Department of Physics

‘Physics then and now – the life and work of Don Perkins’ - 14 March 2024

‘Neutrino Oscillations’

Professor Paul Harrison
Professor of Particle Physics
University of Warwick

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Don Perkins and Neutrino Oscillations

Paul Harrison
University of Warwick

"PerkinsFest", Oxford,
14th March 2024

Special thanks to Bill Scott for collaboration and recollections

Don and Neutrinos Pre-1994

Don worked on proton decay experiments: Soudan 1 and Soudan 2

He championed the importance of atmospheric neutrinos and pioneered calculations of atmospheric neutrino fluxes

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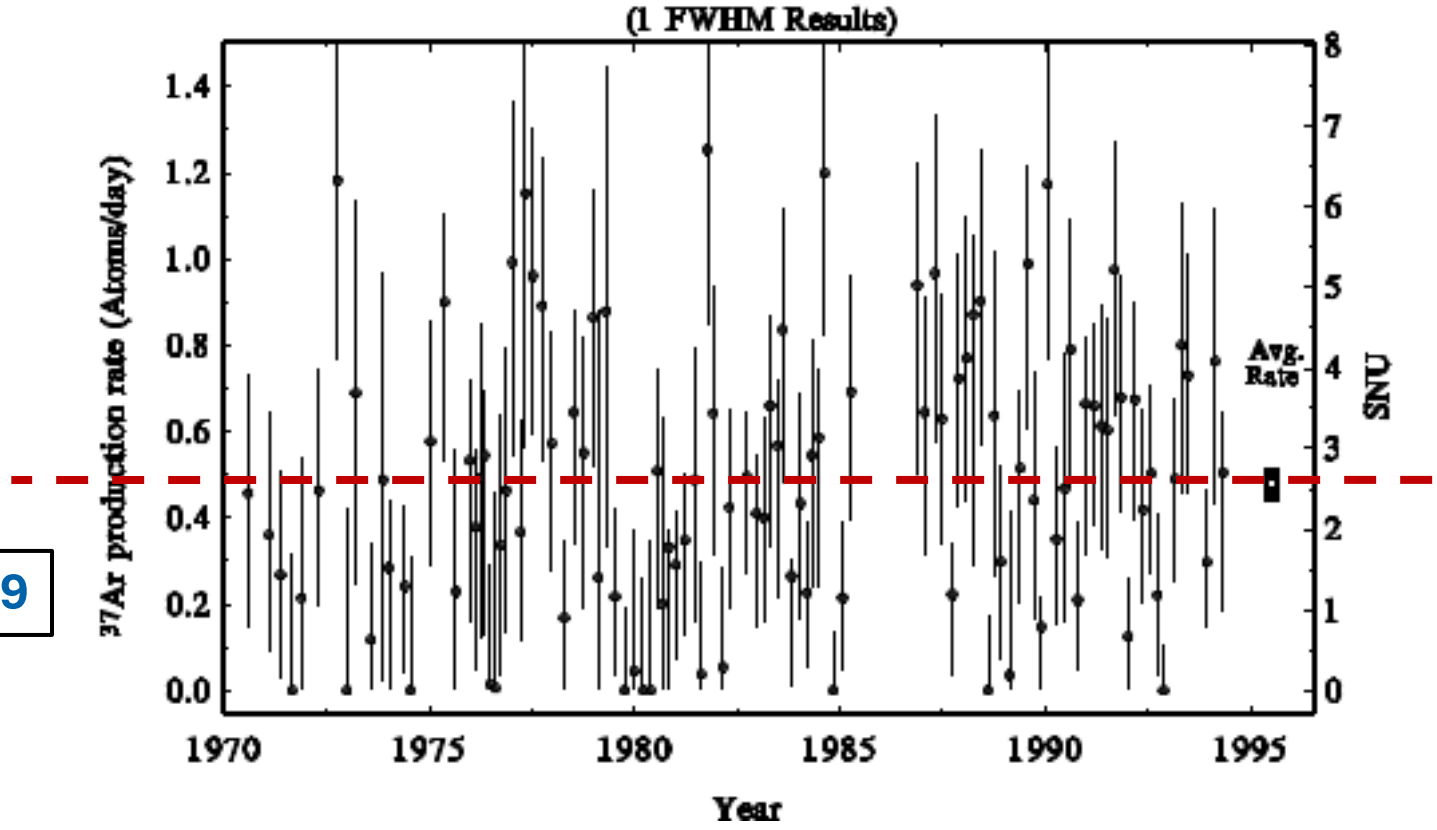
"Dominant background to proton decay experiments is due to atmospheric neutrinos, which are the ultimate limiting factor determining the sensitivity to proton lifetimes.
It has become abundantly clear … that a proper understanding of this background is at least 90% of the battle to discover a proton decay signal."

From "Proton Decay Experiments"
D. H. Perkins, Ann. Rev. Nucl. Part. Sci. 34 (1984) 1 – 32

Context of ~1993: Solar Neutrinos

Homestake solar neutrino data:



=> Data/ SSM = 0.30 ± 0.04 ± 0.09

Also

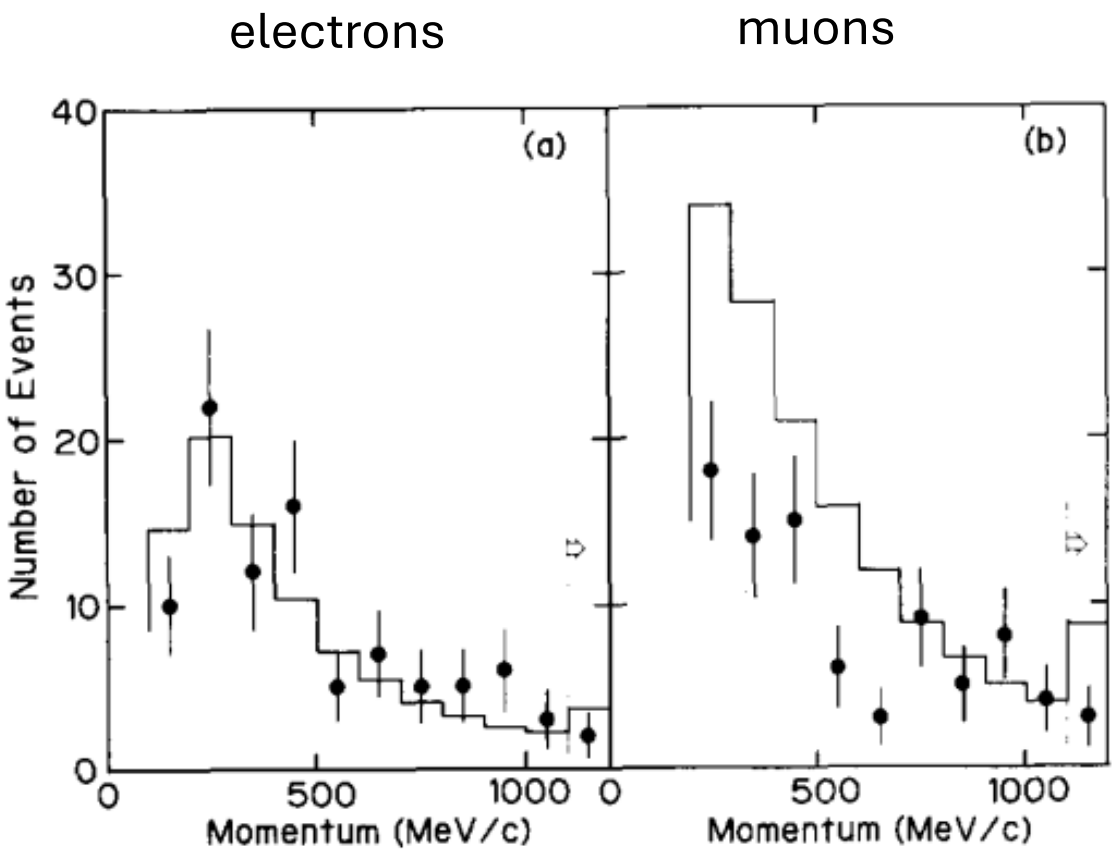
Deficits in Gallium experiments: SAGE and GALLEX, as well as Kamiokande

Generally accepted solution was the small angle MSW effect

First signs of issues with Atmospheric Neutrinos

KAMIOKA 1988

K. S. Hirata et al
PLB 205 (1988) 416



1993: Don was still highly sceptical about ν oscillations

Nuclear Physics B399 (1993) 3–14
North-Holland

NUCLEAR PHYSICS B

The atmospheric neutrino problem: A critique

D.H. Perkins

Nuclear Physics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, UK

Received 16 March 1993
Accepted for publication 26 March 1993

”Interpretations in terms of neutrino oscillations are correspondingly dubious”!!!

Summer 1994: The Turning Point

June

Harrison & Scott (H&S) propose Trimaximal mixing for quarks

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Neutrino '94 Conference: Updated Solar results from Gallium and Kamiokande

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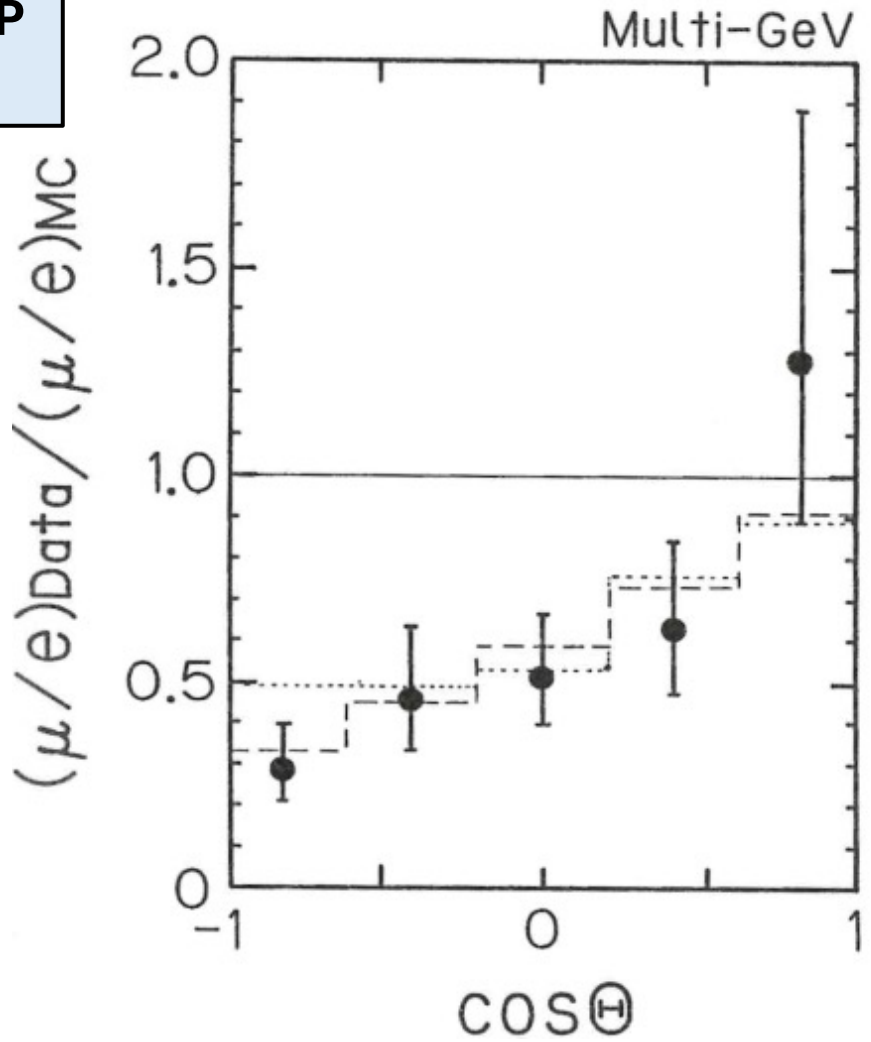
27th Intl. Conf. on HEP, Glasgow: updated Atmospheric ν results from Kamiokande et al.

