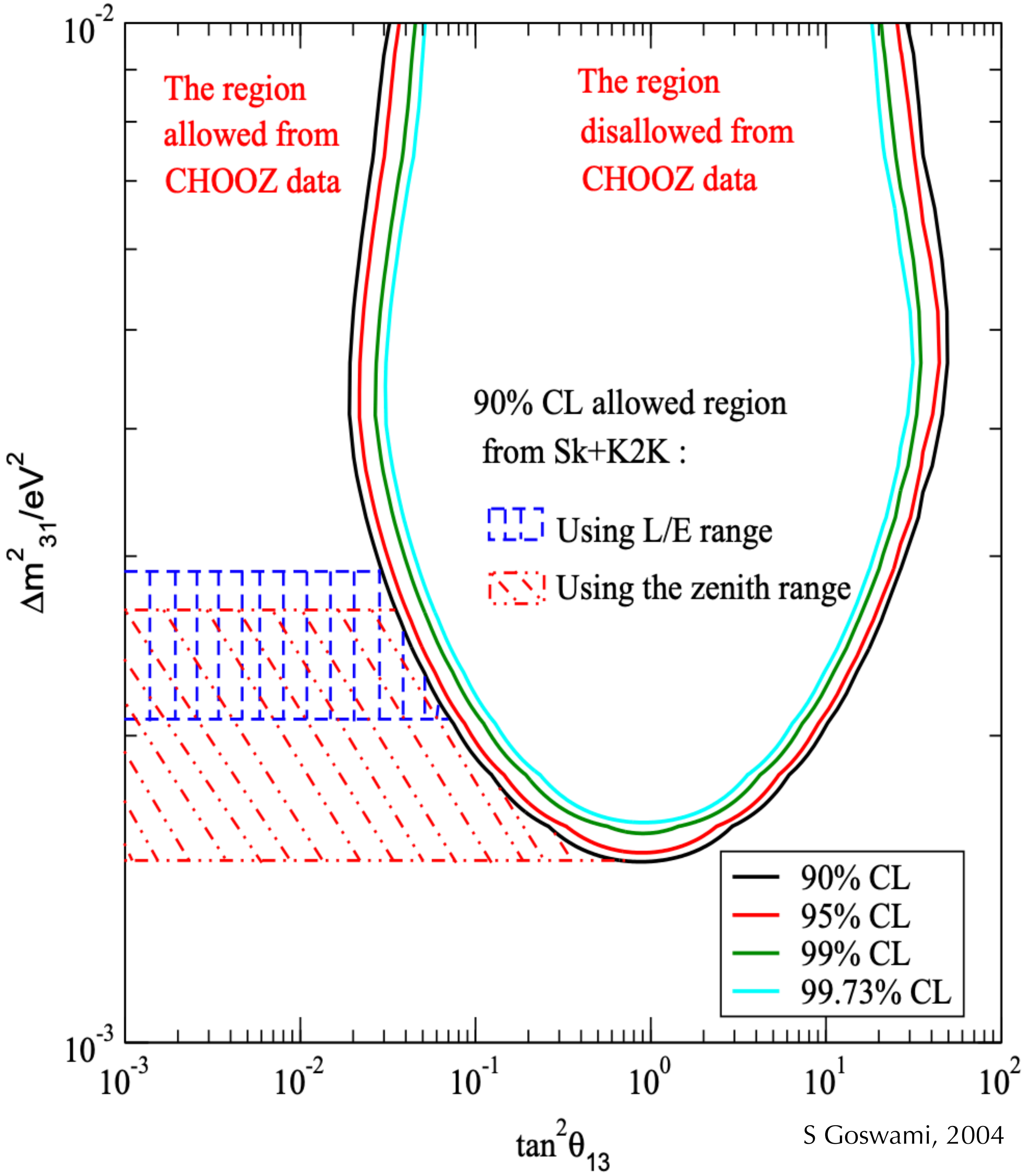

S Goswami, 2004

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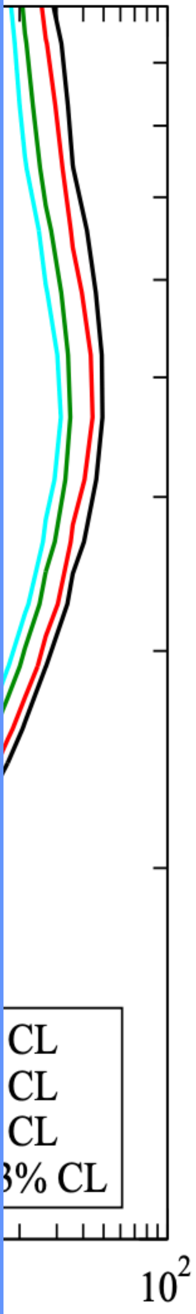
Wha

Which site for the experiment ?

One reactor complex
Two underground cavities @0.1-1 km & ~1-2 km

L. Oberauer, Paris, June 2004

Mai



swami, 2004

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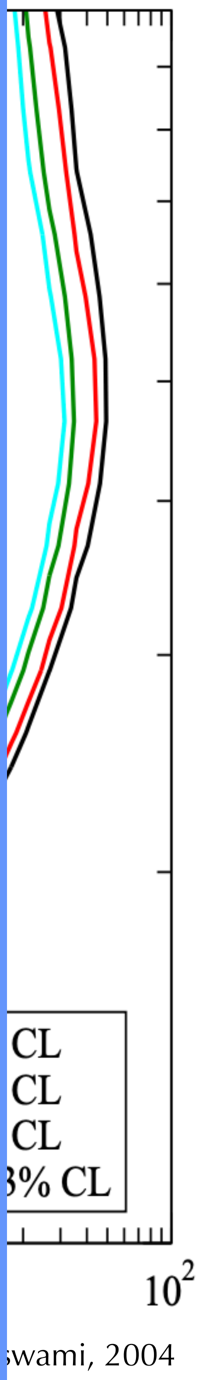

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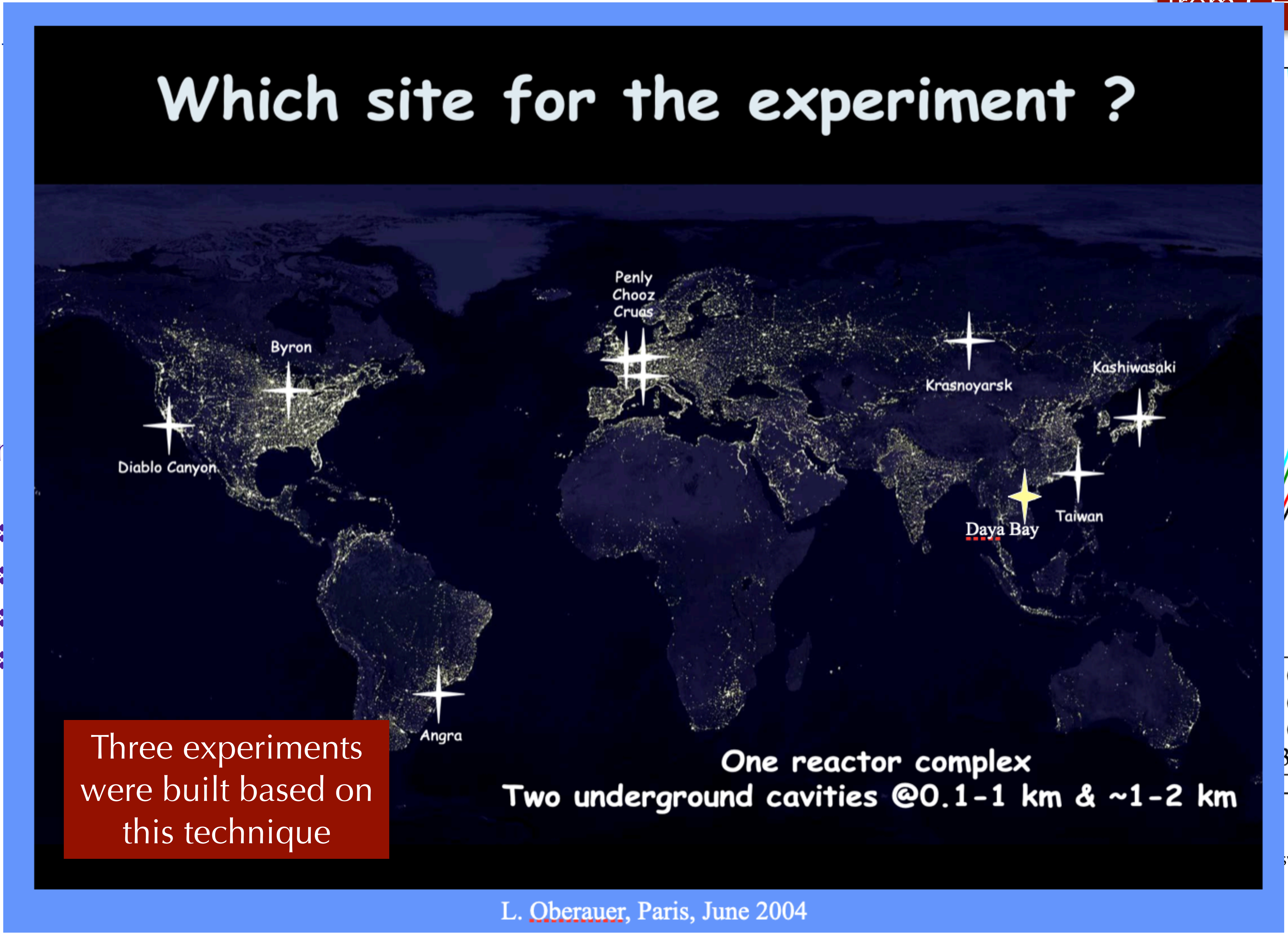

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Two underground cavities @0.1-1 km & ~1-2 km

L. Oberauer, Paris, June 2004

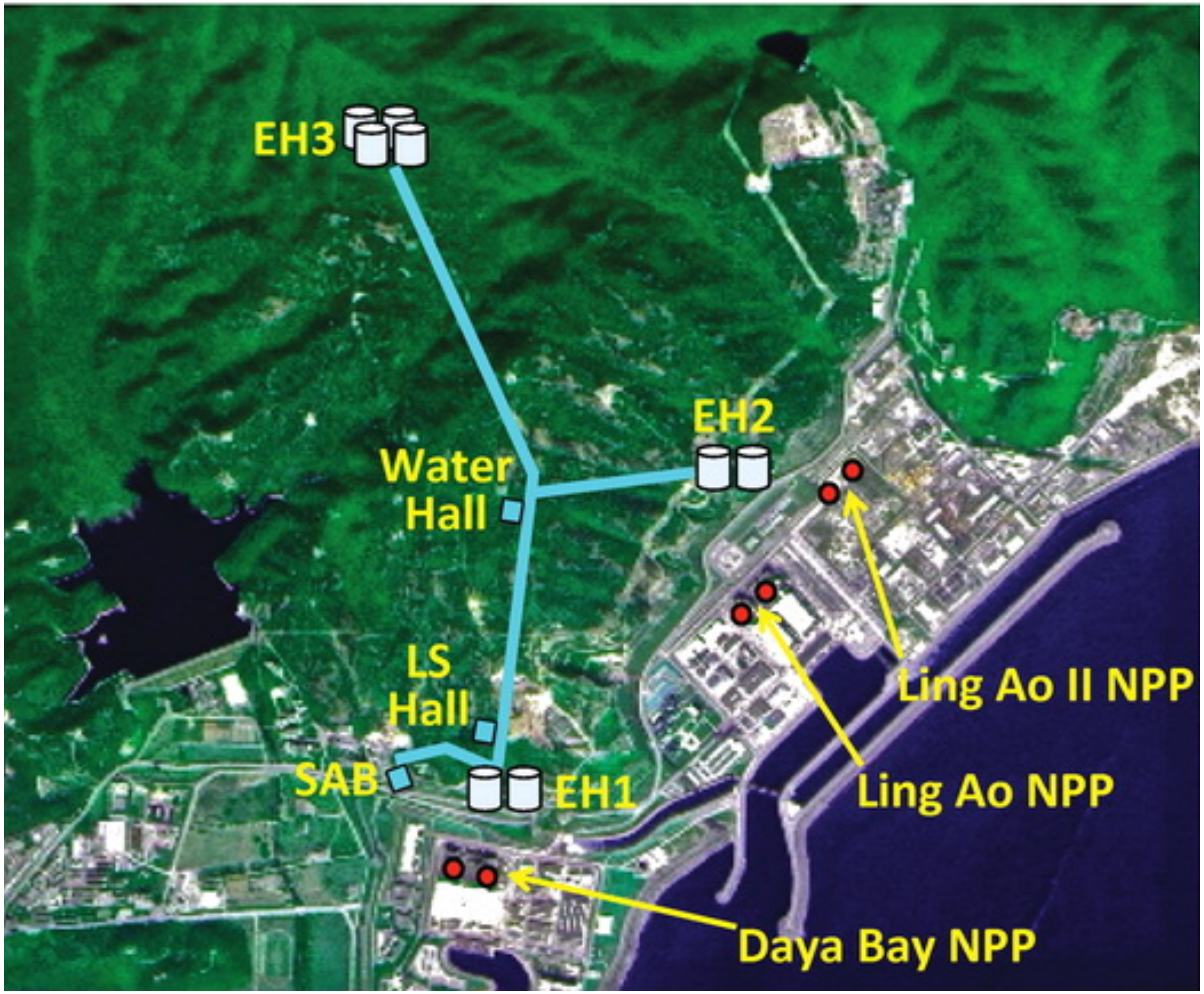
Three experiments were built based on this technique