Kamiokande Multi-Gev data

M. Nakahata, Glasgow ICHEP Conference 1994

A clear zenith angle dependence!

Strongly favoured ν oscillations with large mixing angles



"...I have become more convinced!"

Glasgow ICHEP Conference 1994

P. Darriulat's Conference Summary talk:

Experiment	Data/SSM (BP) %	Data/SSM (TCL) %
GALLEX	$60 \pm 8 \pm 5$	$64 \pm 8 \pm 5$
SAGE	$52 \pm 8 \pm 5$	$56 \pm 9 \pm 5$
Kamiokande	$51 \pm 4 \pm 6$	$66 \pm 5 \pm 8$
Homestake	(Pro memoria) $29 \pm 3 \pm 9$	

"...the gallium experiments are *shouting* five/ninths"

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Rest of year

Don brings to HPS a deep knowledge of atmospheric ν fluxes and a healthy scepticism.

HPS Goals

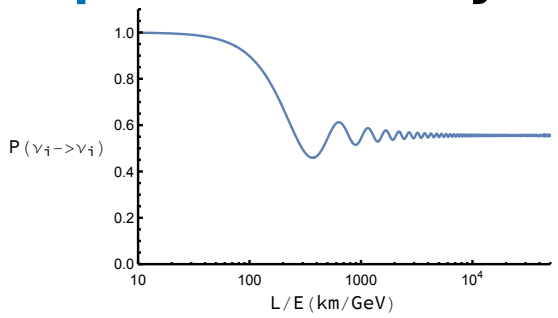
To fully embrace 3 flavours of neutrinos

To understand all the ν data in a single unified framework

To keep it as simple as possible (but not simpler)

3x3 mixing matrix
2 mass-squared differences

To interpret the theory visually



To highlight apparent symmetries, where plausible => Mass Matrix origins

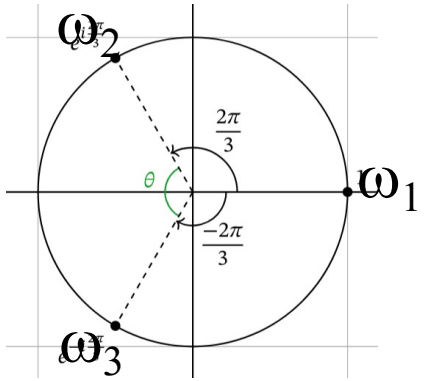
$$\begin{pmatrix} a & b & b^* \\ b^* & a & b \\ b & b^* & a \end{pmatrix} \qquad \begin{pmatrix} x & 0 & y \\ 0 & z & 0 \\ y & 0 & x \end{pmatrix}$$

Threefold maximal lepton mixing and the solar and atmospheric neutrino deficits PLB 349 (1995) 137

“HPS1”
(153 citations)

Basic idea:

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \omega_1 & \omega_1 & \omega_1 \\ \omega_1 & \omega_2 & \omega_3 \\ \omega_1 & \omega_3 & \omega_2 \end{pmatrix}$$



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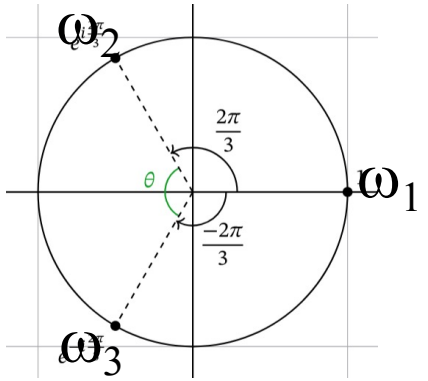
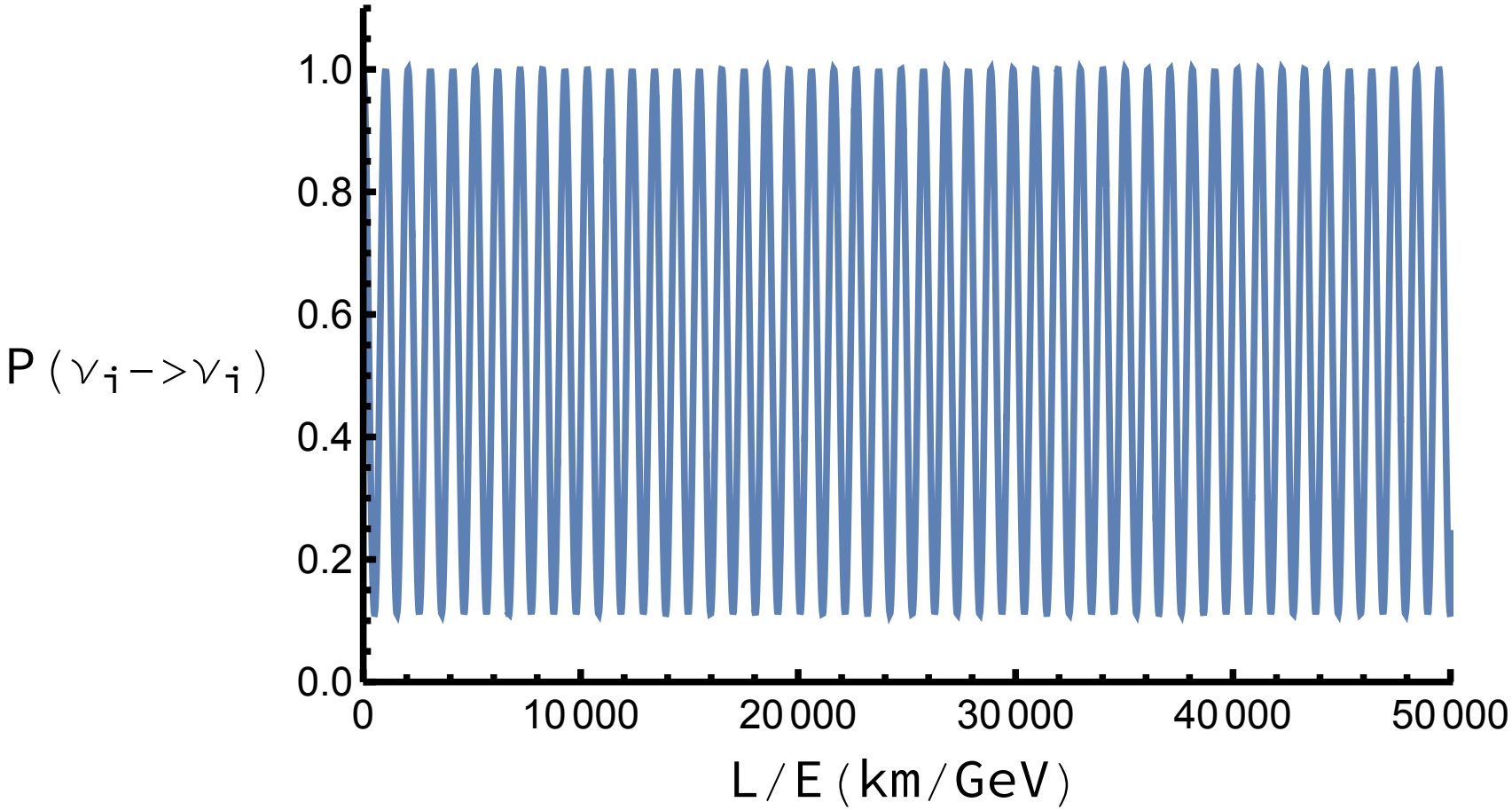