Daya Bay Experiment

Daya Bay Experiment

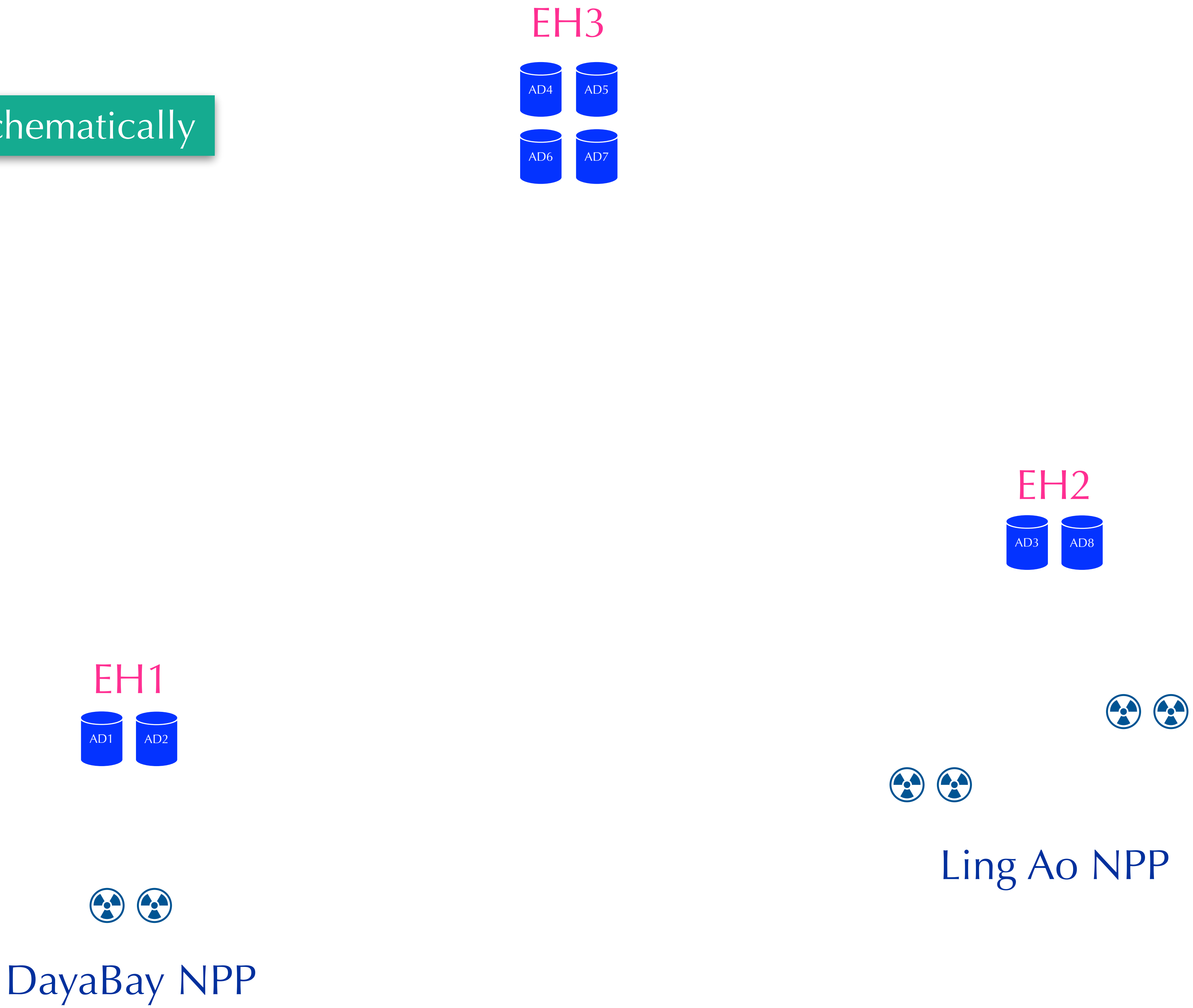
Daya Bay Experiment

Daya Bay Experiment



Daya Bay Experiment

Schematically



EH3

AD4 AD5

AD6 AD7

EH2

AD3 AD8

EH1

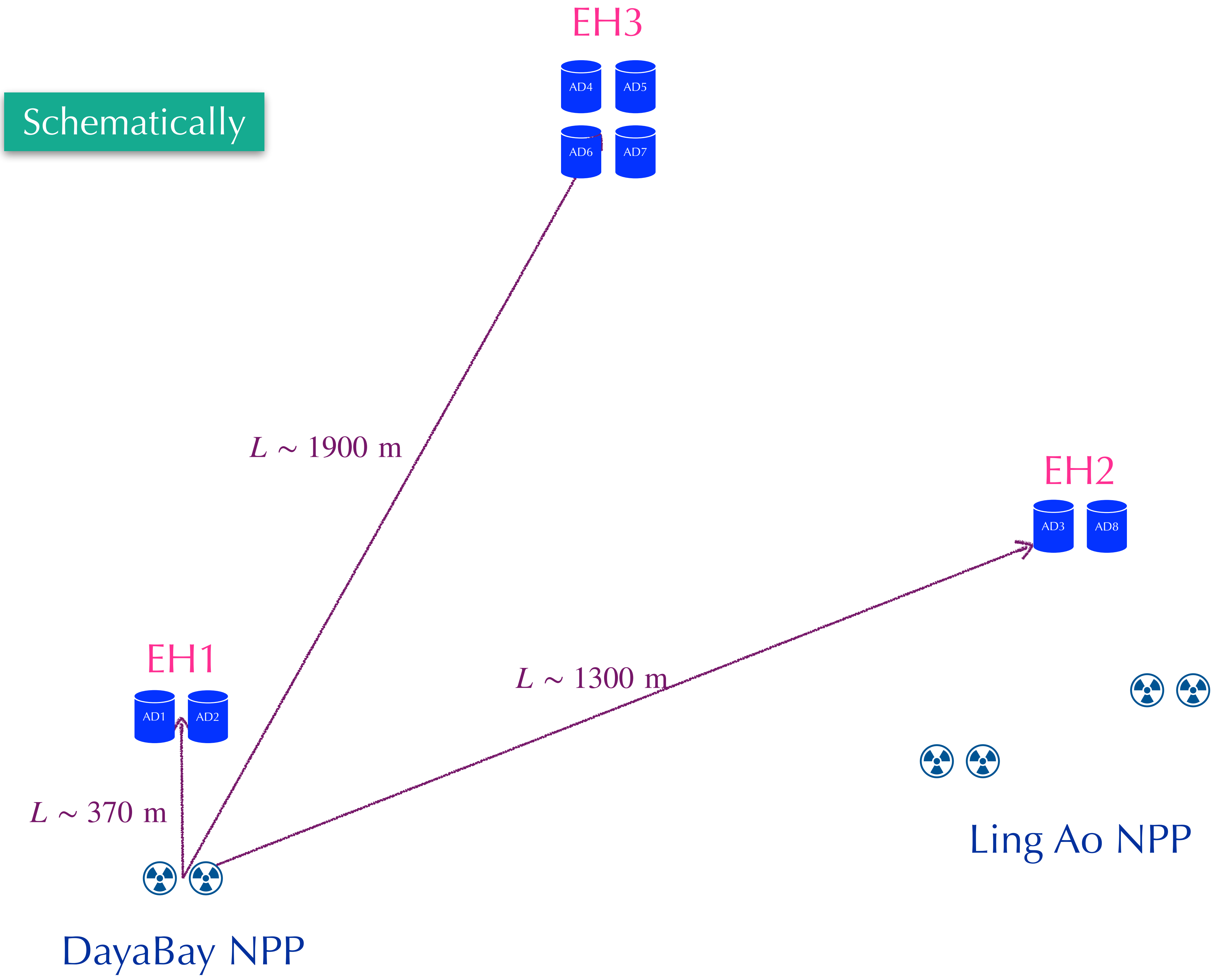
AD1 AD2

Ling Ao NPP

DayaBay NPP

Daya Bay Experiment

Schematically



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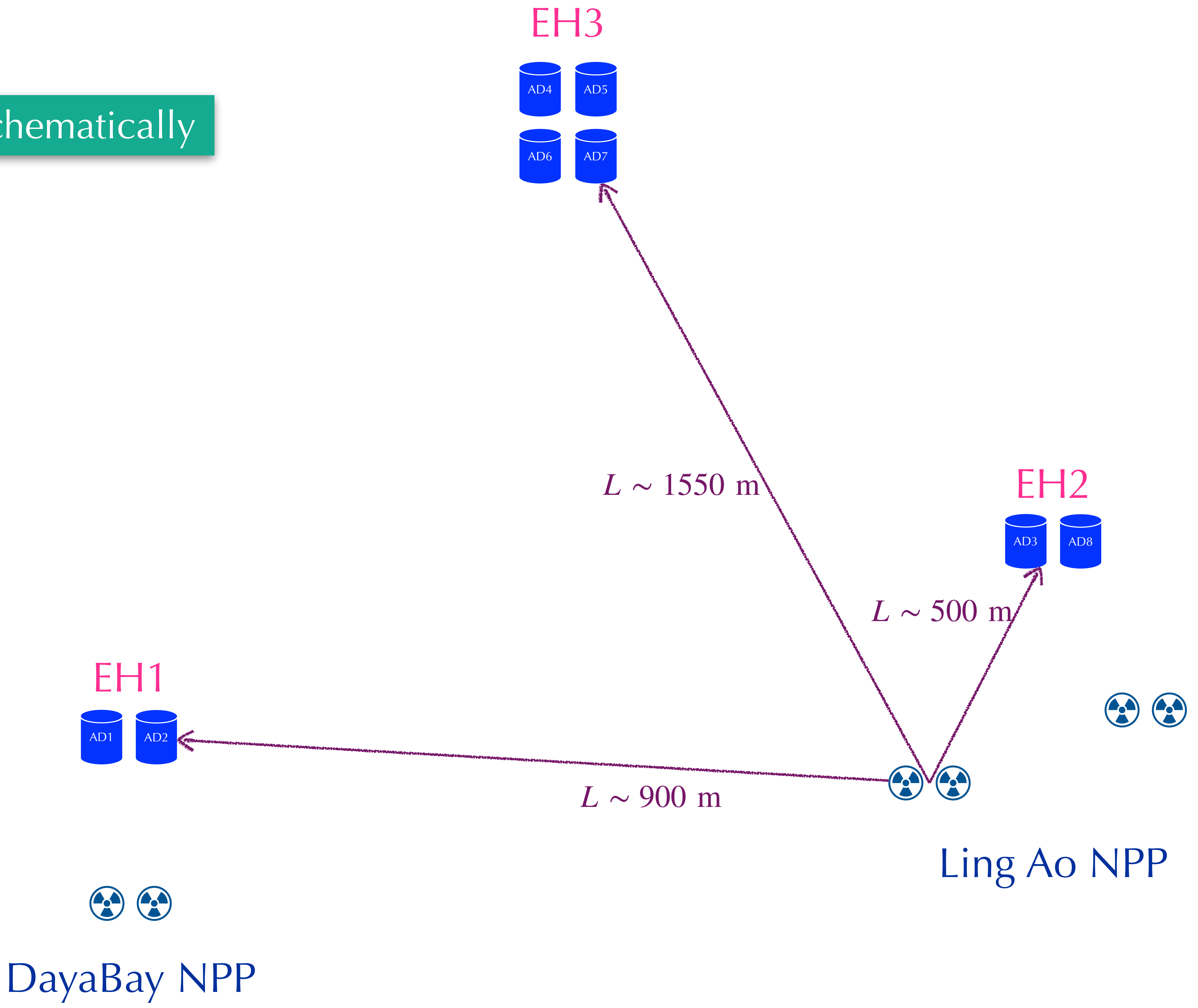

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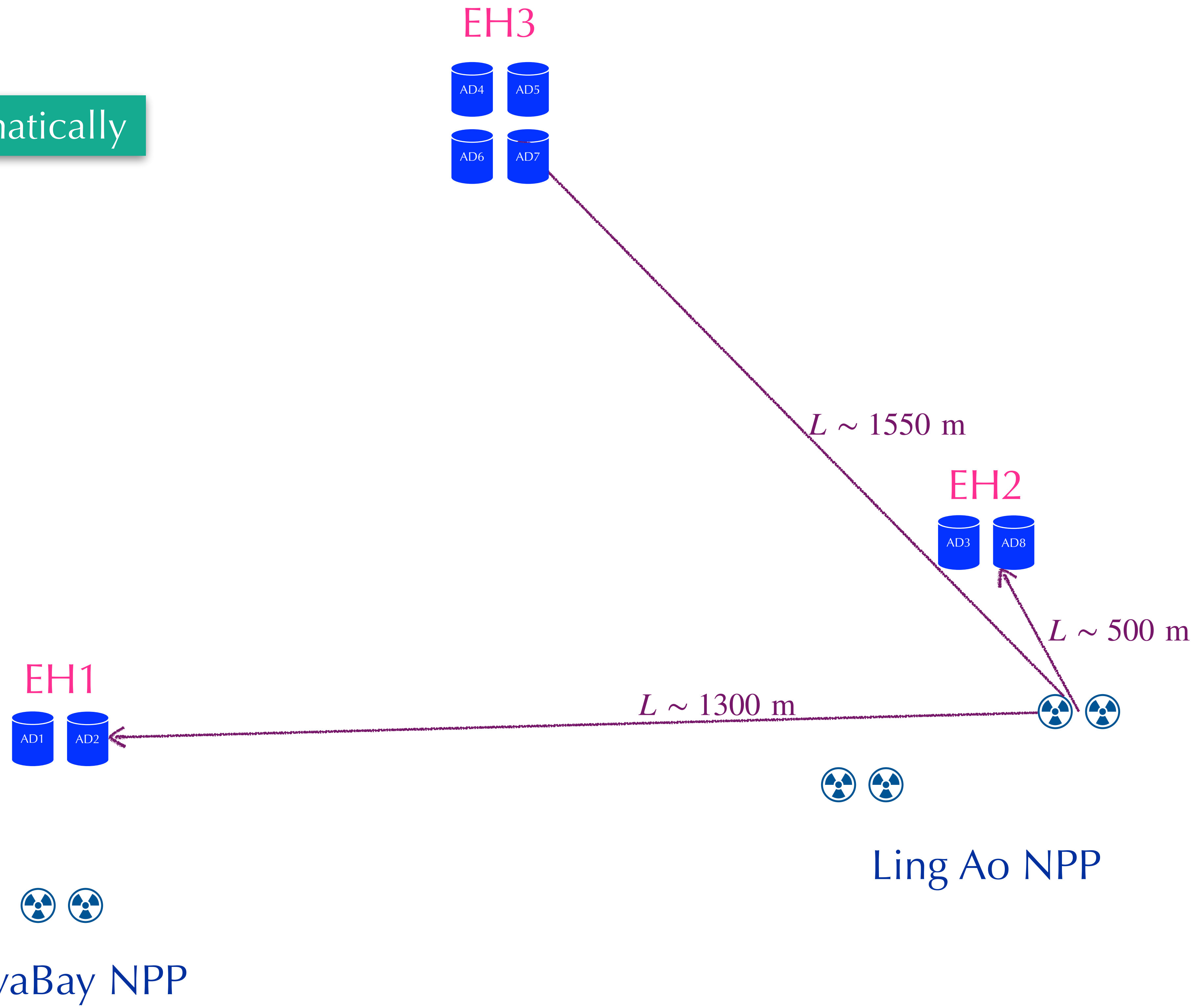


EH3

AD4

AD5

AD6

AD7

$L \sim 1550$ m

EH2

AD3

AD8

$L \sim 500$ m

EH1

AD1

AD2

$L \sim 1300$ m

Ling Ao NPP

DayaBay NPP

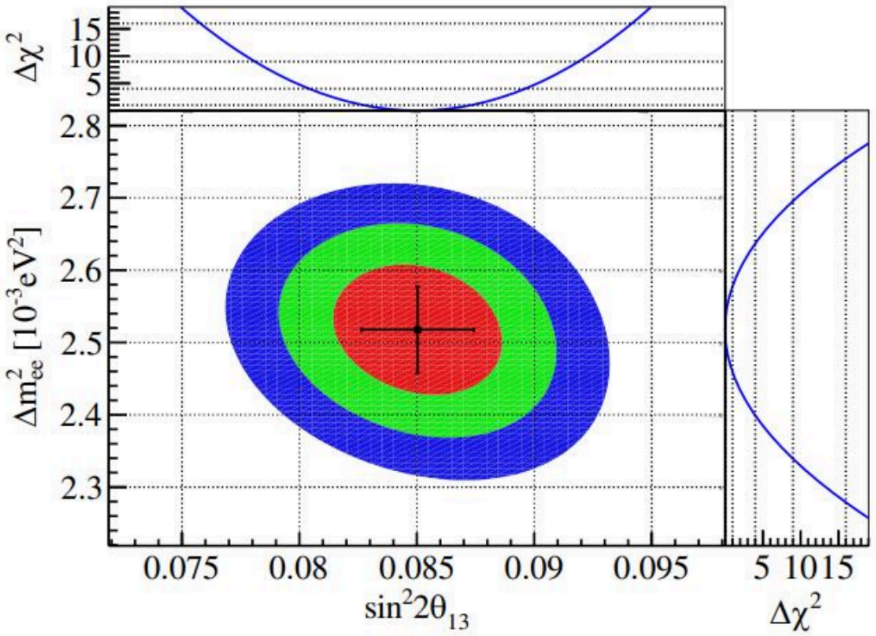
The Year 2024

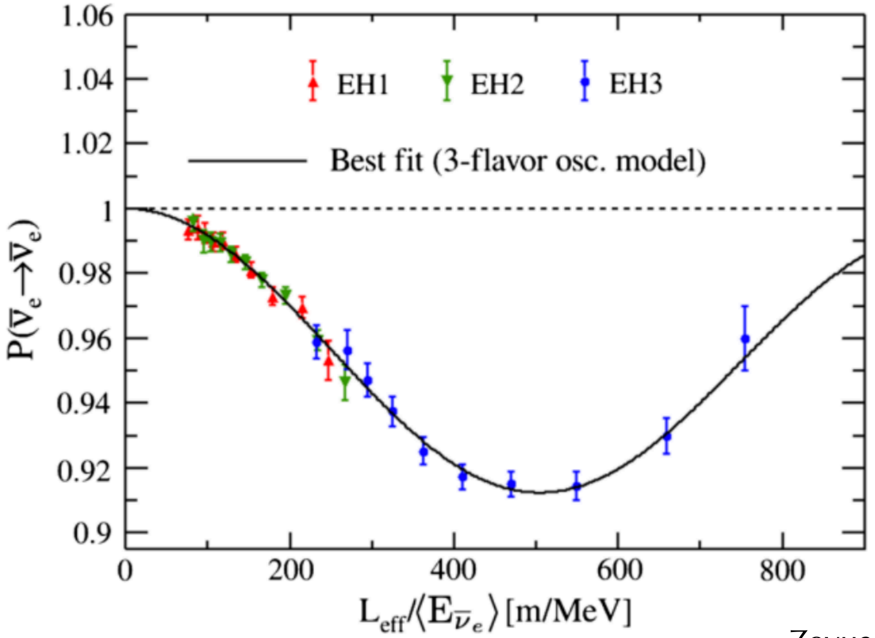
Latest results from Neutrino2024

$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ **precision 2.8%**

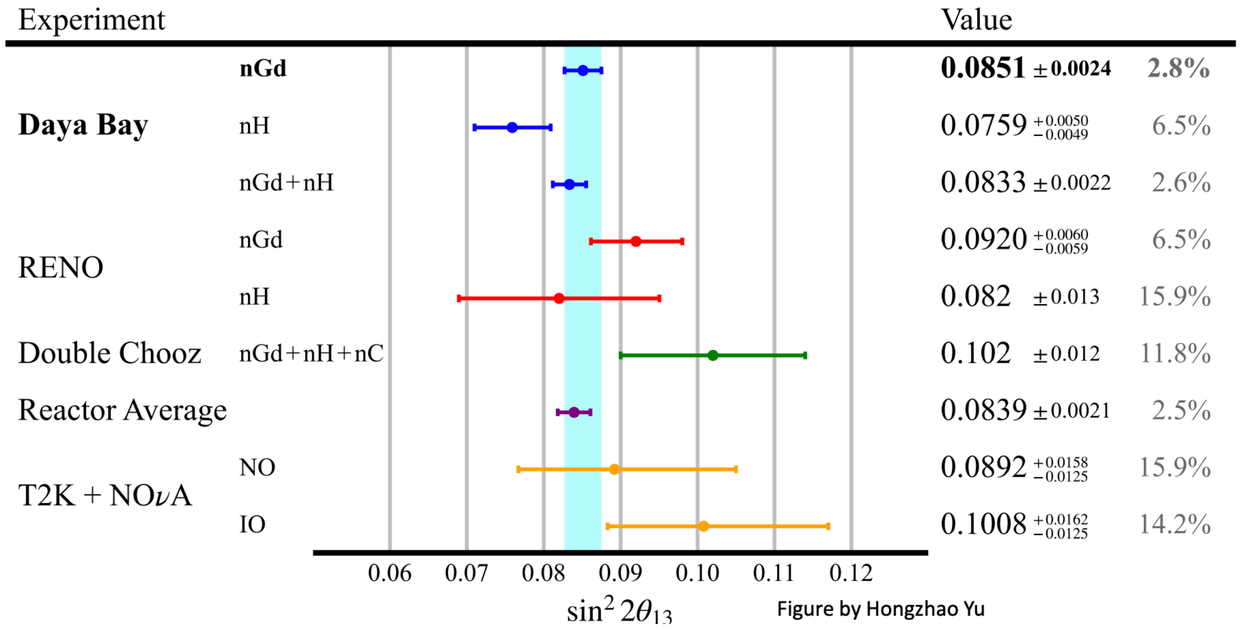
$\Delta m^2_{32} = 2.466 \underset{NO}{\pm} 0.060\ (-2.571 \underset{IO}{\pm} 0.060) \times 10^{-3}\ eV^2$ **precision 2.4%**

Systematics, mainly detector differences, contributed about 50% in the total error





Zeyuan Yu, 2004



Experiment		Value	
	nGd	**0.0851** ± 0.0024	2.8%
Daya Bay	nH	0.0759 $^{+0.0050}_{-0.0049}$	6.5%
	nGd+nH	0.0833 ± 0.0022	2.6%
RENO	nGd	0.0920 $^{+0.0060}_{-0.0059}$	6.5%
	nH	0.082 ± 0.013	15.9%
Double Chooz	nGd+nH+nC	0.102 ± 0.012	11.8%
Reactor Average		0.0839 ± 0.0021	2.5%
T2K + NOνA	NO	0.0892 $^{+0.0158}_{-0.0125}$	15.9%
	IO	0.1008 $^{+0.0162}_{-0.0125}$	14.2%

Figure by Hongzhao Yu

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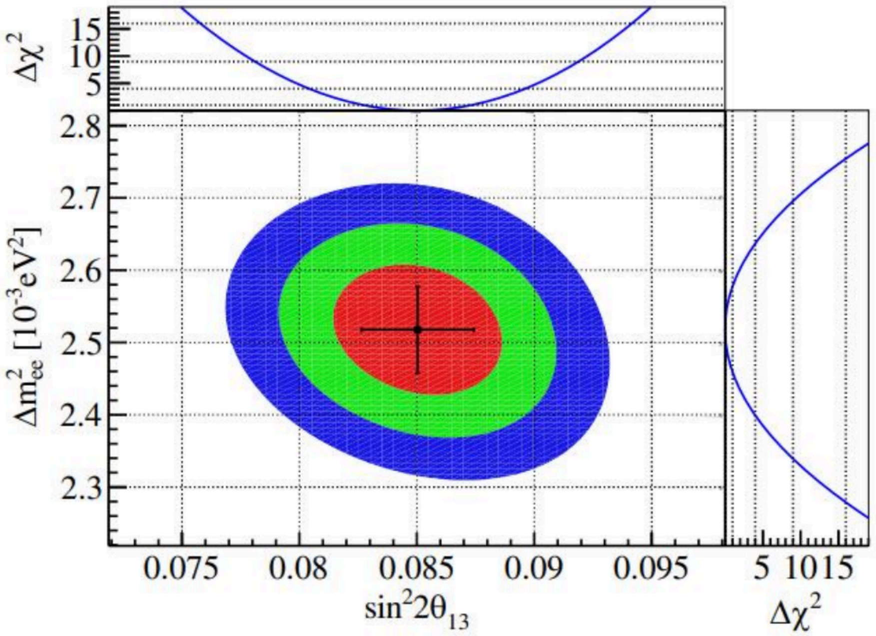
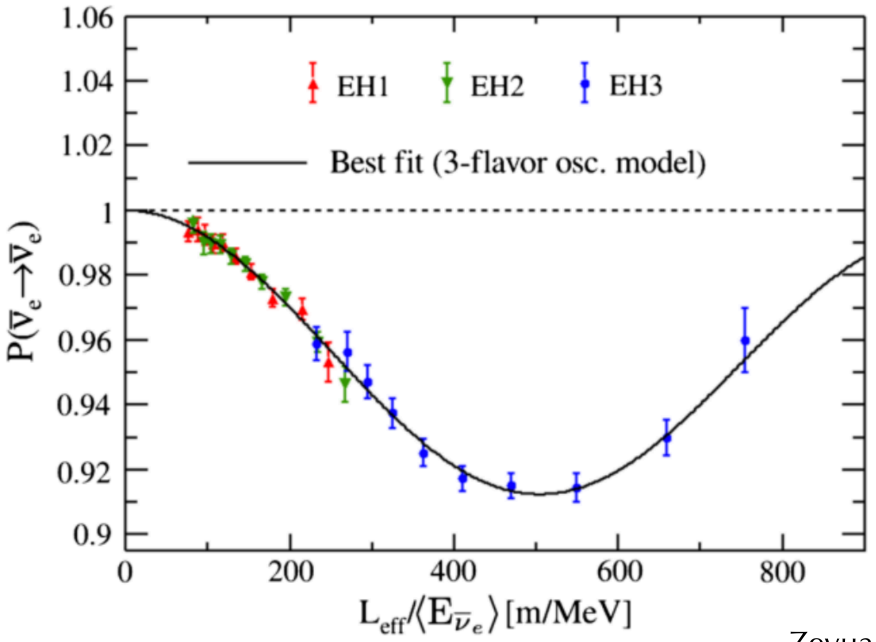
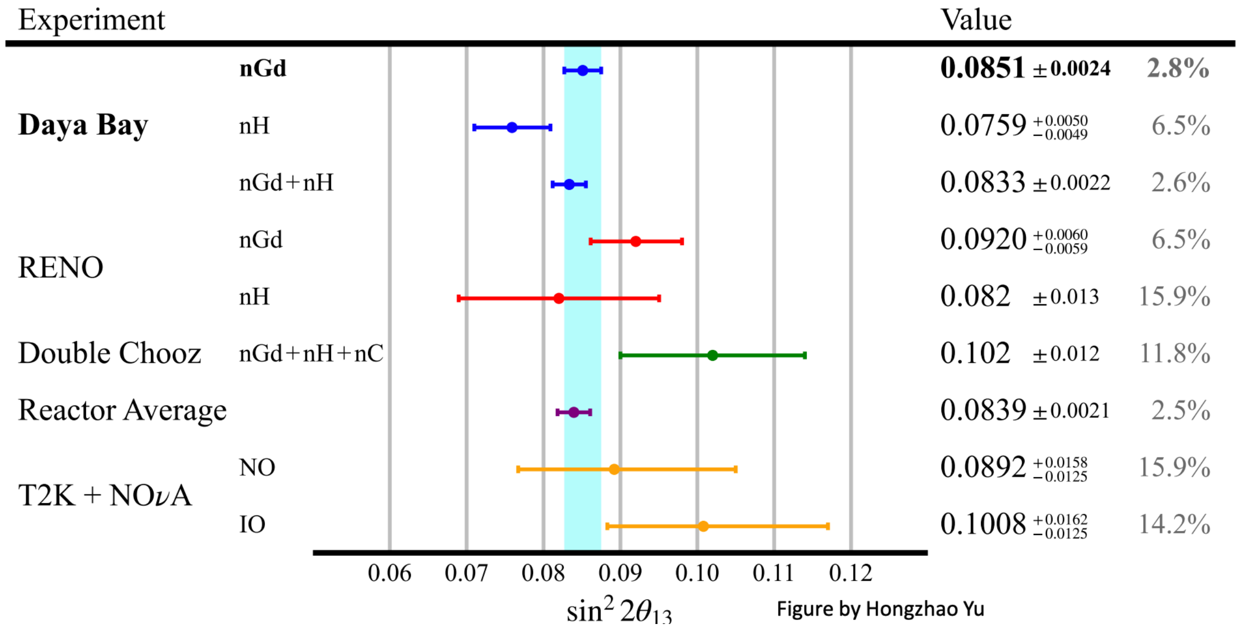
$\Delta m^2_{32} = 2.466 \underset{\text{NO}}{\pm} 0.060\ (-2.571 \underset{\text{IO}}{\pm} 0.060) \times 10^{-3}\ \text{eV}^2$ **precision 2.4%**

Systematics, mainly detector differences, contributed about 50% in the total error





Zeyuan Yu, 2004



Experiment		Value	
	nGd	**0.0851** ± 0.0024	2.8%
Daya Bay	nH	0.0759 $^{+0.0050}_{-0.0049}$	6.5%
	nGd+nH	0.0833 ± 0.0022	2.6%
RENO	nGd	0.0920 $^{+0.0060}_{-0.0059}$	6.5%
	nH	0.082 ± 0.013	15.9%
Double Chooz	nGd+nH+nC	0.102 ± 0.012	11.8%
Reactor Average		0.0839 ± 0.0021	2.5%
T2K + NOνA	NO	0.0892 $^{+0.0158}_{-0.0125}$	15.9%
	IO	0.1008 $^{+0.0162}_{-0.0125}$	14.2%

Figure by Hongzhao Yu

Can we reproduce this result?

Our task: Reproduce the latest result on $\sin^2 2\theta_{13}, \Delta m^2_{ee}$ from Daya Bay

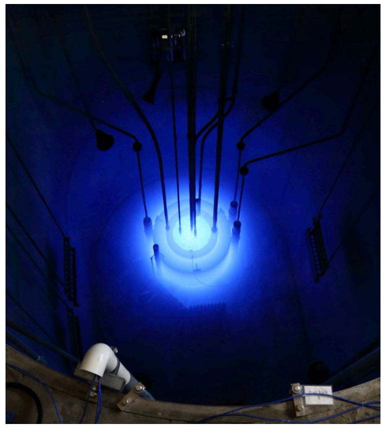
Our task: Reproduce the latest result on $\sin^2 2\theta_{13}, \Delta m^2_{ee}$ from Daya Bay

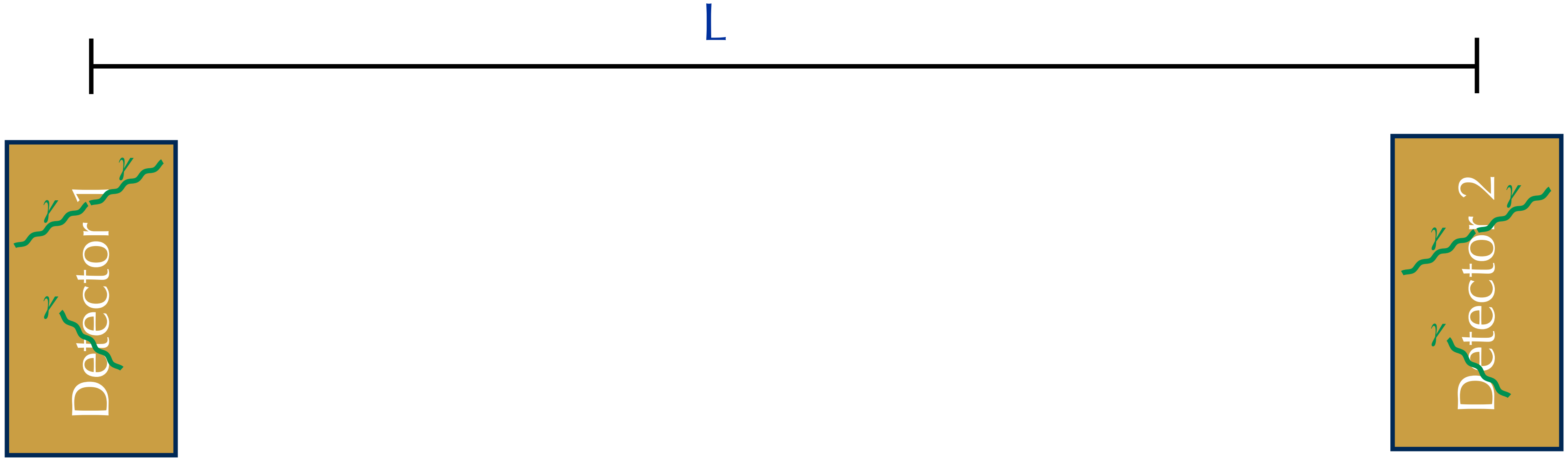
References:

Daya Bay results: 1607.05378, 1610.04802, 2211.14988

NuFit approach: 1811.05487

Neutrino oscillations with Reactor $\overline{\nu}_e$





$$\frac{\Phi_{\overline{\nu}_e}(L)}{\Phi_{\overline{\nu}_e}(0)} \longrightarrow P(\overline{\nu}_e \to \overline{\nu}_e)$$

Disappearance Probability

In the 3-ν framework

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

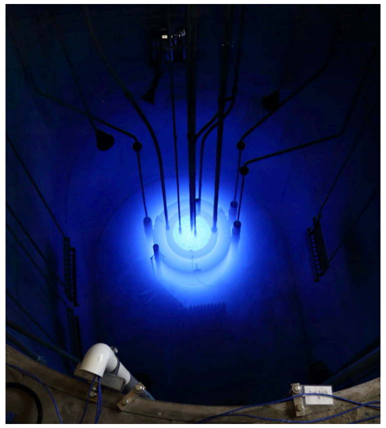
Valid for $L/E \lesssim 1\ \mathrm{km/MeV}$

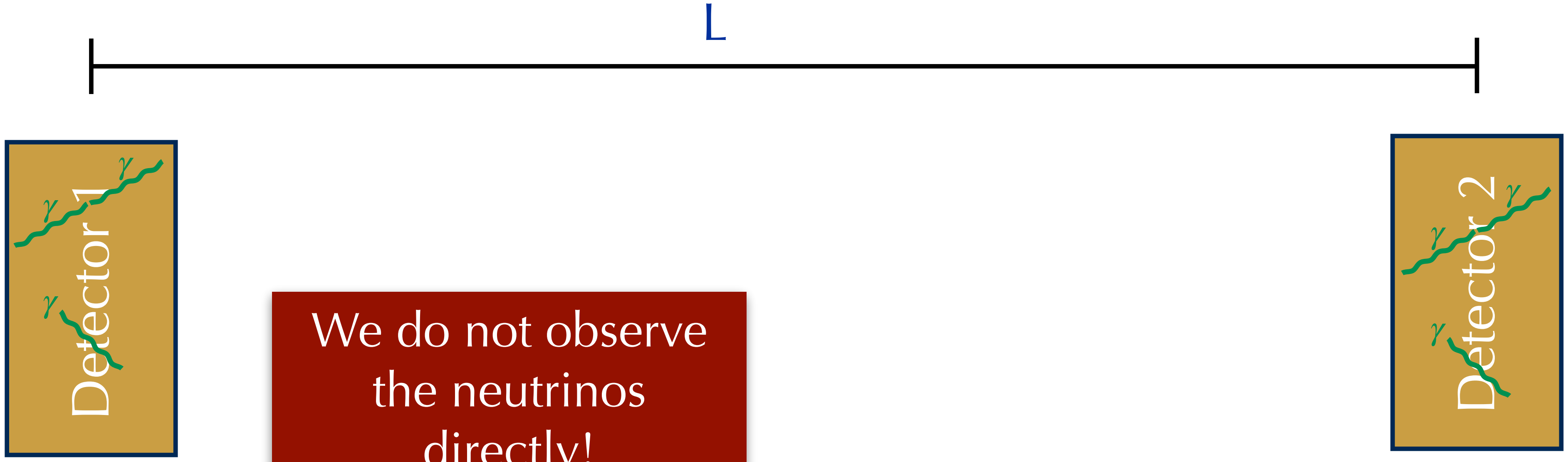
$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Nunokawa et al,
PRD 72, 013009 (2005)

$$\Delta_{ij} = 1.267\left(\frac{\Delta m^2_{ij}}{1\ \mathrm{eV}^2}\right)\left(\frac{L}{1\ \mathrm{m}}\right)\left(\frac{1\ \mathrm{MeV}}{E_\nu}\right)$$

Neutrino oscillations with Reactor $\overline{\nu}_e$





We do not observe the neutrinos directly!

$$\cancel{\frac{\text{[illegible]}L)}{\text{[illegible]}0)}} \longrightarrow P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$$

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$$\frac{N_{\rm IBD}(L)}{N_{\rm IBD}(0)} \longrightarrow P(\overline{\nu}_e \to \overline{\nu}_e)$$

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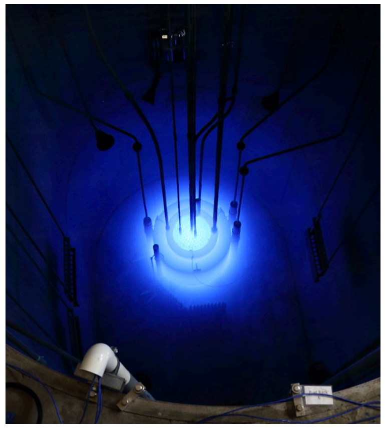

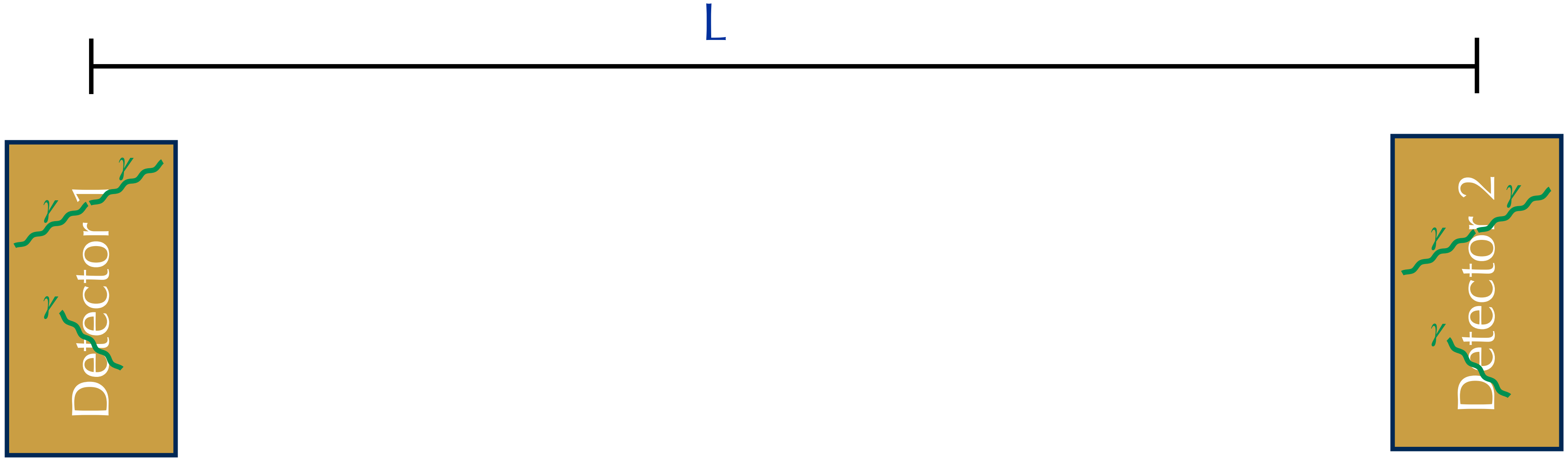

IBD events

$$\frac{N_{\rm IBD}(L)}{N_{\rm IBD}(0)} \longrightarrow P(\overline{\nu}_e \to \overline{\nu}_e)$$

Disappearance Probability

In the 3-ν framework

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Valid for $L/E \lesssim 1$ km/MeV

$$\Delta m_{ee}^2 = \cos^2\theta_{12}\Delta m_{31}^2 + \sin^2\theta_{12}\Delta m_{32}^2$$

$$\Delta_{ij} = 1.267\left(\frac{\Delta m_{ij}^2}{1\ \mathrm{eV}^2}\right)\left(\frac{L}{1\ \mathrm{m}}\right)\left(\frac{1\ \mathrm{MeV}}{E_\nu}\right)$$

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IBD Events

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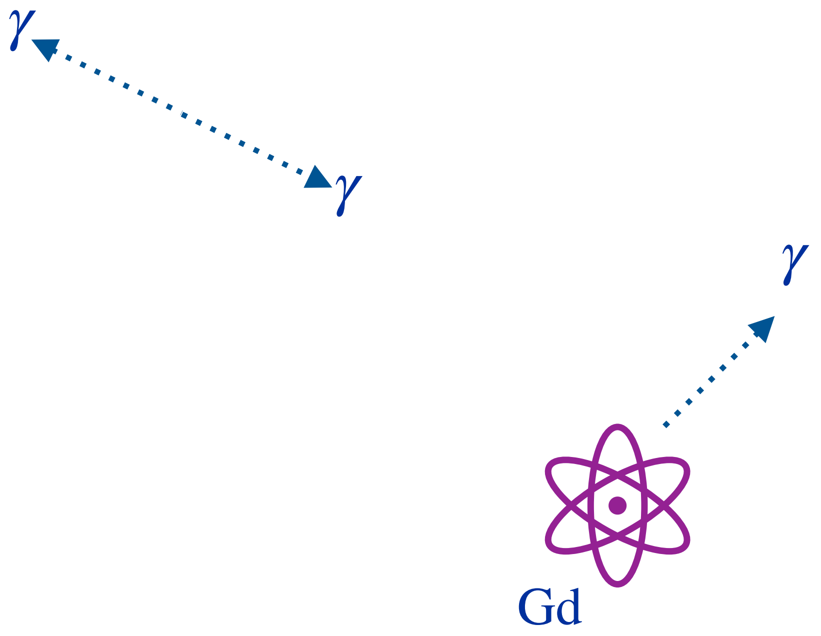
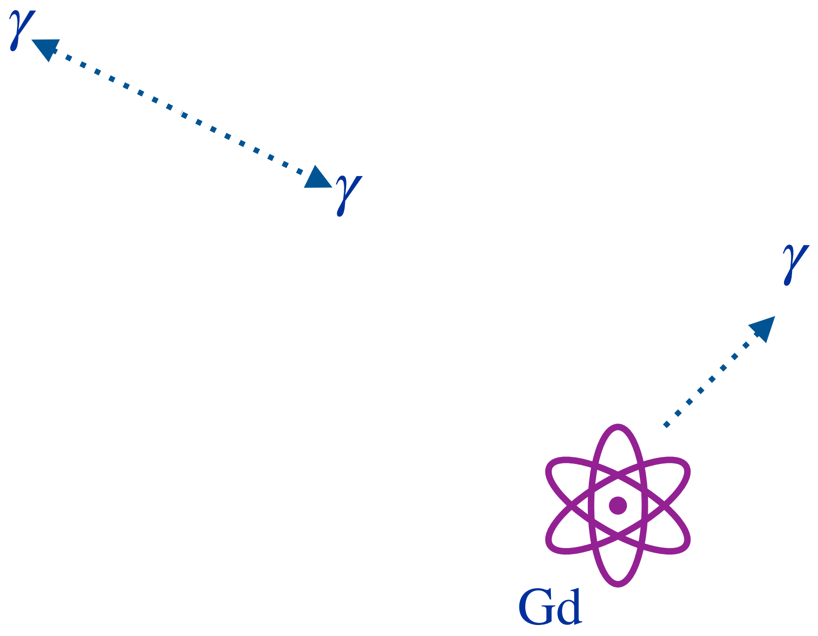


IBD Events



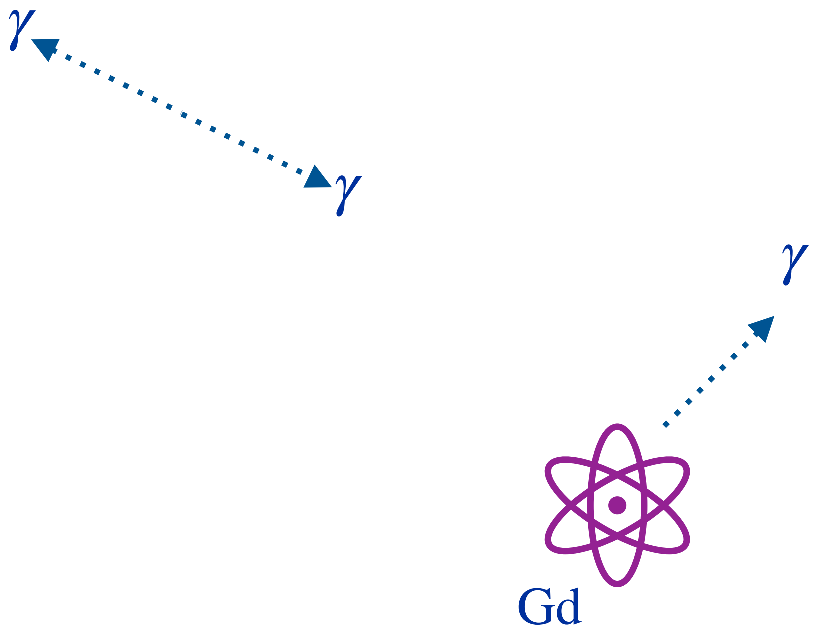
Detector measures the photons total energy

Events will be as function of the "prompt" energy

Kinematics:

$$E_{\text{prompt}} \approx T_{e^+} + 2m_e$$
$$\approx E_{\overline{\nu}} - (m_n - m_p - m_e) = E_{\overline{\nu}} - 0.78\ \text{MeV}$$

IBD Events



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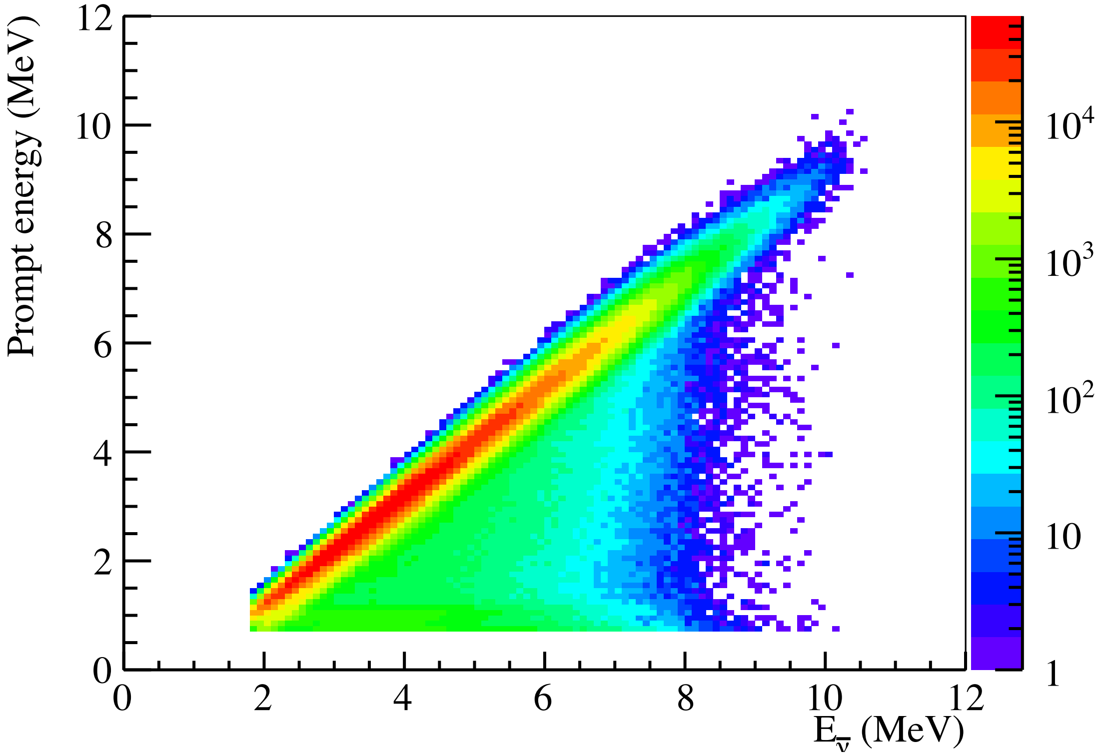
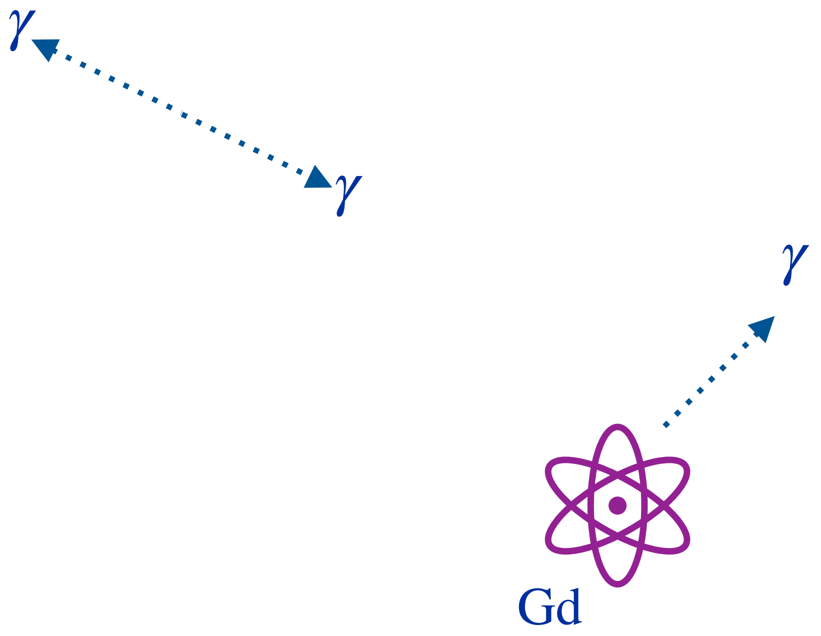
However, detector effects will affect the reconstruction of prompt energies