Trimaximal mixing => universal survival probabilities – eminently testable

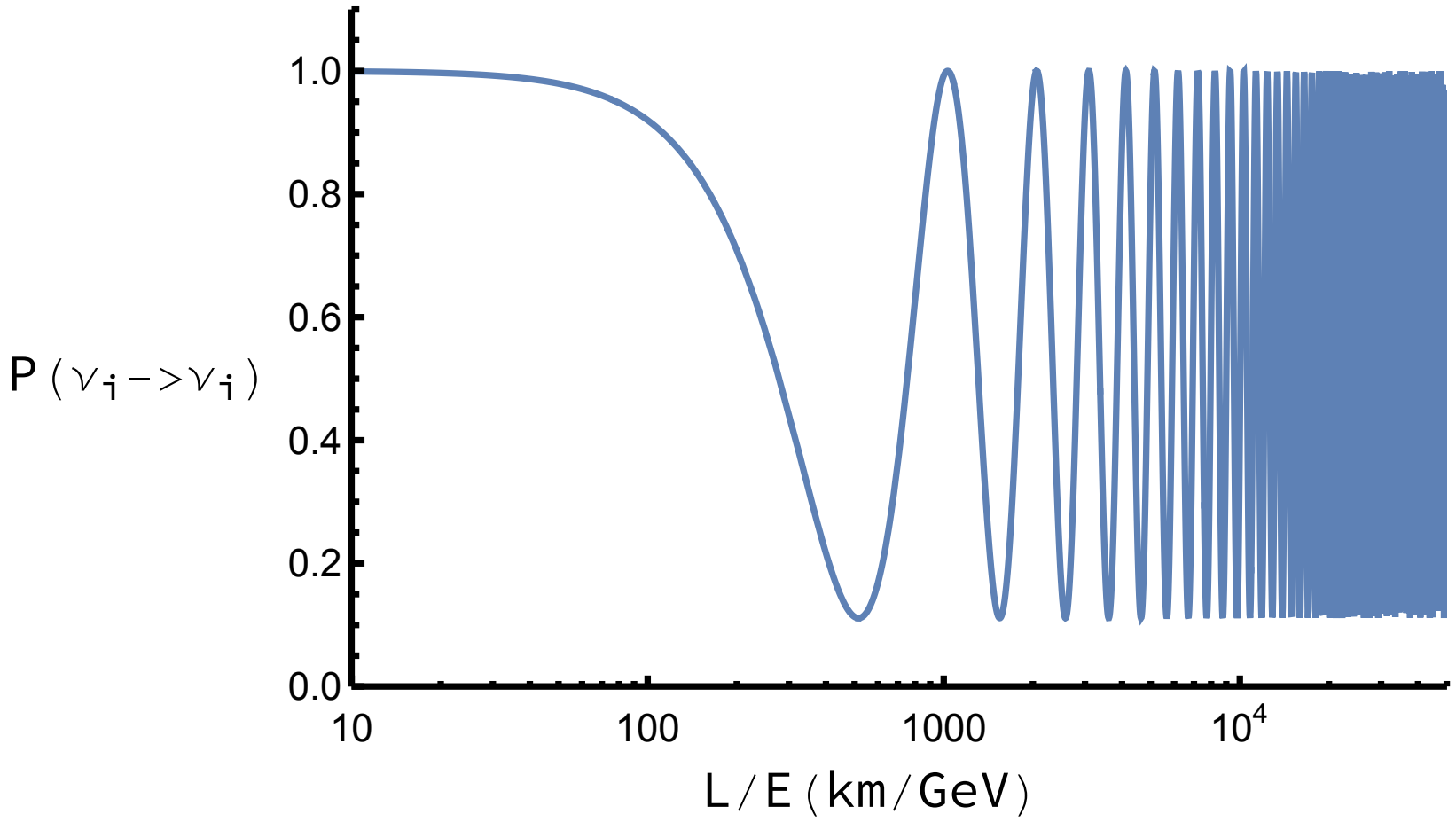
HPS1: The Plot

Survival probability: $P_{(\nu i->\nu i)}$ vs. L/E



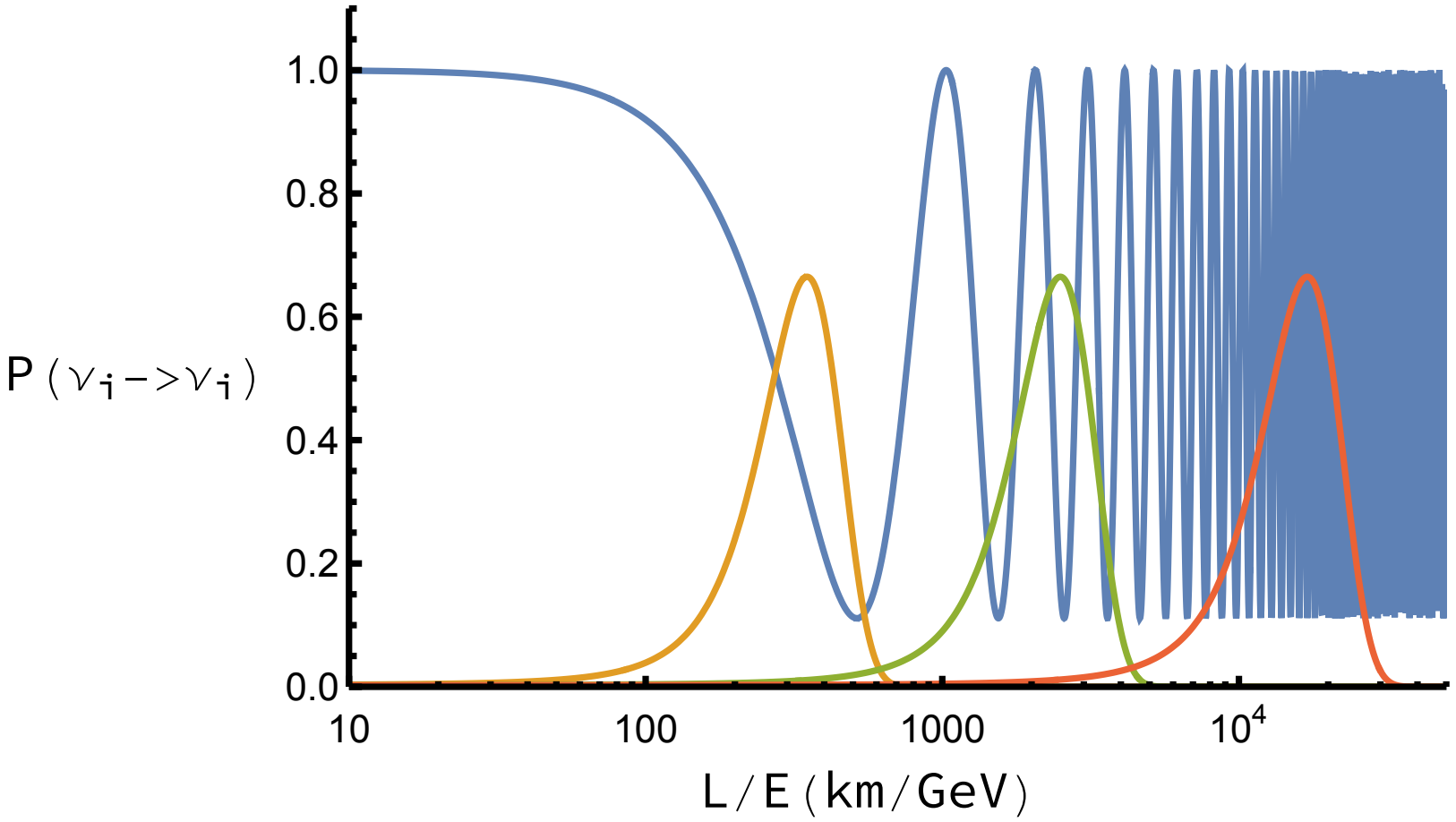
HPS1: The Plot

The Plot: survival probability vs. ν L/E – on a log scale



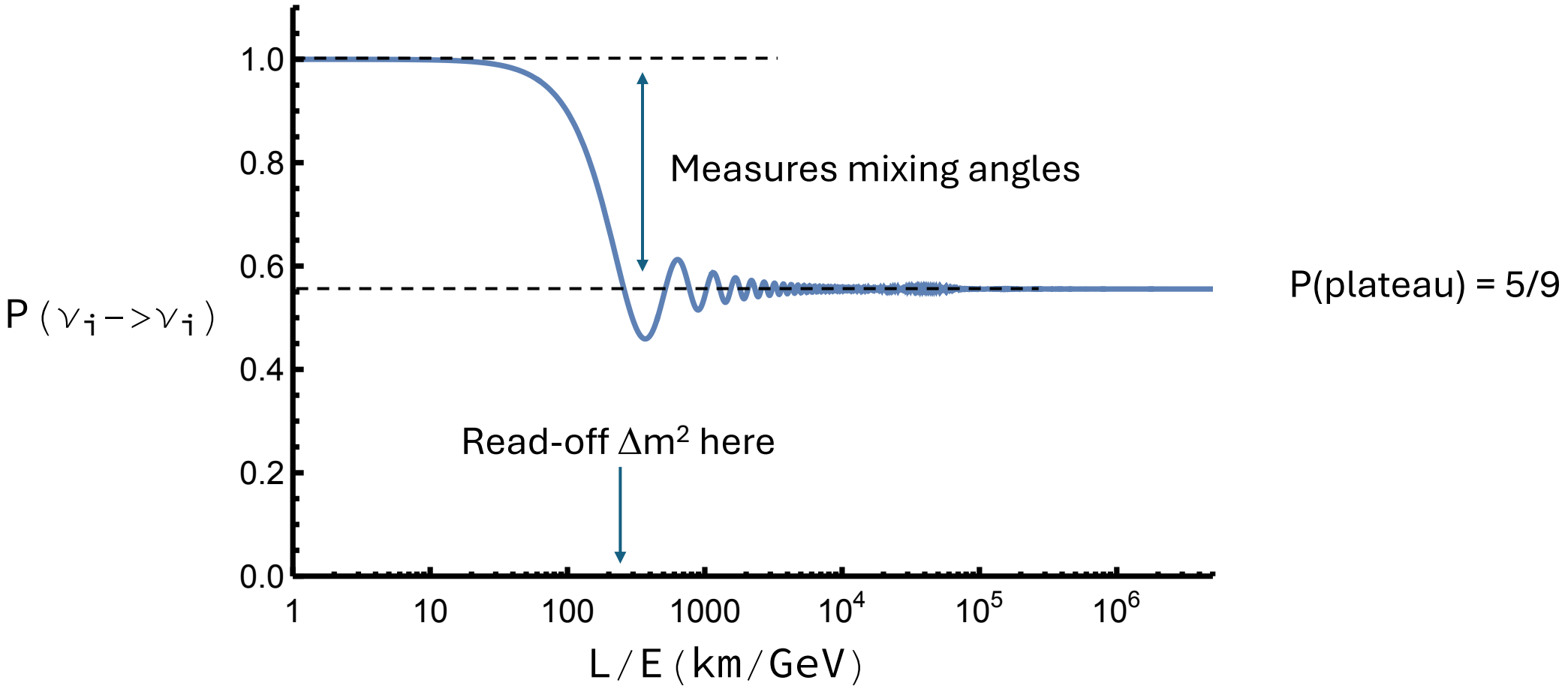
HPS1: The Plot

The Plot: survival probability vs. ν L/E – resolution functions superposed



HPS1: The Plot

The Plot: universal survival probability vs. L/E – including resolution smearing



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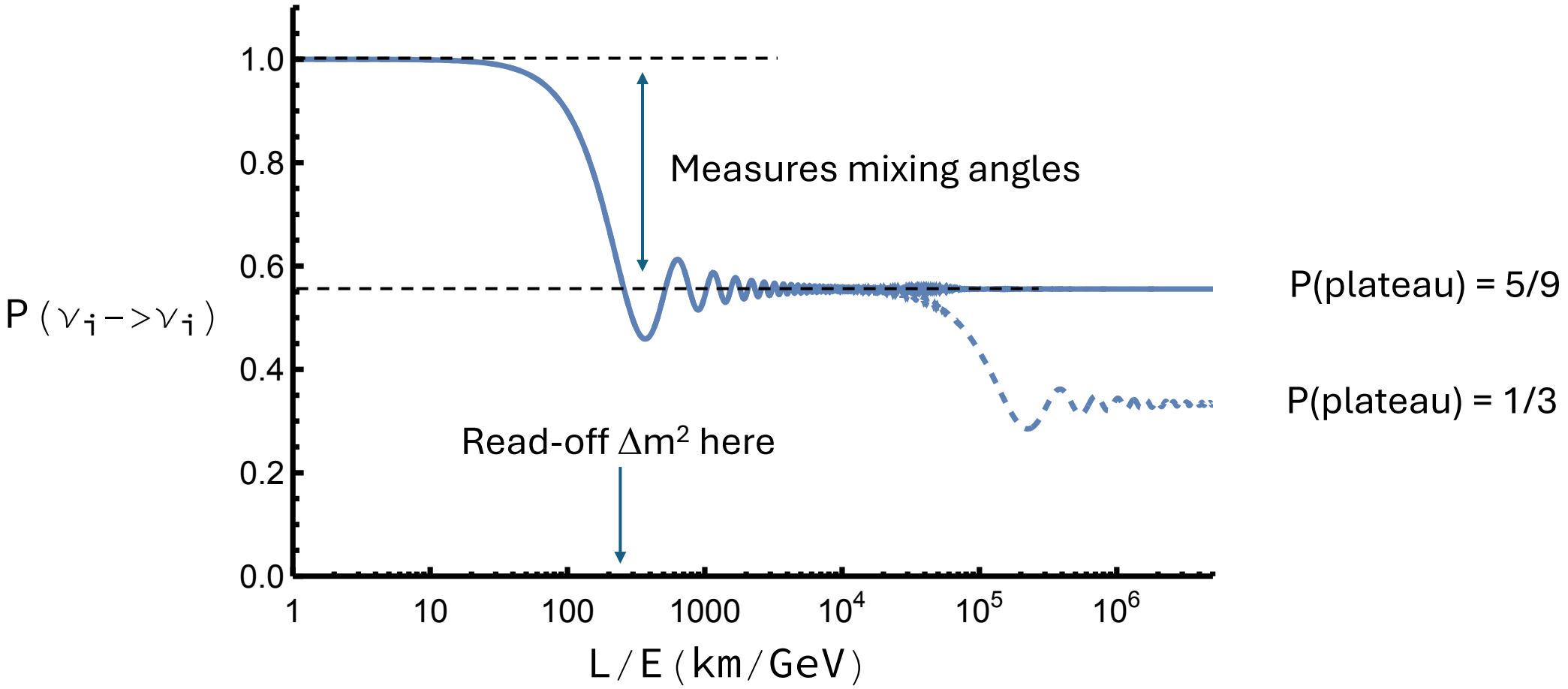
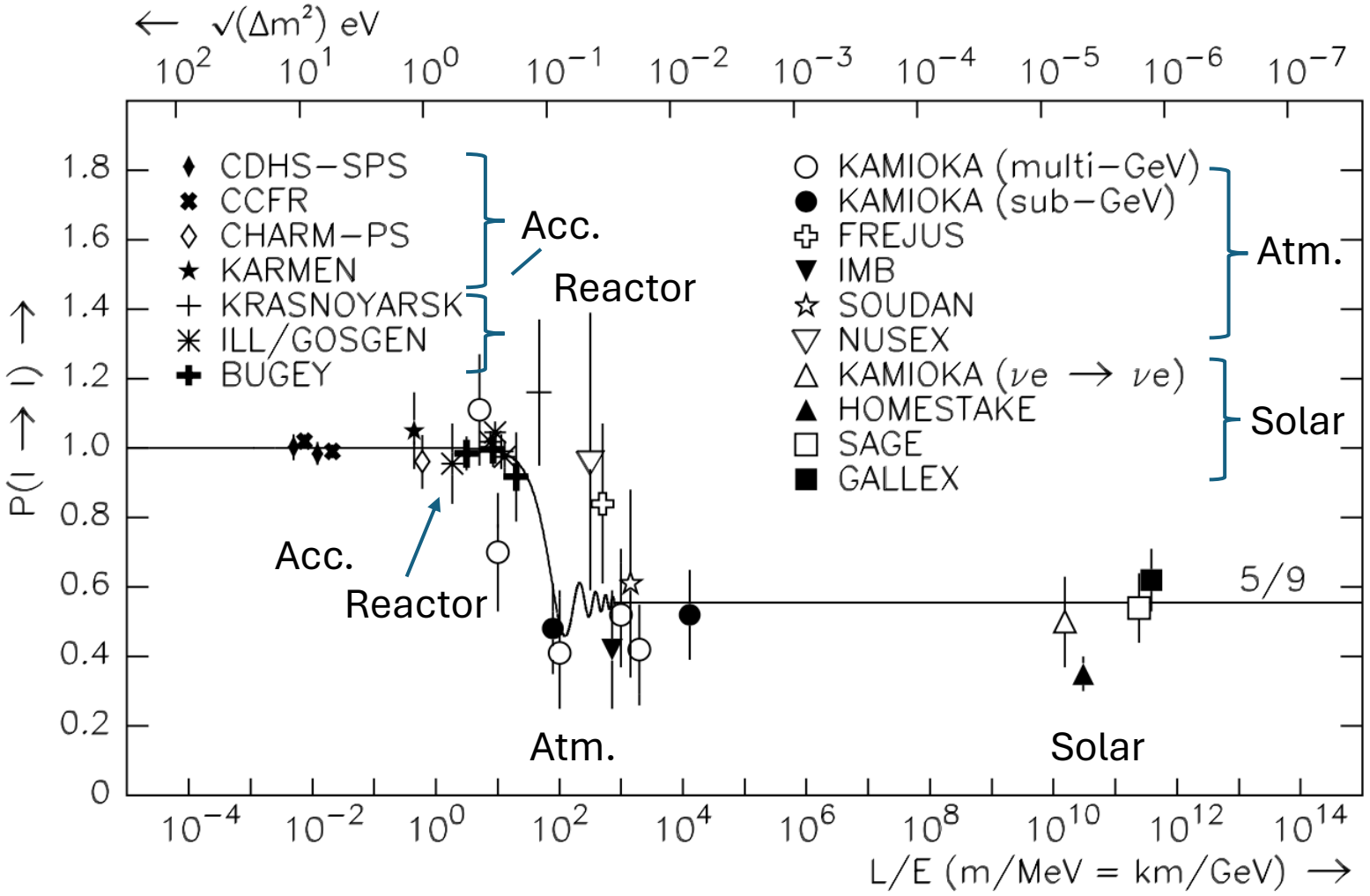


HPS1: The Plot with Data



χ^2/dof=20.5/28

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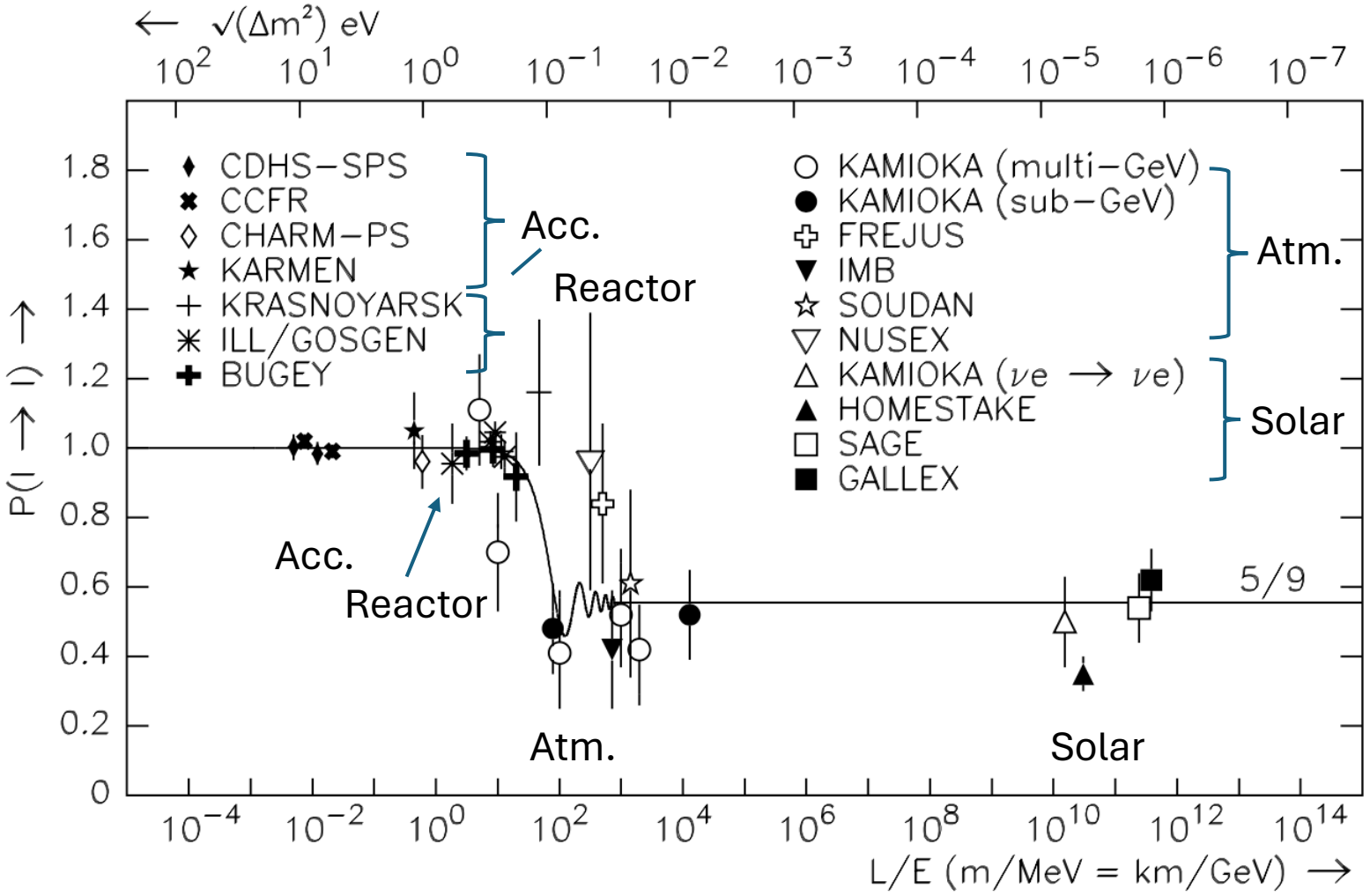

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$\Delta m^2 = 7.2 \pm 1.8 \times 10^{-3}$ eV²