IBD Events



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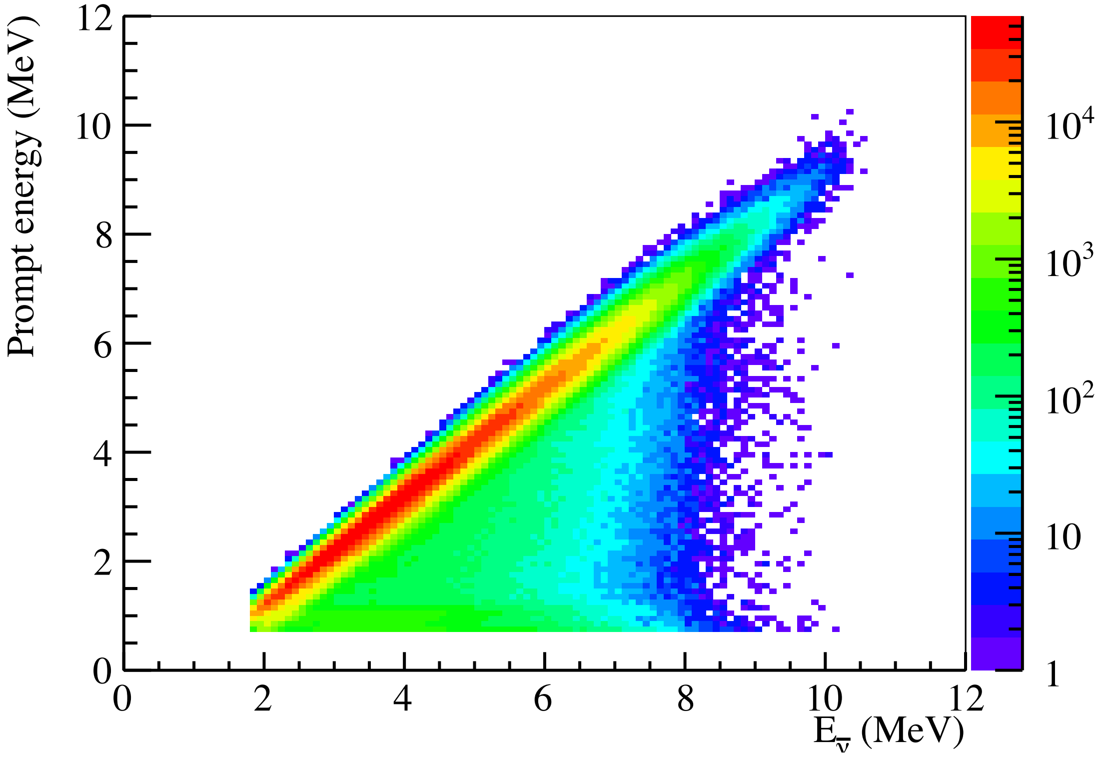
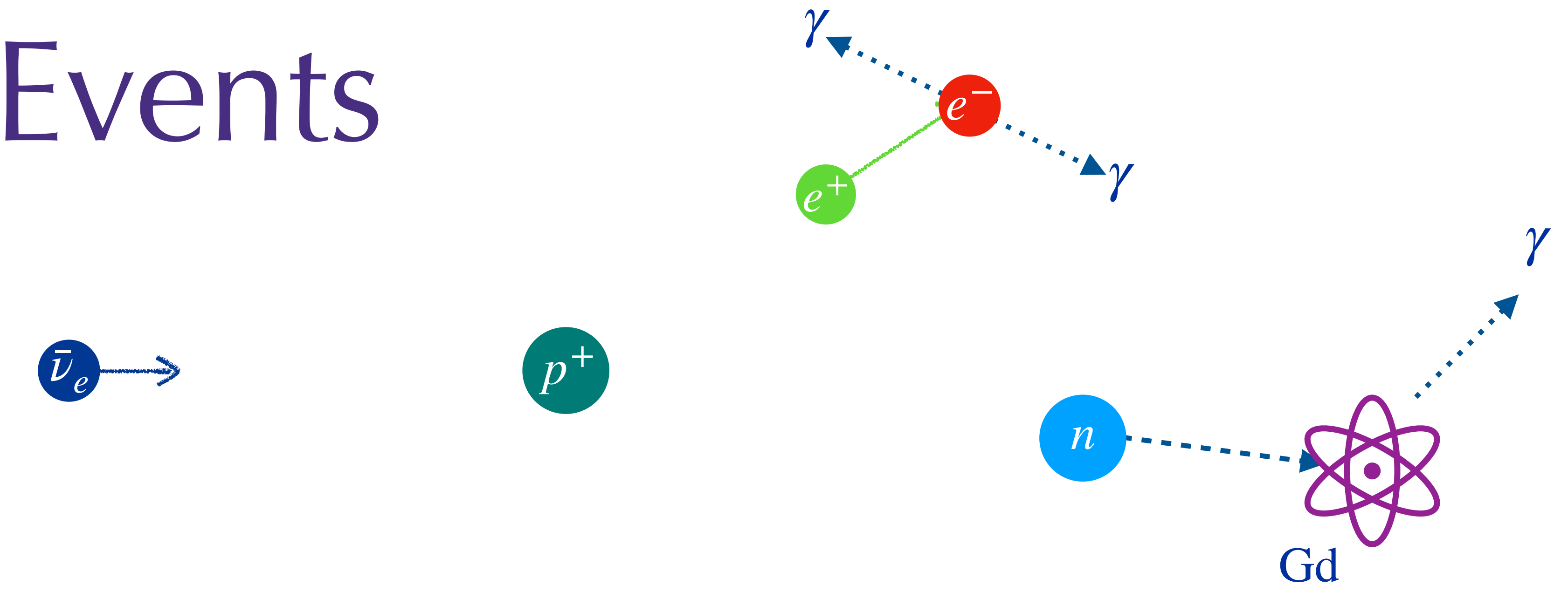


Luckily, the DayaBay collaboration has provided data as function of ***true*** prompt energy

IBD Events



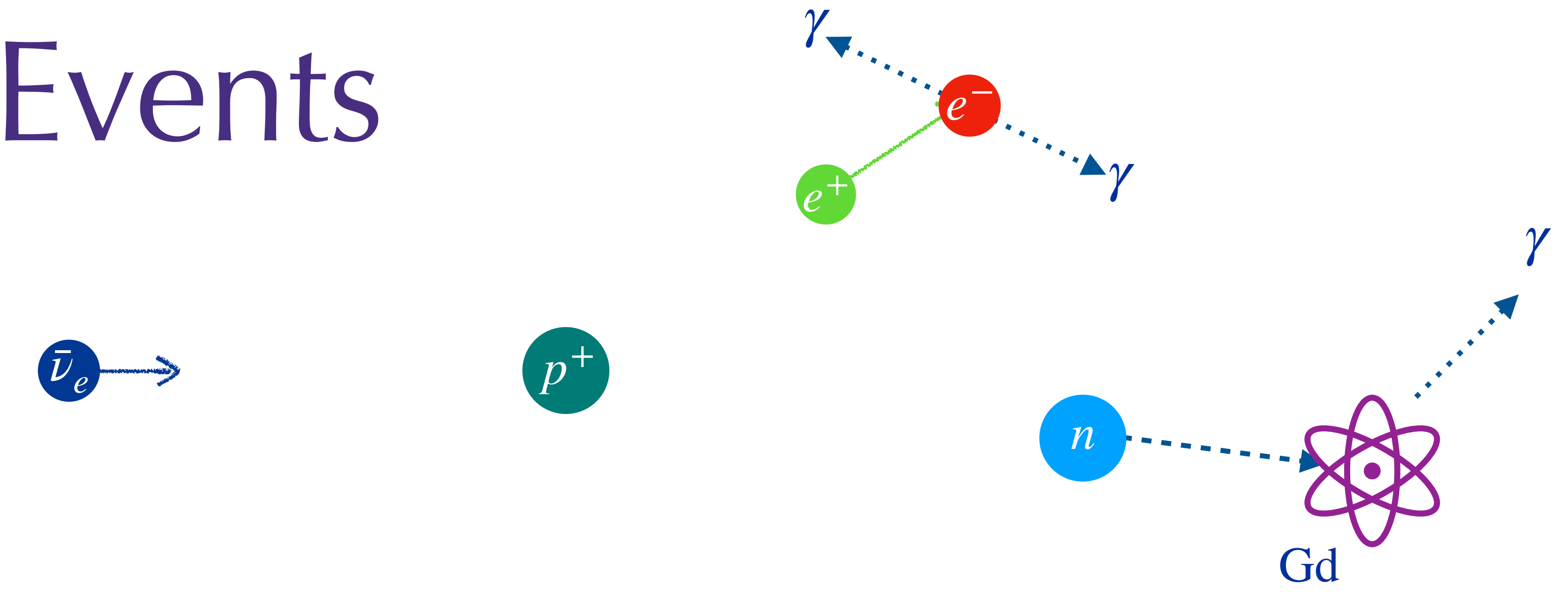
Detector measures the photons total energy

Events will be as function of the "prompt" energy

Events at detector d during period p in the prompt energy bin b:

$$N_{pdb} = \mathcal{N}_{pd}\ \epsilon_d \sum_{r=\text{reactors}} \int_{E_b}^{E_{b+1}} dE_{\text{prompt}}\ \frac{d\phi_{rd}(\overline{\nu}_e)}{dE_\nu}\ P(\overline{\nu}_e \to \overline{\nu}_e; L_{dr})\ \sigma_{\text{IBC}}(E_\nu)$$

IBD Events



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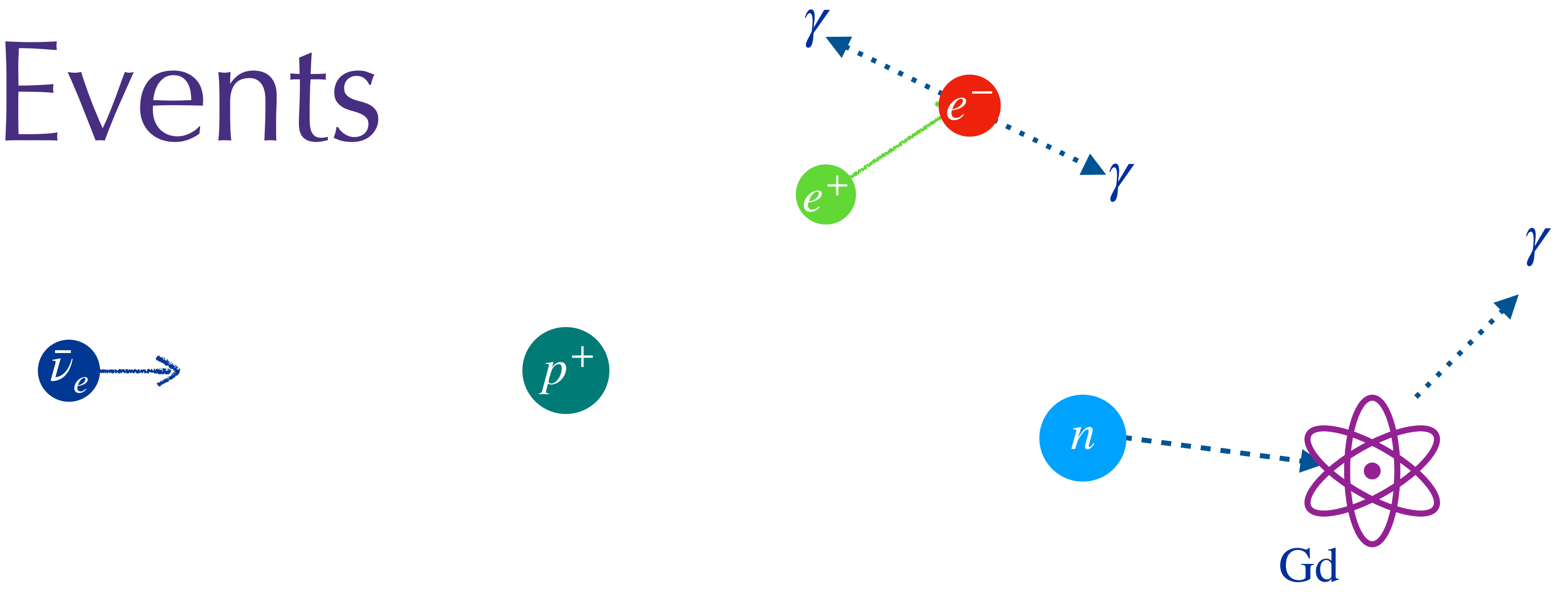
Neutrino flux

IBD Events



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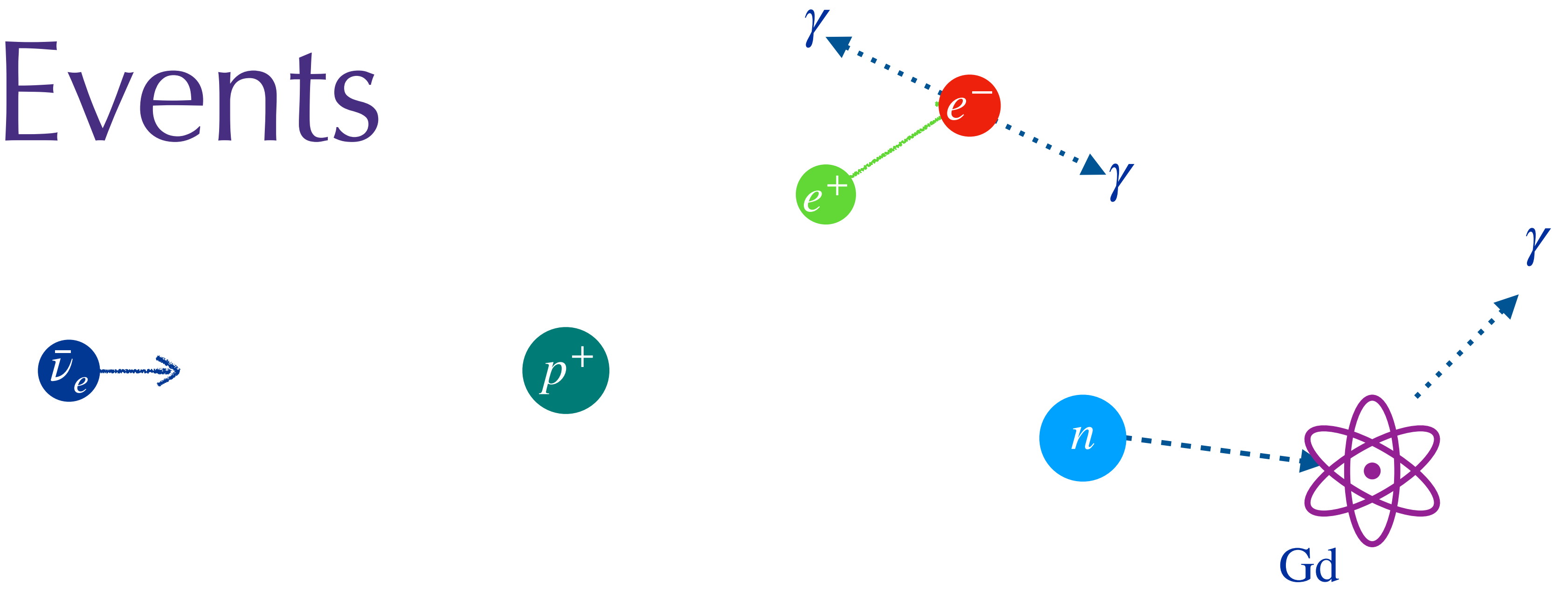
Neutrino flux

IBD cross section

IBD Events



Detector measures the photons total energy

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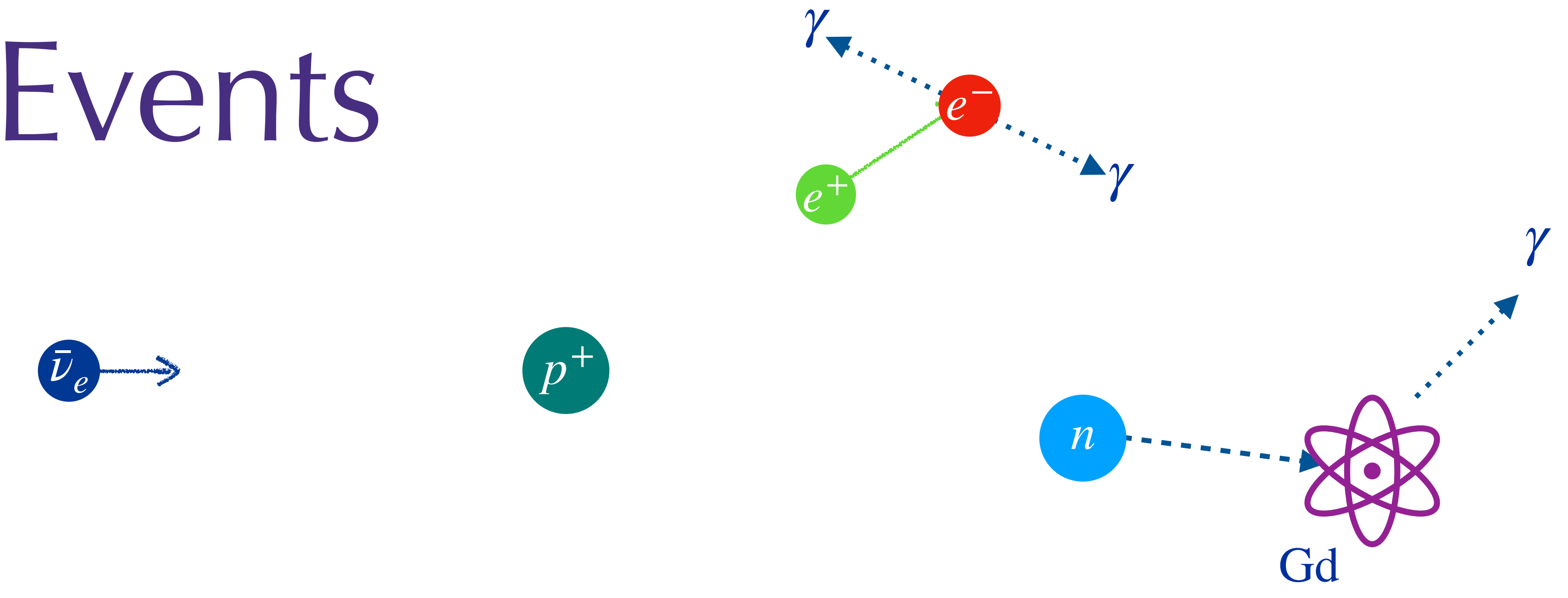
Events at detector d during period p in the prompt energy bin b:

$$N_{pdb} = \underbrace{\boxed{\mathcal{N}_{pd}}}_{\text{Exposure}} \epsilon_d \sum_{r=\text{reactors}} \int_{E_b}^{E_{b+1}} dE_{\text{prompt}} \underbrace{\boxed{\frac{d\phi_{rd}(\overline{\nu}_e)}{dE_\nu}}}_{\text{Neutrino flux}} P(\overline{\nu}_e \to \overline{\nu}_e; L_{dr}) \underbrace{\boxed{\sigma_{\text{IBC}}(E_\nu)}}_{\text{IBD cross section}}$$

IBD Events



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$$N_{pdb} = \underbrace{\boxed{\mathcal{N}_{pd}}}_{\text{Exposure}} \underbrace{\boxed{\epsilon_d}}_{\text{Efficiency}} \sum_{r=\text{reactors}} \int_{E_b}^{E_{b+1}} dE_{\text{prompt}} \underbrace{\boxed{\frac{d\phi_{rd}(\overline{\nu}_e)}{dE_\nu}}}_{\text{Neutrino flux}} P(\overline{\nu}_e \to \overline{\nu}_e; L_{dr}) \underbrace{\boxed{\sigma_{\text{IBC}}(E_\nu)}}_{\text{IBD cross section}}$$

Ingredients: IBD Cross Section

$$\sigma(E_\nu) = \frac{G_F^2 \cos^2\theta_C}{\pi}(f^2 + 3g^2)E_{e^+}p_{e^+}$$

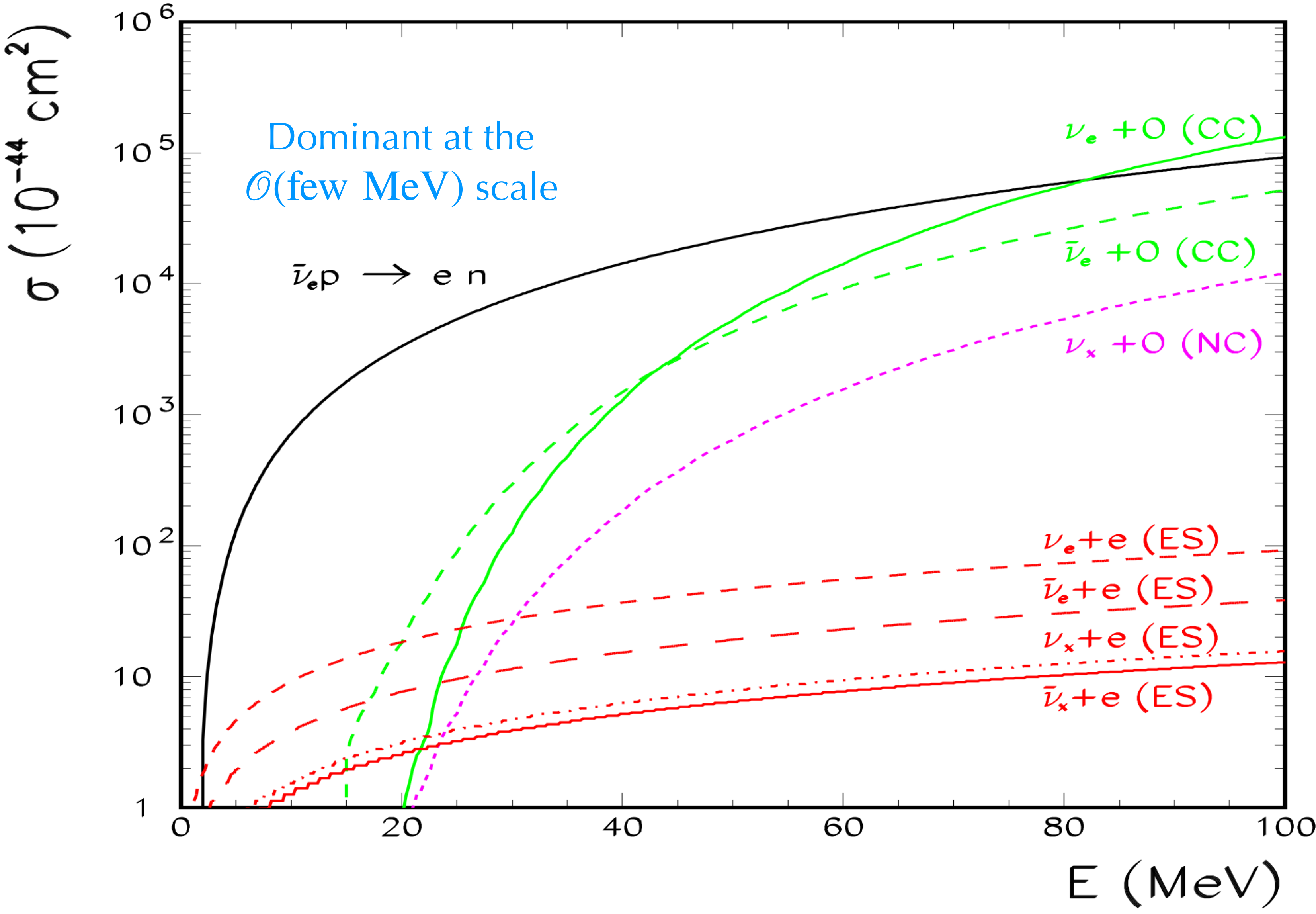
$f = 1,\ g = 1.26$

E_{e^+}: Total energy

$$E_{e^+} = E_\nu - (m_n - m_p)$$

Additional corrections:

- Expansion in powers of $1/m_n$

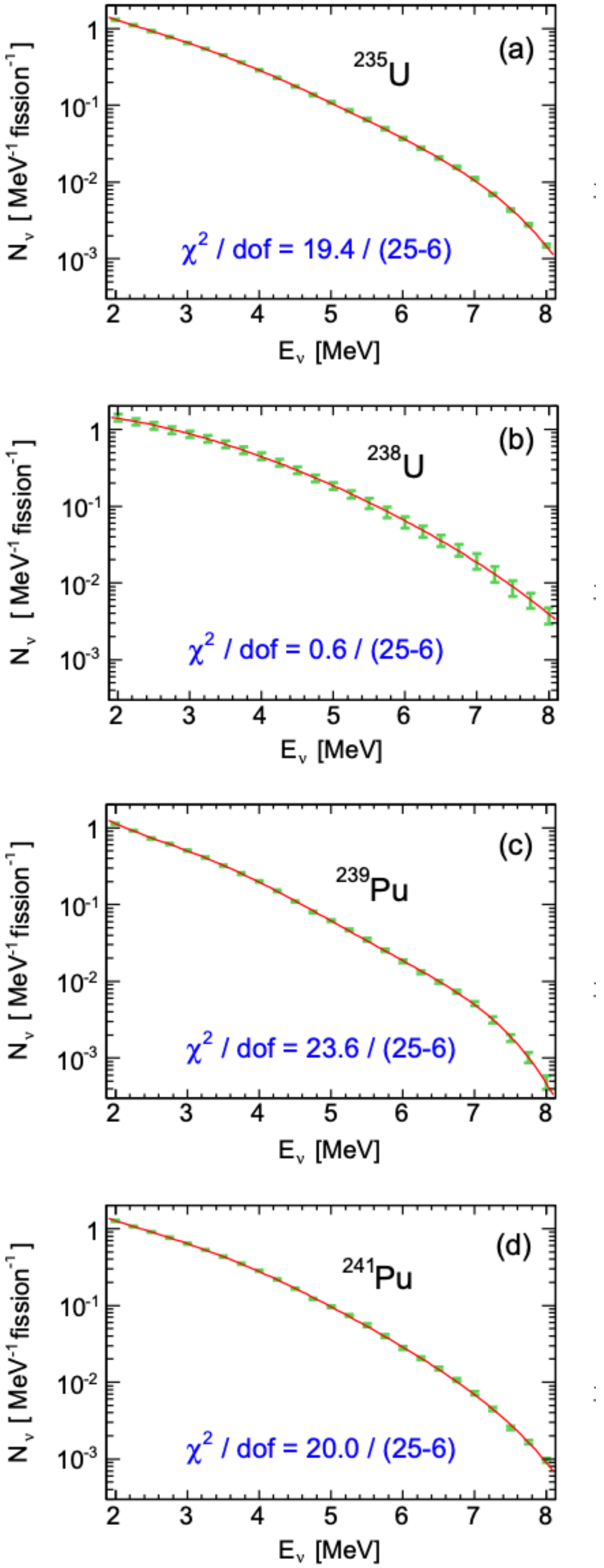


Skadhauge, Zukanovich Funchal
JCAP 0704:014,2007

Vogel, Beacom
PRD 60 (1999) 053003

Ingredients: Neutrino Flux

$$\frac{d\phi_{rd}(\overline{\nu}_e)}{dE_\nu} = \frac{W_{\rm th}}{4\pi L_{rd}^2} \sum_{\rm isotopes} \frac{p_i}{Q_i} S_i(E_\nu)$$



$W_{\rm th}$ → Thermal Power, $W_{\rm th} = N_i Q_i$

N_i → Number of fissions per s

Q_i → Energy released per isotope

p_i → Power fraction

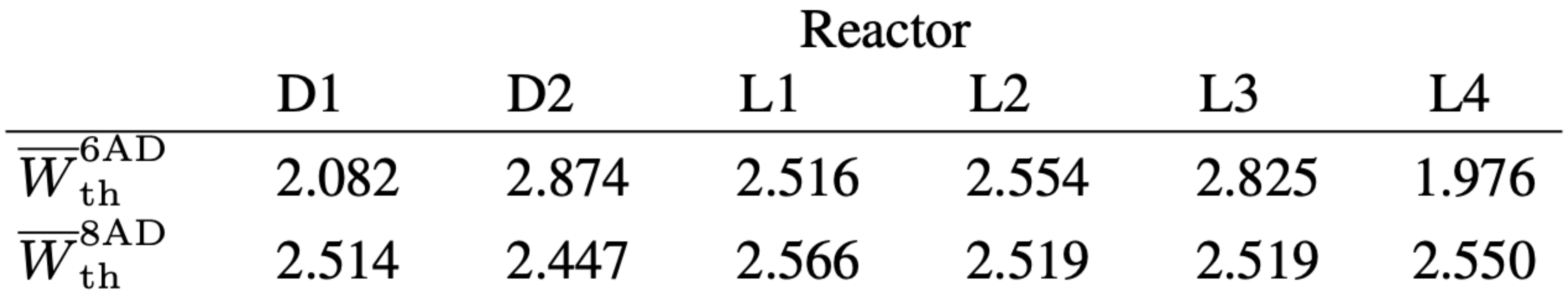
$S_i(E_\nu)$ → Antineutrino spectrum per fission

We will use the interpolated formulae for $S_i(E_\nu)$ from Huber-Mueller (HM)

Huber, PRC84:024617(2011)
Mueller et al, PRC83:054615(2011)

Ingredients: Neutrino Flux — 2

Thermal power for Daya Bay and Ling Ao NPPs?