$\Delta m'^2$ unresolved

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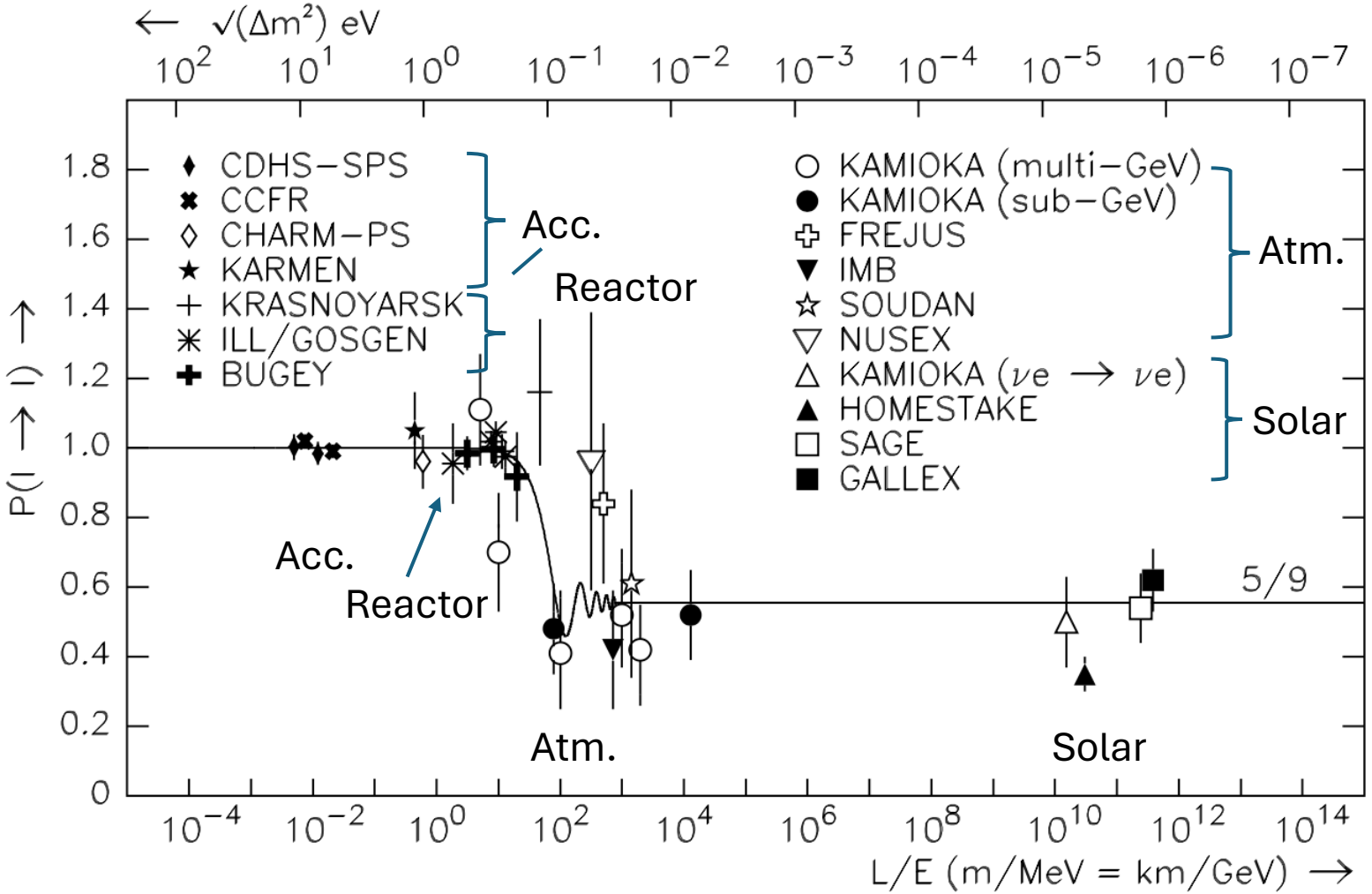


χ^2/dof=20.5/28

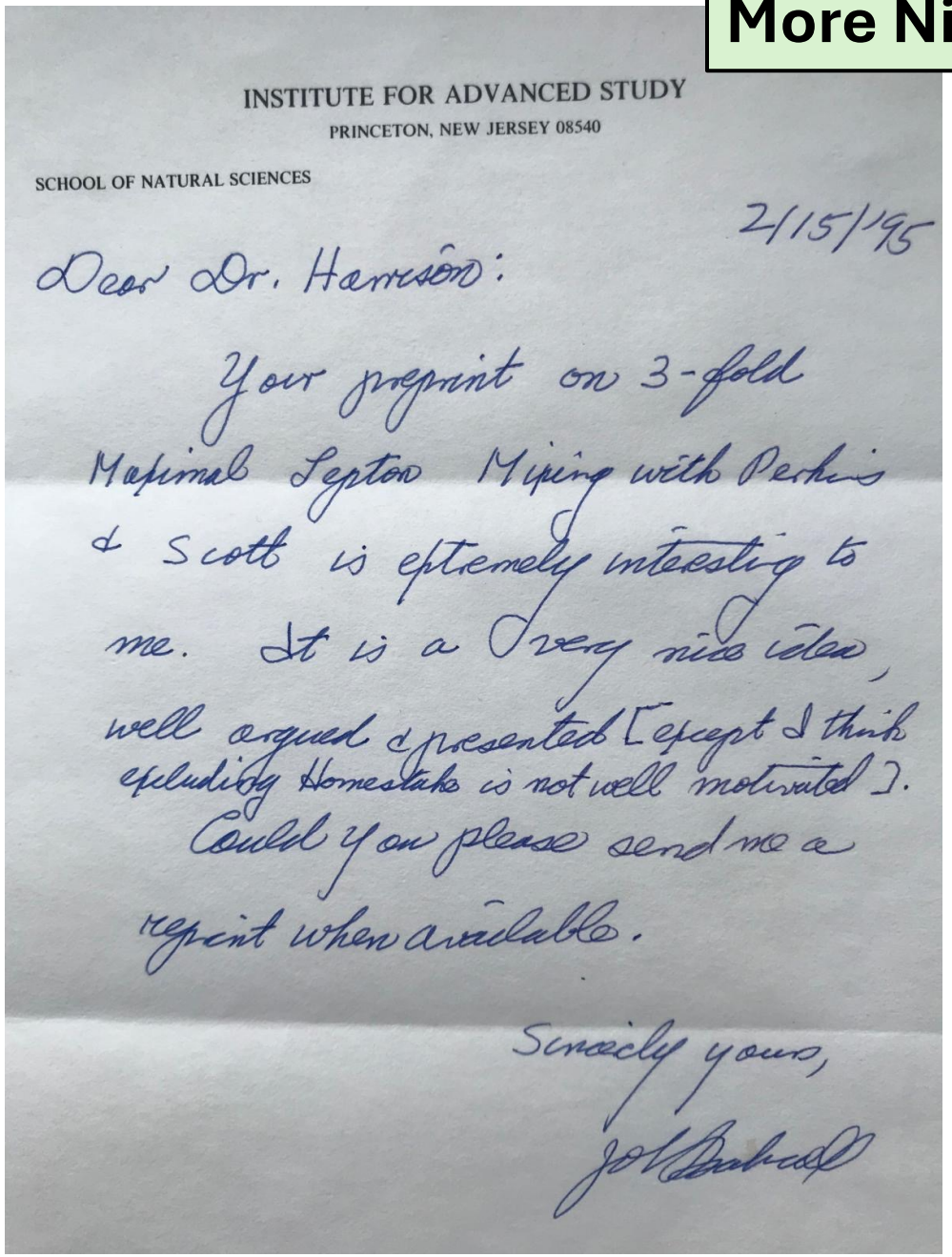
$\Delta m^2 = 7.2 \pm 1.8 \times 10^{-3}$ eV²

$\Delta m'^2$ unresolved

"...this wonderful plot"

L. Maiani
XVIth WIN
Workshop 1997
(re. L/E Plot
In HPS1)

More Nice Feedback



INSTITUTE FOR ADVANCED STUDY
PRINCETON, NEW JERSEY 08540

SCHOOL OF NATURAL SCIENCES

2/15/95

Dear Dr. Harrison:

Your preprint on 3-fold Maximal Lepton Mixing with Perkins & Scott is extremely interesting to me. It is a very nice idea, well argued & presented [except I think explicitly Homestake is not well motivated].

Could you please send me a reprint when available.

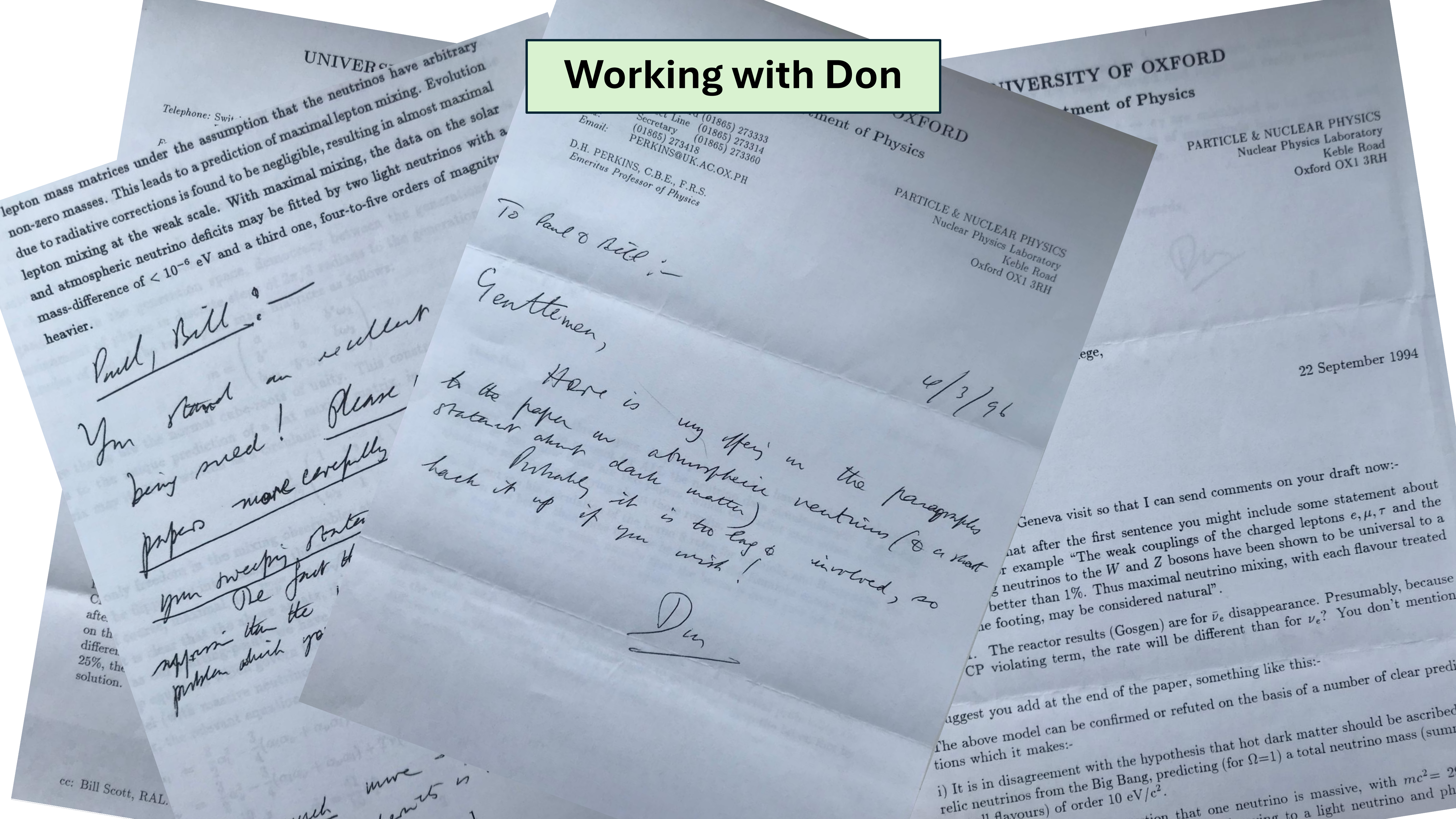
Sincerely yours,

Joh Bahcall

"Your preprint…with Perkins and Scott is extremely interesting to me. It is a very nice idea, well argued and presented"

John Bahcall: Letter 15/2/95

Working with Don



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D.H. PERKINS, C.B.E., F.R.S.
Emeritus Professor of Physics

PARTICLE & NUCLEAR PHYSICS
Nuclear Physics Laboratory
Keble Road
Oxford OX1 3RH

To Paul & Bill :–

Gentlemen,

4/3/96

Here is my effort on the paragraphs to the paper on atmospheric neutrinos (& a short statement about dark matter). Probably it is too long & involved, so hack it up if you wish!