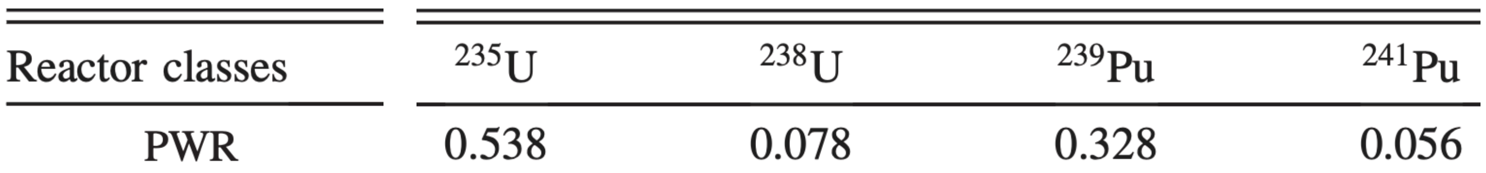


	Reactor					
	D1	D2	L1	L2	L3	L4
$\overline{W}_{\rm th}^{\rm 6AD}$	2.082	2.874	2.516	2.554	2.825	1.976
$\overline{W}_{\rm th}^{\rm 8AD}$	2.514	2.447	2.566	2.519	2.519	2.550

In GWs

DB Collaboration,
PRD 95, 072006 (2017)
1610.04802

Power fractions?



Reactor classes	^{235}U	^{238}U	^{239}Pu	^{241}Pu
PWR	0.538	0.078	0.328	0.056

Energy released per isotope?

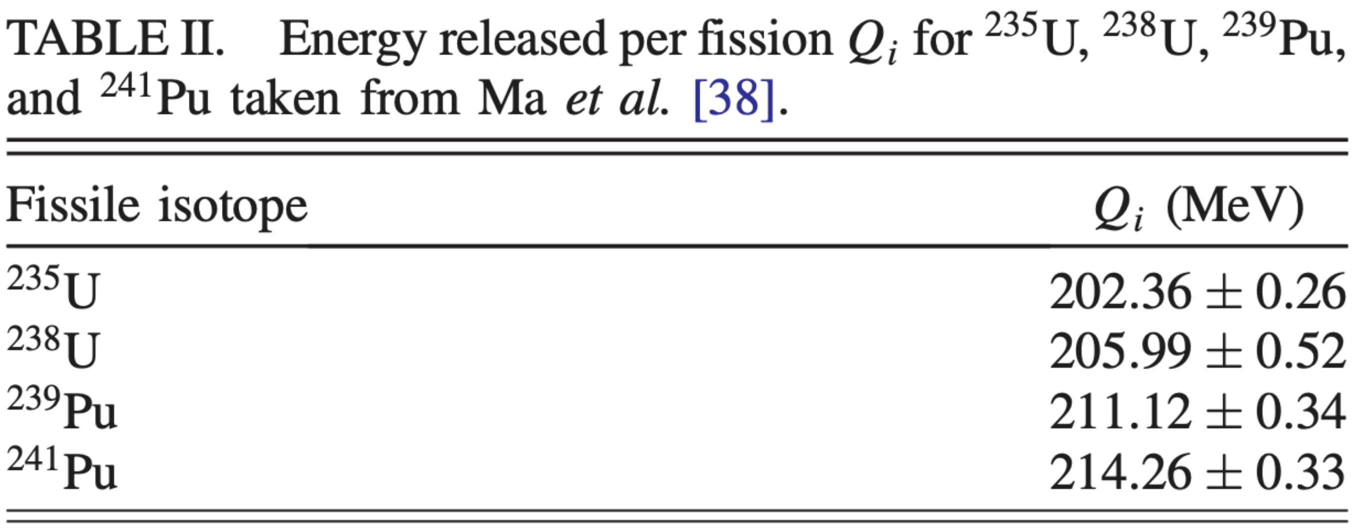


TABLE II. Energy released per fission Q_i for ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu taken from Ma *et al.* [38].

Fissile isotope	Q_i (MeV)
^{235}U	202.36 ± 0.26
^{238}U	205.99 ± 0.52
^{239}Pu	211.12 ± 0.34
^{241}Pu	214.26 ± 0.33

Baldoncini et al,
PRD 91 (2015) 065002

Condiments: Efficiencies, DAQ time, …

3 Different periods of data taking

DB Collaboration, 2211.14988

Condiments: Efficiencies, DAQ time, …

3 Different periods of data taking

DB Collaboration, 2211.14988

	6AD 217 days	8AD 1524 days	7AD 1417 days
EH1	AD1, AD2	AD1, AD2	AD2
EH2	AD3	AD3, AD8	AD3, AD8
EH3	AD4, AD5, AD6	AD4, AD5, AD6, AD7	AD4, AD5, AD6, AD7

Condiments: Efficiencies, DAQ time, …

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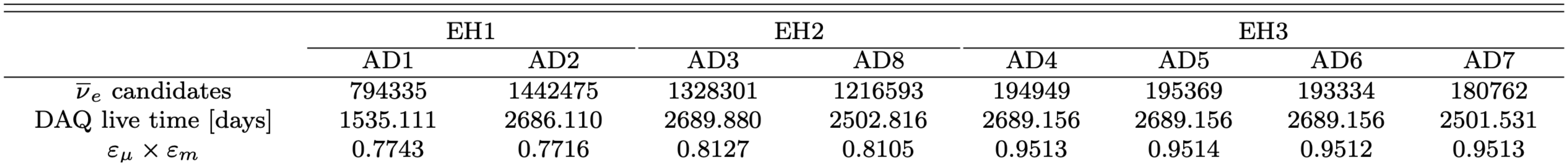
Efficiencies



	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.156	2501.531
$\varepsilon_\mu \times \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	0.9514	0.9512	0.9513

Condiments: Efficiencies, DAQ time, …

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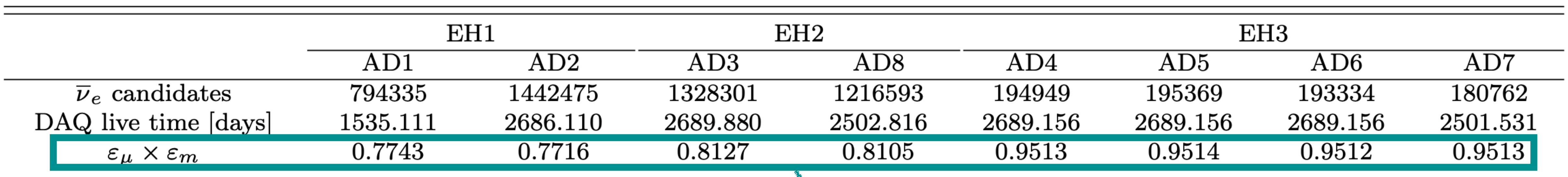
Efficiencies



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Muon veto and multiplicity selection

Backgrounds

Instrumental

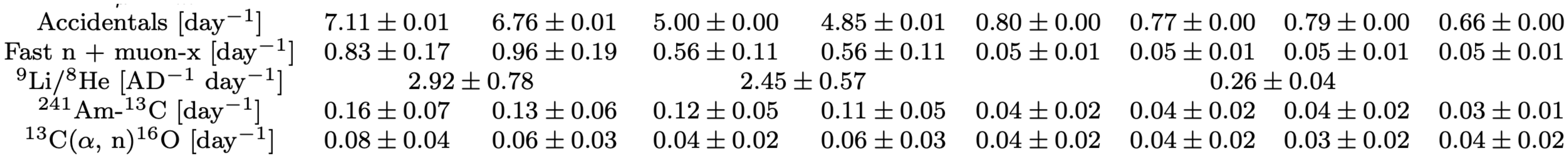
- PMTs emitting light

Uncorrelated

- Accidentals:
  Events producing two photons within the time interval expected for an IBD

Correlated

- Muons
- Fast neutrons
- ^{9}Li and ^{8}He
- ^{241}Am — ^{13}C neutron sources
- (α, n) interactions
- High multiplicity signals



Accidentals [day^{-1}]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast n + muon-x [day^{-1}]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li/^{8}He [AD^{-1} day^{-1}]	2.92 ± 0.78		2.45 ± 0.57		0.26 ± 0.04			
^{241}Am-^{13}C [day^{-1}]	0.16 ± 0.07	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
^{13}C(α, n)^{16}O [day^{-1}]	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02

DB Collaboration,
2211.14988

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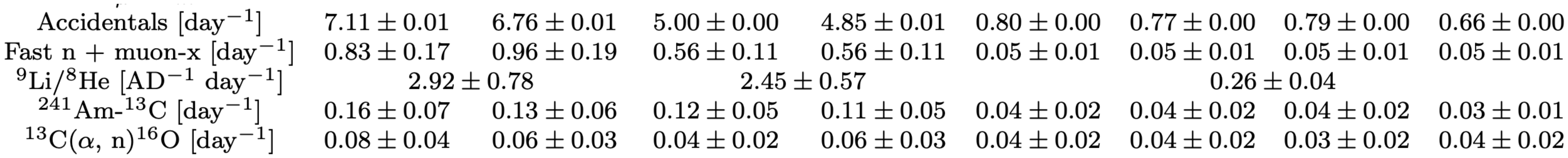

Accidentals [day^{-1}]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast n + muon-x [day^{-1}]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li/^{8}He [AD^{-1} day^{-1}]	2.92 ± 0.78		2.45 ± 0.57		0.26 ± 0.04			
^{241}Am-^{13}C [day^{-1}]	0.16 ± 0.07	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
^{13}C(α, n)^{16}O [day^{-1}]	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02

DB Collaboration,
2211.14988

DayaBay collaboration has also provided us data with the full backgrounds!

Putting Things Together

$$N_{pdb} = \underbrace{\boxed{\mathcal{N}_{pd}}}_{\text{Exposure}} \underbrace{\boxed{\epsilon_d}}_{\text{Efficiency}} \sum_{r=\text{reactors}} \int_{E_b}^{E_{b+1}} dE_{\text{prompt}} \underbrace{\boxed{\frac{d\phi_{rd}(\overline{\nu}_e)}{dE_\nu}}}_{\text{Neutrino flux}} P(\overline{\nu}_e \to \overline{\nu}_e; L_{dr}) \underbrace{\boxed{\sigma_{\text{IBC}}(E_\nu)}}_{\text{IBD cross section}}$$

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$$N_{pdb} = \underbrace{\boxed{\mathcal{N}_{pd}}}_{\text{Exposure}} \underbrace{\boxed{\epsilon_d}}_{\text{Efficiency}} \sum_{r=\text{reactors}} \int_{E_b}^{E_{b+1}} dE_{\text{prompt}} \underbrace{\boxed{\frac{d\phi_{rd}(\overline{\nu}_e)}{dE_\nu}}}_{\text{Neutrino flux}} P(\overline{\nu}_e \to \overline{\nu}_e; L_{dr}) \underbrace{\boxed{\sigma_{\text{IBC}}(E_\nu)}}_{\text{IBD cross section}}$$

Events at experimental hall *eh* during period p in the *true* prompt energy bin b:

$$N^{eh}_{pb} = \sum_{d=\text{detectors in EH}_{eh}\text{ during period }p} N_{pdb}$$

Putting Things Together

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Efficiency

Exposure

Neutrino flux

IBD cross section

Events at experimental hall *eh* during period p in the *true* prompt energy bin b:

$$N_{pb}^{eh} = \sum_{d=\text{detectors in EH}_{eh}\text{ during period }p} N_{pdb}$$

We will provide you all these quantities!

Putting Things Together

As there is some information we don't know about the data taking, we take a ratio of the events to the EH1 to perform the analysis

χ^2 analysis, including systematic uncertainties

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$$\left. + \frac{1}{(\sigma^{31}_{pb})^2} \left(\frac{O^3_{pb} - (1+\alpha^3_{Bp})B^3_{pb}}{O^1_{pb} - (1+\alpha^1_{Bp})B^1_{pb}} - (1+\alpha^{31}_{\epsilon p})\frac{N^3_{pb}}{N^1_{pb}} \right)^2 \right]$$

We will follow an approach similar to NuFit's 1811.05487

Putting Things Together

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Observed minus background in EH2

$$\chi^2(\sin^2\theta_{13}, \Delta m^2_{ee}; \overrightarrow{\alpha}) = \sum_{p=\text{periods}} \sum_{b=\text{bins}} \left[\frac{1}{(\sigma^{21}_{pb})^2} \left(\frac{\boxed{O^2_{pb} - (1+\alpha^2_{Bp})B^2_{pb}}}{O^1_{pb} - (1+\alpha^2_{Bp})B^1_{pb}} - (1+\alpha^{21}_{\epsilon p})\frac{N^2_{pb}}{N^1_{pb}} \right)^2 + \frac{1}{(\sigma^{31}_{pb})^2} \left(\frac{O^3_{pb} - (1+\alpha^3_{Bp})B^3_{pb}}{O^1_{pb} - (1+\alpha^1_{Bp})B^1_{pb}} - (1+\alpha^{31}_{\epsilon p})\frac{N^3_{pb}}{N^1_{pb}} \right)^2 \right]$$

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Expected events in EH2, depending on $\sin^2 2\theta_{13}, \Delta m^2_{ee}$

$$\chi^2(\sin^2\theta_{13}, \Delta m^2_{ee}; \vec{\alpha}) = \sum_{p=\text{periods}} \sum_{b=\text{bins}} \Bigg[\frac{1}{(\sigma^{21}_{pb})^2} \left(\frac{\boxed{O^2_{pb} - (1+\alpha^2_{Bp})B^2_{pb}}}{O^1_{pb} - (1+\alpha^2_{Bp})B^1_{pb}} - (1+\alpha^{21}_{\epsilon p}) \frac{\boxed{N^2_{pb}}}{N^1_{pb}} \right)^2 + \frac{1}{(\sigma^{31}_{pb})^2} \left(\frac{O^3_{pb} - (1+\alpha^3_{Bp})B^3_{pb}}{O^1_{pb} - (1+\alpha^1_{Bp})B^1_{pb}} - (1+\alpha^{31}_{\epsilon p}) \frac{N^3_{pb}}{N^1_{pb}} \right)^2 \Bigg]$$

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Error related to observed minus background ratio

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Error related to observed minus background ratio

Systematic uncertainty related to background at EH1 During period p

We will follow an approach similar to NuFit's 1811.05487

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χ^2 analysis, including systematic uncertainties

Observed minus background in EH2

Expected events in EH2, depending on $\sin^2 2\theta_{13}, \Delta m^2_{ee}$

$$\chi^2(\sin^2\theta_{13}, \Delta m^2_{ee}; \vec{\alpha}) = \sum_{p=\text{periods}}\sum_{b=\text{bins}} \left[\frac{1}{(\sigma^{21}_{pb})^2}\left(\frac{\boxed{O^2_{pb} - (1+\alpha^2_{Bp})B^2_{pb}}}{O^1_{pb} - (1+\alpha^2_{Bp})B^1_{pb}} - (1+\alpha^{21}_{\epsilon p})\frac{\boxed{N^2_{pb}}}{N^1_{pb}}\right)^2 + \frac{1}{\boxed{(\sigma^{31}_{pb})^2}}\left(\frac{O^3_{pb}-(1+\alpha^3_{Bp})B^3_{pb}}{O^1_{pb}-(1+\boxed{\alpha^1_{Bp}})B^1_{pb}} - (1+\boxed{\alpha^{31}_{\epsilon p}})\frac{N^3_{pb}}{N^1_{pb}}\right)^2\right]$$

Error related to observed minus background ratio

Systematic uncertainty related to background at EH1 During period p

Systematic uncertainty related to detector efficiency at EH1 During period p

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Putting Things Together

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$$\chi^2(\sin^2\theta_{13}, \Delta m^2_{ee}; \overrightarrow{\alpha}) = \sum_{p=\text{periods}} \sum_{b=\text{bins}} \left[\frac{1}{(\sigma^{21}_{pb})^2}\left(\frac{\boxed{O^2_{pb} - (1+\alpha^2_{Bp})B^2_{pb}}}{O^1_{pb} - (1+\alpha^2_{Bp})B^1_{pb}} - (1+\alpha^{21}_{\epsilon p})\frac{\boxed{N^2_{pb}}}{N^1_{pb}}\right)^2 + \frac{1}{\boxed{(\sigma^{31}_{pb})^2}}\left(\frac{O^3_{pb} - (1+\alpha^3_{Bp})B^3_{pb}}{O^1_{pb} - (1+\boxed{\alpha^1_{Bp}})B^1_{pb}} - (1+\boxed{\alpha^{31}_{\epsilon p}})\frac{N^3_{pb}}{N^1_{pb}}\right)^2\right]$$

Error related to observed minus background ratio

Systematic uncertainty related to background at EH1 During period p

Systematic uncertainty related to detector efficiency at EH1 During period p

As $\overrightarrow{\alpha} = \{\alpha^{eh}_{(B,\epsilon)p}\}$ are nuisance parameters, we need to marginalise over them

$$\chi^2_{\text{mar}} = \min_{\vec{\alpha}} \chi^2(\sin^2\theta_{13}, \Delta m^2_{ee}; \overrightarrow{\alpha})$$

We will follow an approach similar to NuFit's 1811.05487

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We assume you have knowledge of python and that each one of you have a laptop

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6. Compare with official Daya Bay results!

To do so:

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Go to:

https://yeti-2425.notebooks.danielmaitre.phyip3.dur.ac.uk/

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Access with your credentials, and then click on Assignments:

Released, downloaded, and submitted assignments for course:

Released assignments	
dayabay_analysis	Fetch
neutrino_oscillations	Fetch
test	Fetch

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Select dayabay_analysis by clicking Fetch

To do so:

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Released, downloaded, and submitted assignments for course:

Released assignments

neutrino_oscillations

test

Downloaded assignments

dayabay_analysis

dayabay_analysis

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Downloaded assignments	
dayabay_analysis ▾	Submit
dayabay_analysis	Validate

Click on dayabay_analysis, which should open a new tab with a jupyter notebook for you to work in

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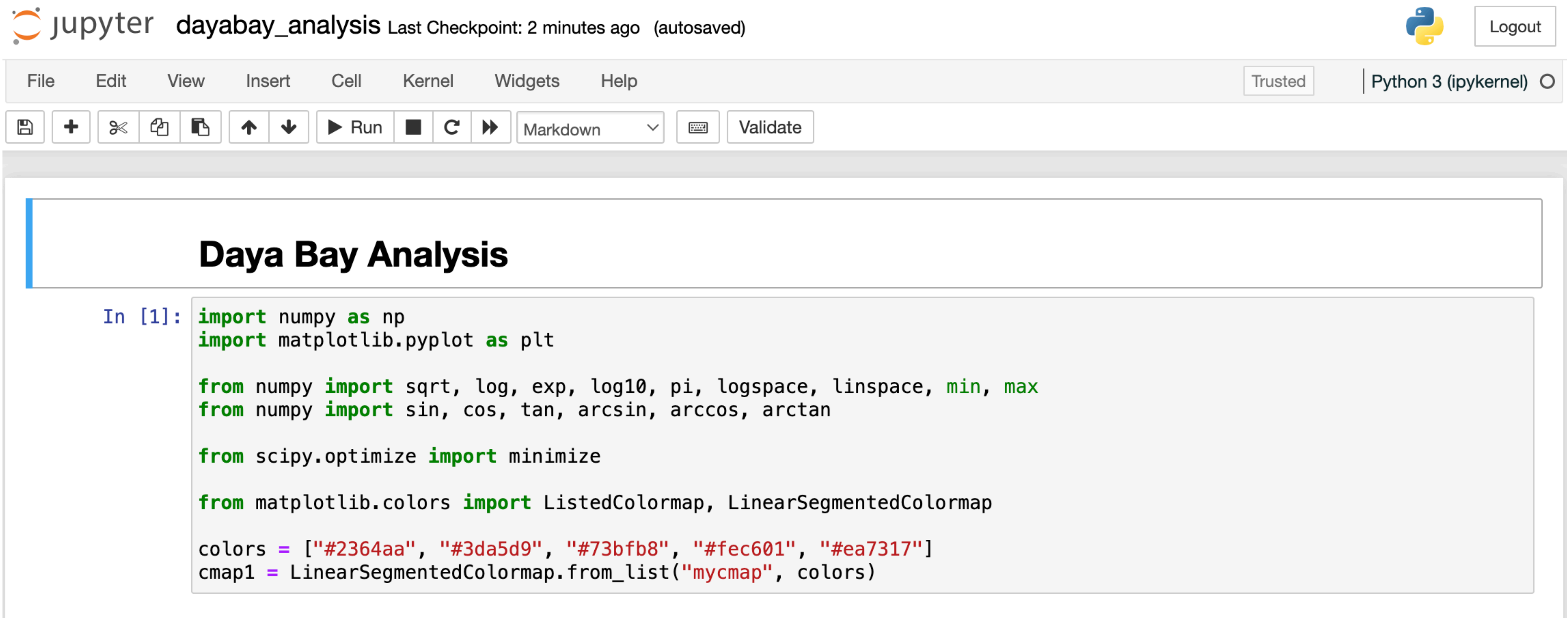


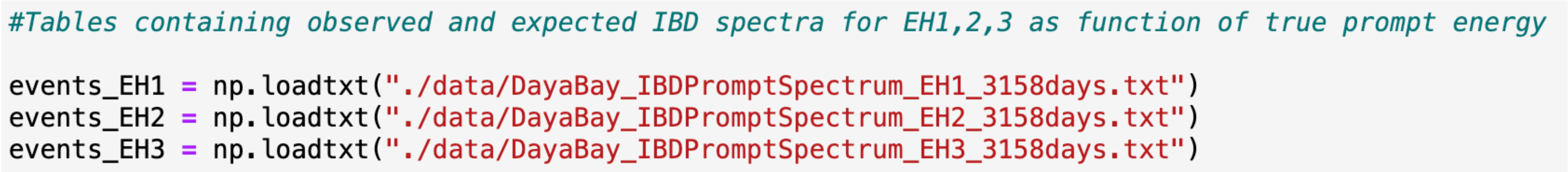
Daya Bay Analysis

In [1]:

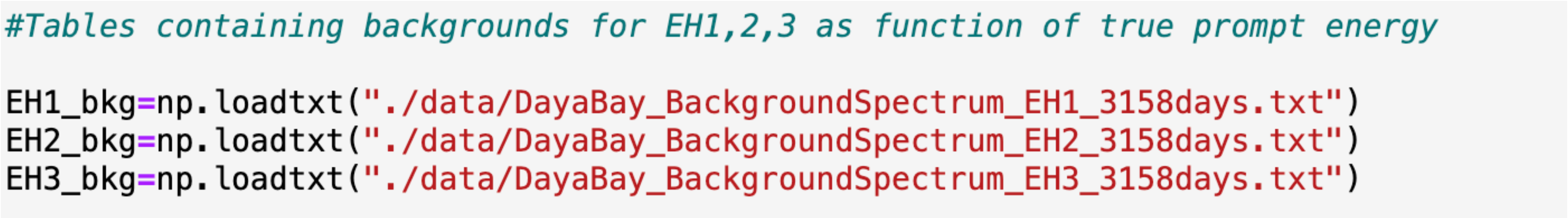
```
import numpy as np
import matplotlib.pyplot as plt

from numpy import sqrt, log, exp, log10, pi, logspace, linspace, min, max
from numpy import sin, cos, tan, arcsin, arccos, arctan

from scipy.optimize import minimize

from matplotlib.colors import ListedColormap, LinearSegmentedColormap

colors = ["#2364aa", "#3da5d9", "#73bfb8", "#fec601", "#ea7317"]
cmap1 = LinearSegmentedColormap.from_list("mycmap", colors)
```

What's already on the notebook

- Data provided by Daya Bay



```
#Tables containing observed and expected IBD spectra for EH1,2,3 as function of true prompt energy

events_EH1 = np.loadtxt("./data/DayaBay_IBDPromptSpectrum_EH1_3158days.txt")
events_EH2 = np.loadtxt("./data/DayaBay_IBDPromptSpectrum_EH2_3158days.txt")
events_EH3 = np.loadtxt("./data/DayaBay_IBDPromptSpectrum_EH3_3158days.txt")
```

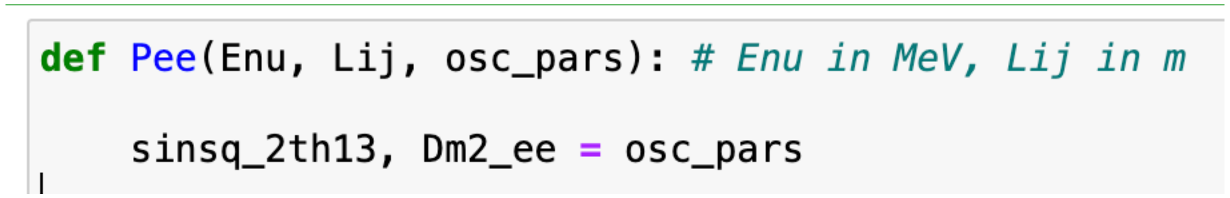


```
#Tables containing backgrounds for EH1,2,3 as function of true prompt energy

EH1_bkg=np.loadtxt("./data/DayaBay_BackgroundSpectrum_EH1_3158days.txt")
EH2_bkg=np.loadtxt("./data/DayaBay_BackgroundSpectrum_EH2_3158days.txt")
EH3_bkg=np.loadtxt("./data/DayaBay_BackgroundSpectrum_EH3_3158days.txt")
```

- IBD cross-section

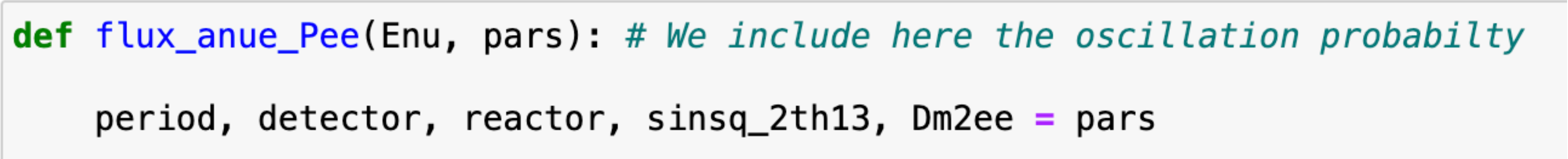
```
def sigma(Enu):
    '''Total cross section, in cm^2'''
```

- Oscillation probability



```
def Pee(Enu, Lij, osc_pars): # Enu in MeV, Lij in m

    sinsq_2th13, Dm2_ee = osc_pars
```

- Neutrino flux at a given EH



```
def flux_anue_Pee(Enu, pars): # We include here the oscillation probabilty

    period, detector, reactor, sinsq_2th13, Dm2ee = pars
```

What’s already on the notebook

```python
# Detectors properties:
#                       fiducial mass in kg, efficiency, detector-reactors distances in m

Detectors_dict = {'AD1':{'mass':19941, 'eff':0.7743,
                         'DB1':362.38,  'DB2':371.76, 'LA1':903.47,  'LA2':817.16, 'LA3':1353.62, 'LA4':1265.32},

                  'AD2':{'mass':19967, 'eff':0.7716,
                         'DB1':357.94,  'DB2':368.41, 'LA1':903.35,  'LA2':816.90,  'LA3':1354.23, 'LA4':1265.89},

                  'AD3':{'mass':19891, 'eff':0.8127,
                         'DB1':1332.48, 'DB2':1358.15,'LA1':467.57,  'LA2':498.58,  'LA3':557.58,  'LA4':499.21},

                  'AD8':{'mass':19944, 'eff':0.8105,
                         'DB1':1337.43, 'DB2':1362.88, 'LA1':472.97,  'LA2':495.35,  'LA3':558.71,  'LA4':501.07},

                  'AD4':{'mass':19917, 'eff':0.9513,
                         'DB1':1919.63, 'DB2':1894.34, 'LA1':1533.18, 'LA2':1533.63, 'LA3':1551.38, 'LA4':1524.94},

                  'AD5':{'mass':19989, 'eff':0.9514,
                         'DB1':1917.52, 'DB2':1891.98, 'LA1':1534.92, 'LA2':1535.03, 'LA3':1554.77, 'LA4':1528.05},

                  'AD6':{'mass':19892, 'eff':0.9512,
                         'DB1':1925.26, 'DB2':1899.86, 'LA1':1538.93, 'LA2':1539.47, 'LA3':1556.34, 'LA4':1530.08},

                  'AD7':{'mass':19931, 'eff':0.9513,
                         'DB1':1923.15, 'DB2':1897.51, 'LA1':1540.67, 'LA2':1540.87, 'LA3':1559.72, 'LA4':1533.18}}
```

- Mass: detector mass in kg
- Eff: Efficiency associated with the detector
- Reactors: detector-reactor distance in m

What’s already on the notebook

```
experiment_data = { '6AD' : {'exposure':217*24.*3600., # in seconds
                                  'EH1':['AD1', 'AD2'],
                                  'EH2':['AD3'],
                                  'EH3':['AD4', 'AD5', 'AD6'],
                                  'Wth':{'DB1':2082, 'DB2':2874, 'LA1':2516,
                                         'LA2':2554, 'LA3':2825, 'LA4':1976}},

                    '8AD' : {'exposure':1524*24.*3600., # in seconds
                                  'EH1':['AD1', 'AD2'],
                                  'EH2':['AD3', 'AD8'],
                                  'EH3':['AD4', 'AD5', 'AD6', 'AD7'],
                                  'Wth':{'DB1':2514, 'DB2':2447, 'LA1':2566,
                                         'LA2':2519, 'LA3':2519, 'LA4':2550}},

                    '7AD' : {'exposure':1417*24.*3600., # in seconds
                                  'EH1':['AD2'],
                                  'EH2':['AD3', 'AD8'],
                                  'EH3':['AD4', 'AD5', 'AD6', 'AD7'],
                                  'Wth':{'DB1':0.5*(2082+2514), 'DB2':0.5*(2874+2447),
                                         'LA1':0.5*(2516+2566), 'LA2':0.5*(2554+2519),
                                         'LA3':0.5*(2825+2519), 'LA4':0.5*(1976+2550)}}}
```

- Exposure: time of data taking in s
- EHx: Detectors present in period
- Wth: Average thermal power associated with each reactors

Note that for 7AD we take the $W_{\rm th}$ average of 6AD and 8AD as this information is not provided by the collaboration afaik

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Any question?

Let's get down to business!

Thanks!