Don

---

lepton mass matrices under the assumption that the neutrinos have arbitrary non-zero masses. This leads to a prediction of maximal lepton mixing. Evolution due to radiative corrections is found to be negligible, resulting in almost maximal lepton mixing at the weak scale. With maximal mixing, the data on the solar and atmospheric neutrino deficits may be fitted by two light neutrinos with a mass-difference of $< 10^{-6}$ eV and a third one, four-to-five orders of magnitude heavier.

Paul, Bill :–

You stand an excellent chance of being sued! Please write papers more carefully. Your sweeping statement ...

cc: Bill Scott, RAL.

UNIVERSITY OF OXFORD

Department of Physics

PARTICLE & NUCLEAR PHYSICS
Nuclear Physics Laboratory
Keble Road
Oxford OX1 3RH

22 September 1994

... Geneva visit so that I can send comments on your draft now:-

... that after the first sentence you might include some statement about ... for example "The weak couplings of the charged leptons e, μ, τ and the ... neutrinos to the W and Z bosons have been shown to be universal to a ... better than 1%. Thus maximal neutrino mixing, with each flavour treated ... the footing, may be considered natural".

... The reactor results (Gosgen) are for $\bar{\nu}_e$ disappearance. Presumably, because ... CP violating term, the rate will be different than for ν_e? You don't mention ...

... suggest you add at the end of the paper, something like this:-

The above model can be confirmed or refuted on the basis of a number of clear predictions which it makes:-

i) It is in disagreement with the hypothesis that hot dark matter should be ascribed to relic neutrinos from the Big Bang, predicting (for Ω=1) a total neutrino mass (summed over all flavours) of order 10 eV/c^2.

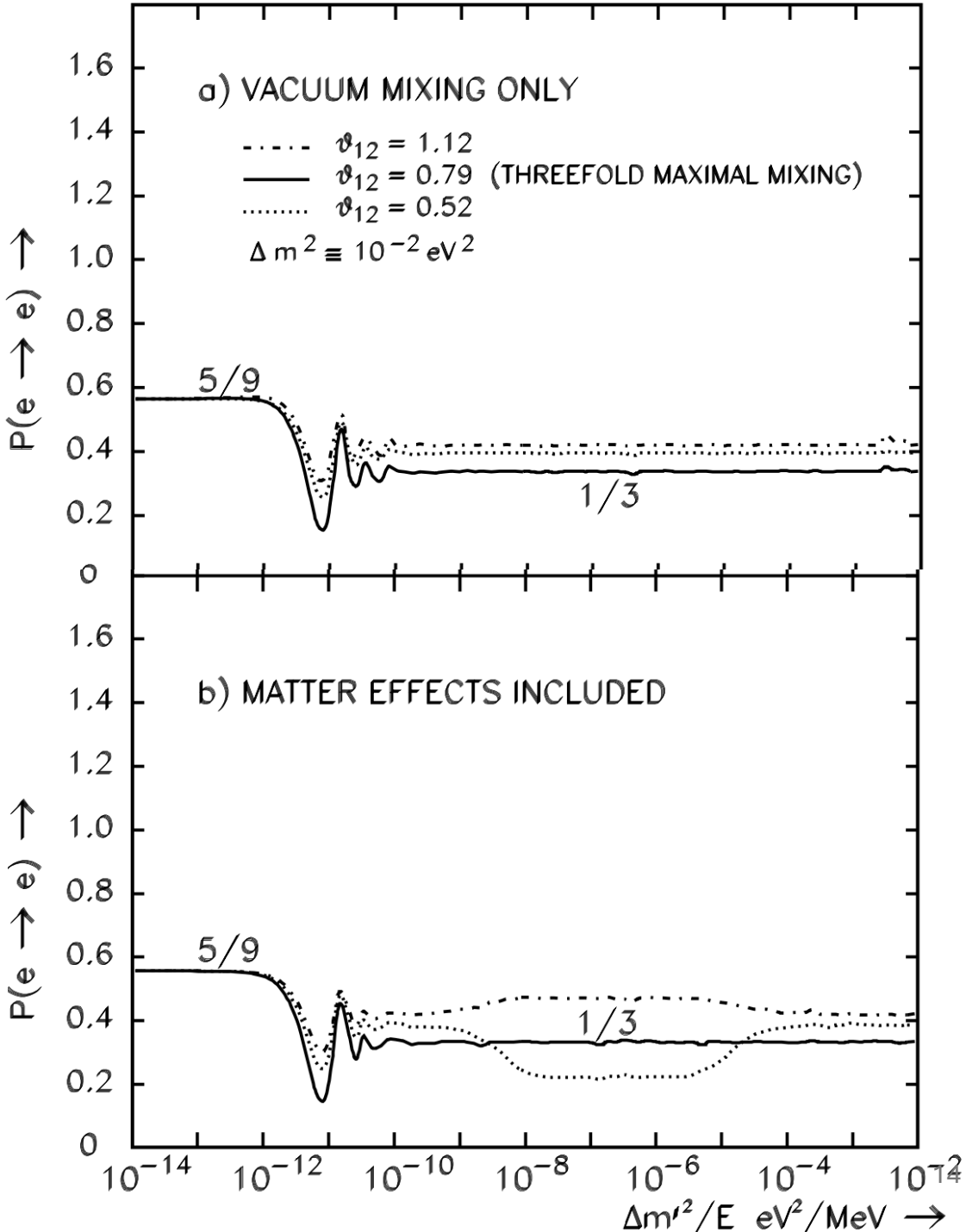
Working with Don

"You stand an excellent chance of being sued!"

No MSW Effect in Maximal Mixing,
PLB 374 (1996) 111

“HPS2” (42 citations)

Full numerical integration of the ν propagation equations in sun, plus energy resolution.



No MSW Effect in Maximal Mixing,
PLB 374 (1996) 111

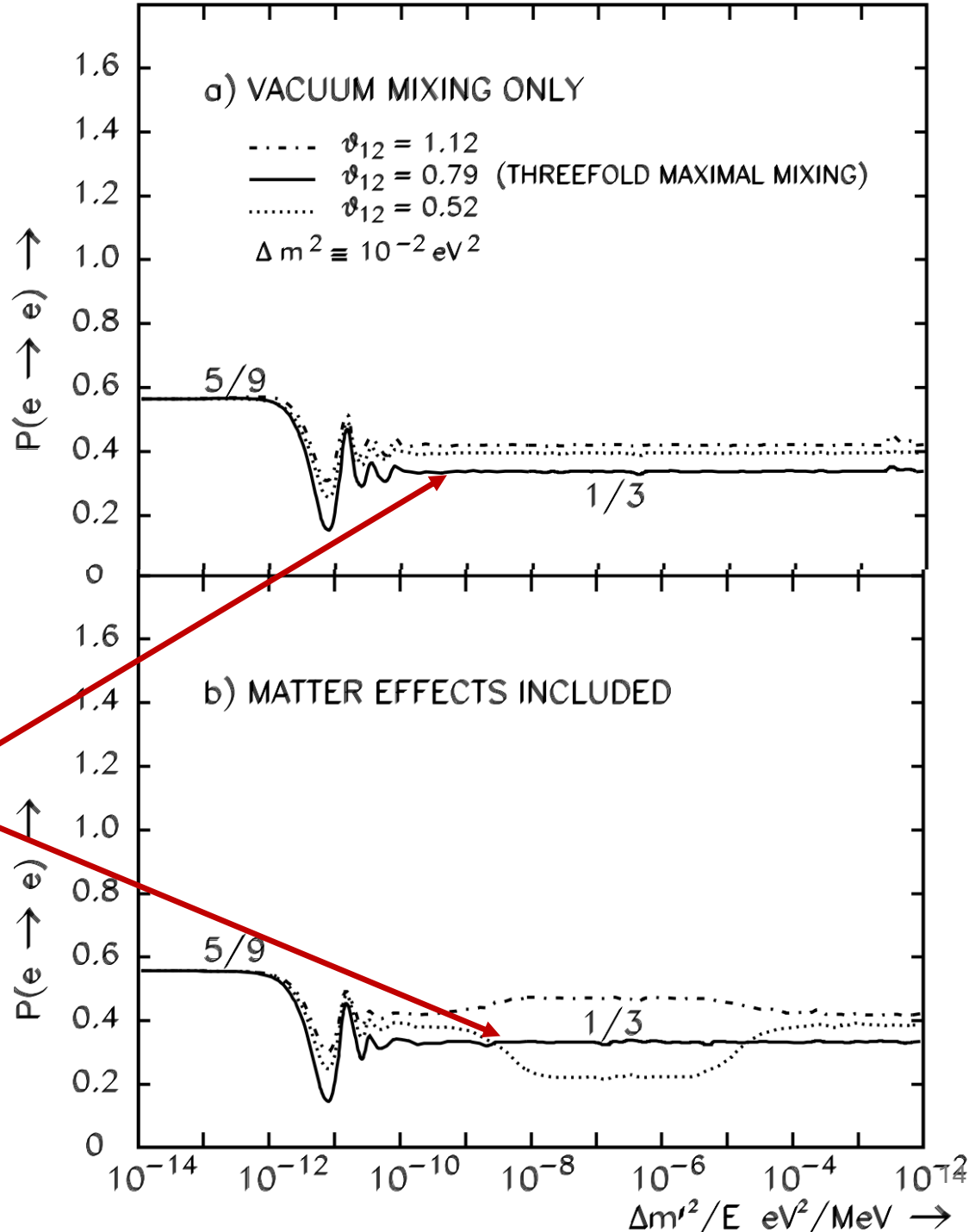
"HPS2" (42 citations)

Full numerical integration of the ν propagation equations in sun, plus energy resolution.

Conclusion:

Naive vacuum predictions are left completely undisturbed [only] in maximal mixing.

Also explained MSW effect via analogy of adiabatic reversal of the spin of a dipole.



No MSW Effect in Maximal Mixing,
PLB 374 (1996) 111

John Bahcall: Email 19/2/96

"I was very surprised by the result, initially wondering if your computer program could possibly have been in error. But, the analogy with the spin ½ dipole in the magnetic field is very convincing. Quite a remarkable result ''

UK.AC.QMW, D.Perkins1@UK.AC.OX
W Effect in Maximal Mixing
on: 1.0
-Type: text/plain; charset-us-ascii
: Mon, 19 Feb 1996 15:42:36 EST
From: "John N. Bahcall" <jnb@EDU.IAS>
Sender: jnb@edu.ias.sns

Dear Professor Harrison:

Many thanks for sending me the preprint of your paper with Perkins and Scott on NO MSW effect in maximal mixing.

I was very surprised by the result, initially wondering if your computer program could possibly have been in error. But, the analogy with the spin 1/2 dipole in a magnetic field is very convincing. Quite a remarkable result.

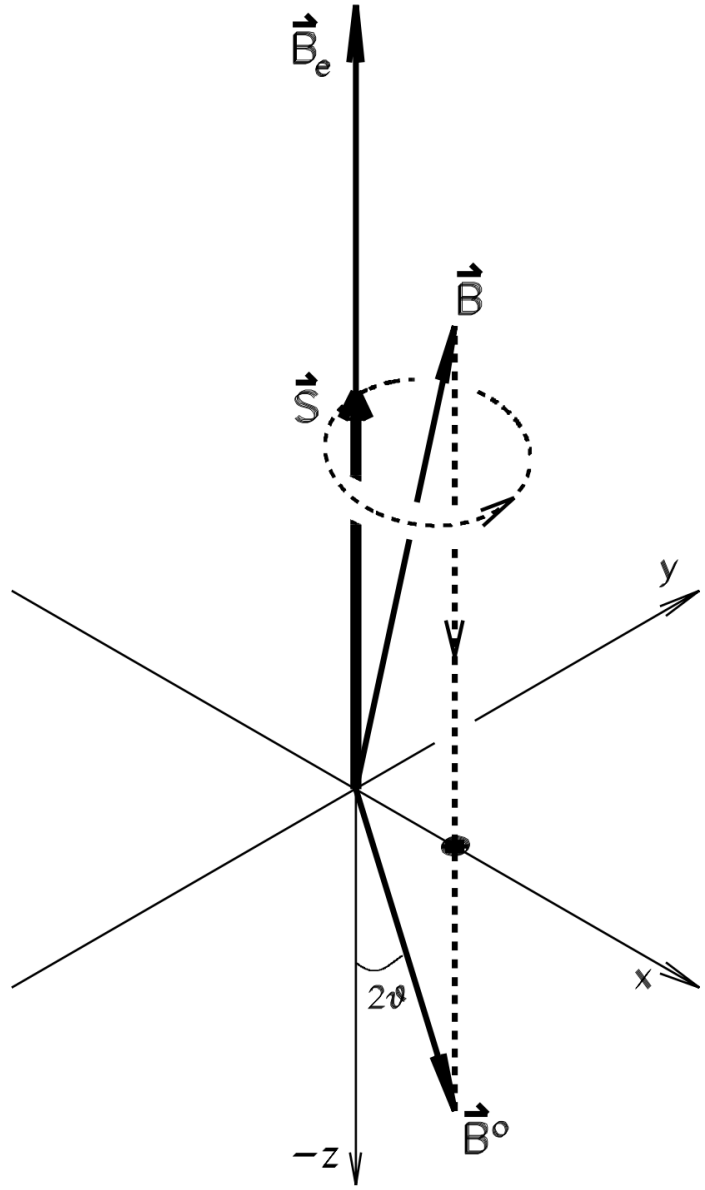
Could you send me a reprint of your paper when it comes out in PLB? I hope that you will continue to send me your work on this problem.

Incidentally, you may be interested in some recent preprints available at my home page: http://www.sns.ias.edu/~jnb . Just look under Recent Preprints and Reprints.

The most unexpected result in that set of preprints is described in: How Does the Sun Shine?

Sincerely yours,

John Bahcall

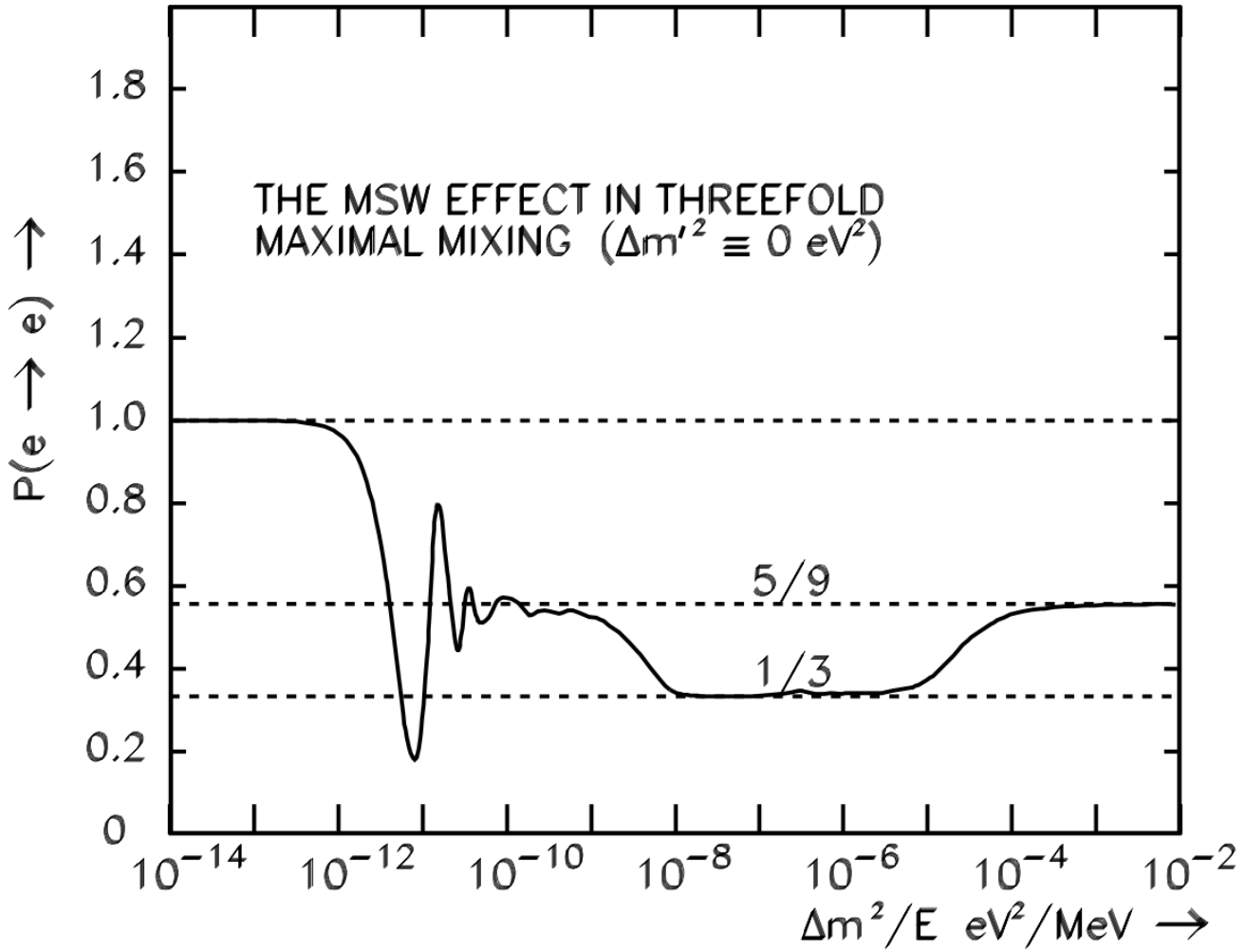


HPS2 (cont.)

Also included

A prediction:

The HPS “5/9-1/3-5/9” Bathtub



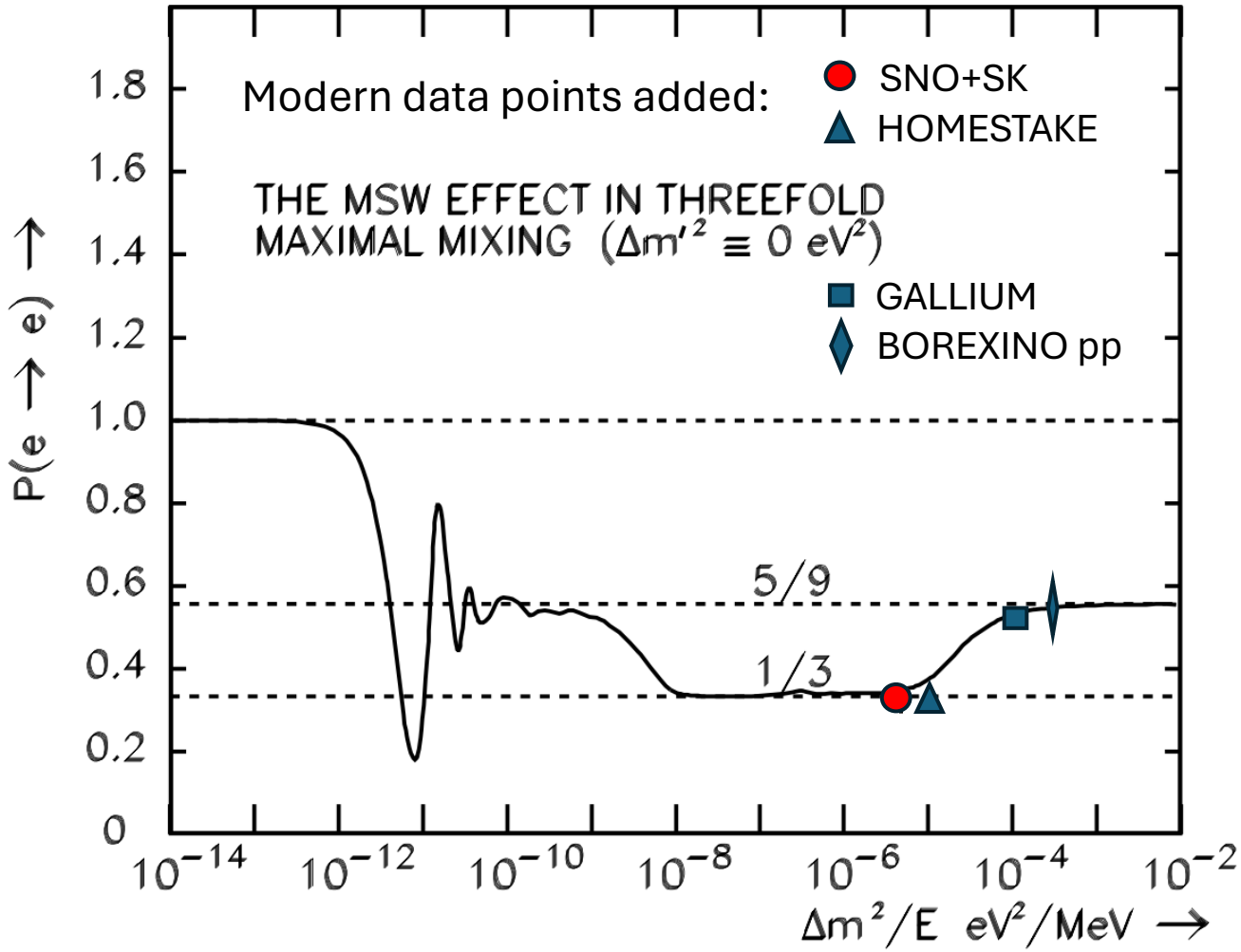
HPS2 (cont.)

Also included

A prediction:

The HPS "5/9-1/3-5/9" Bathtub

In fact, it is the case as understood today for Large Mixing Angle MSW effect in TriBimaximal mixing (see later).



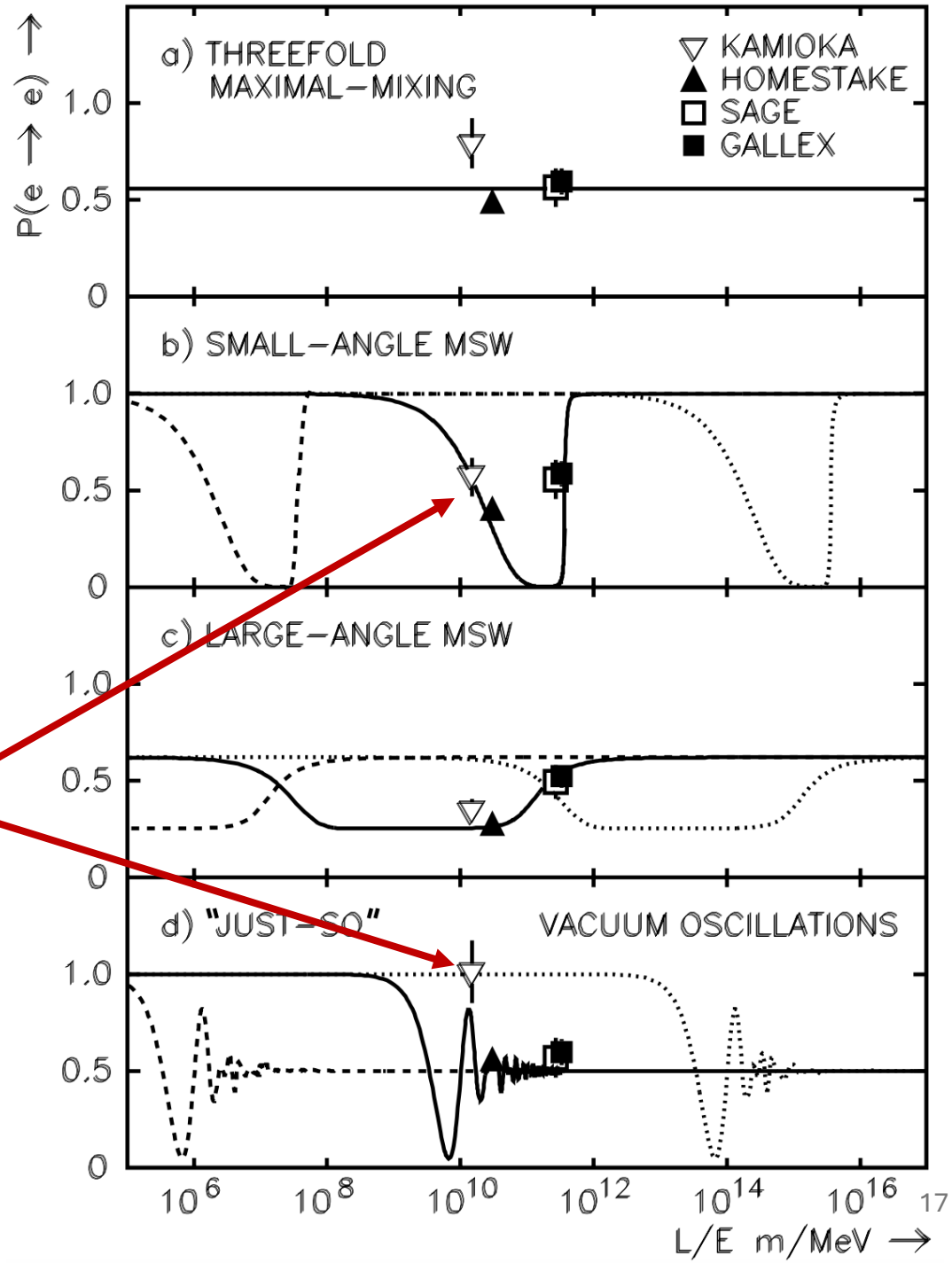
Further evidence for threefold maximal mixing and a hierarchical spectrum of neutrino mass-squared differences PLB 396 (1997) 186.

"HPS3" (72 citations)

A redetermination of the neutrino mass-squared difference in trimaximal mixing with terrestrial matter effects PLB 458 (1999) 79.

"HPS4" (225 citations)

Preferred trimaximal: other options "fine-tuned"



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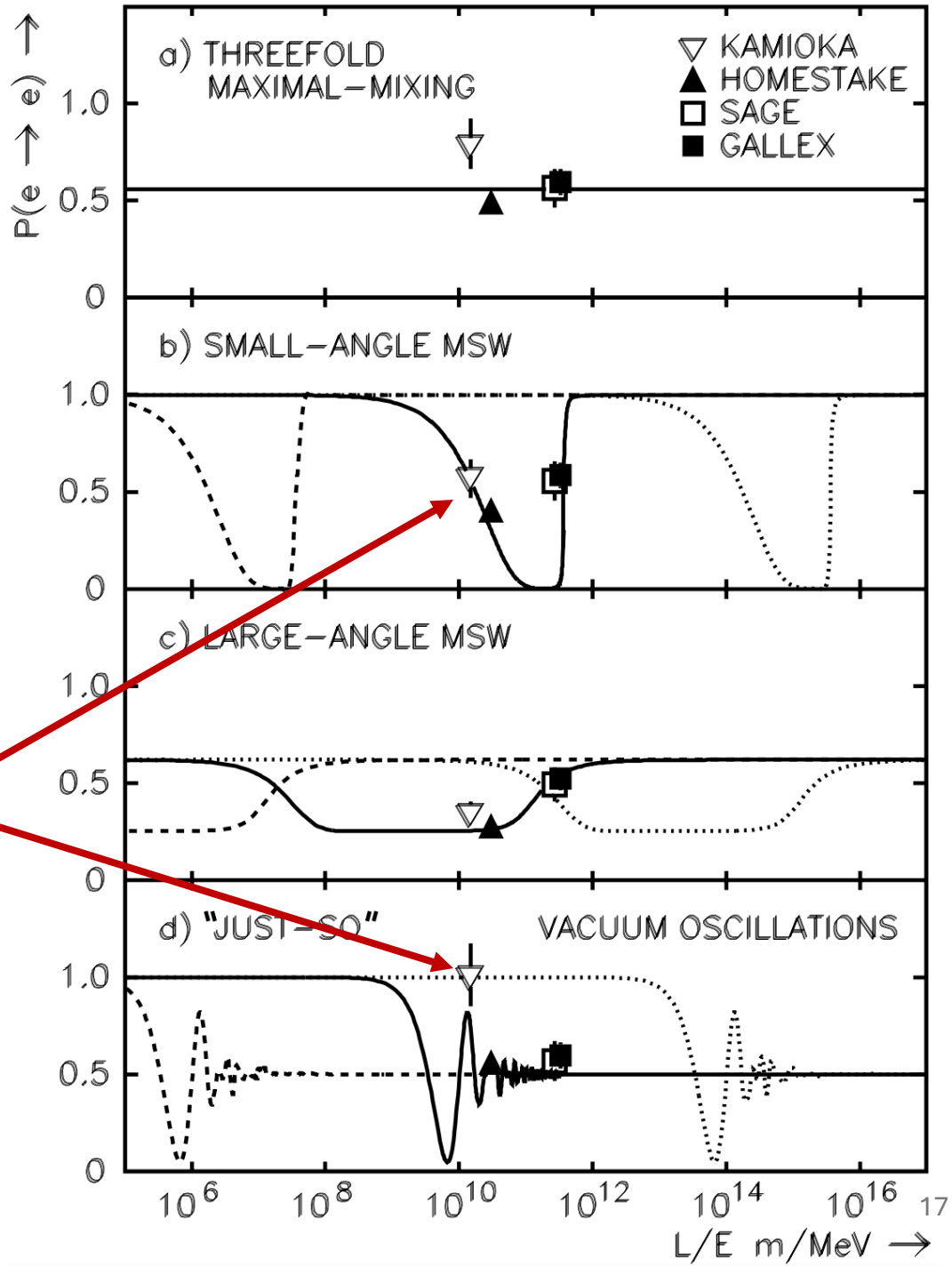
Preferred trimaximal: other options "fine-tuned"

Prediction:

"Spectacular effects expected in long-baseline reactor and accelerator experiments" **viz. CHOOZ, PALO VERDE, MINOS etc.**

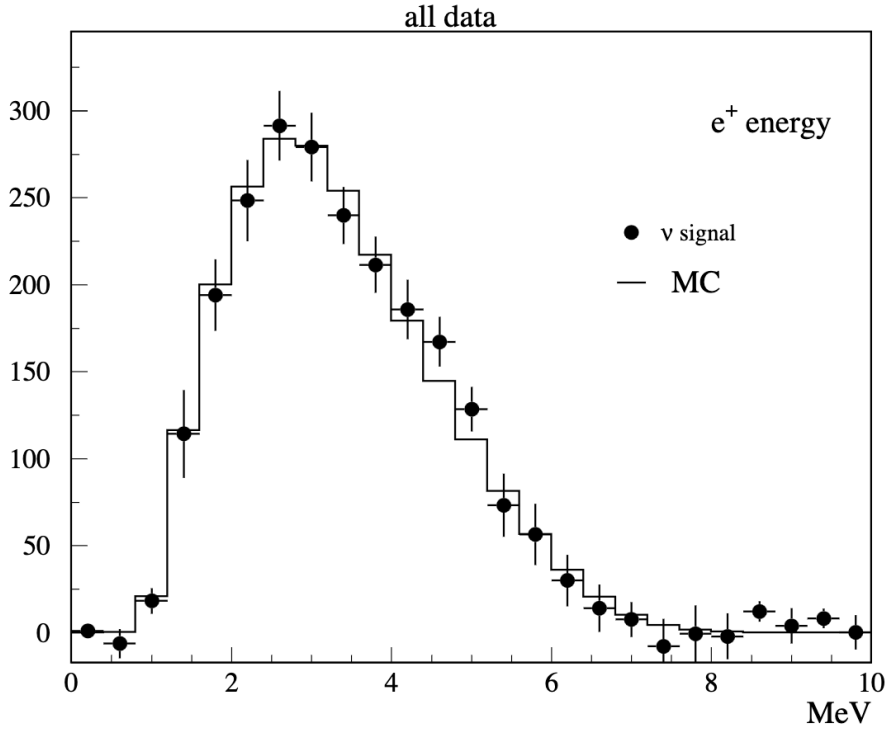


BUT…

The CHOOZ Reactor result 1999

R= 1.01 ± 0.03 (stat) ± 0.03 (sys)
(L ~ 1 km, E ~ 3 MeV)
No Spectacular Effect!

Conclude: $|Ue3|^2$ small if $\Delta m^2 > 10^{-3}$ eV^2



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Conclude: $|Ue3|^2$ small if $\Delta m^2 > 10^{-3}$ eV^2

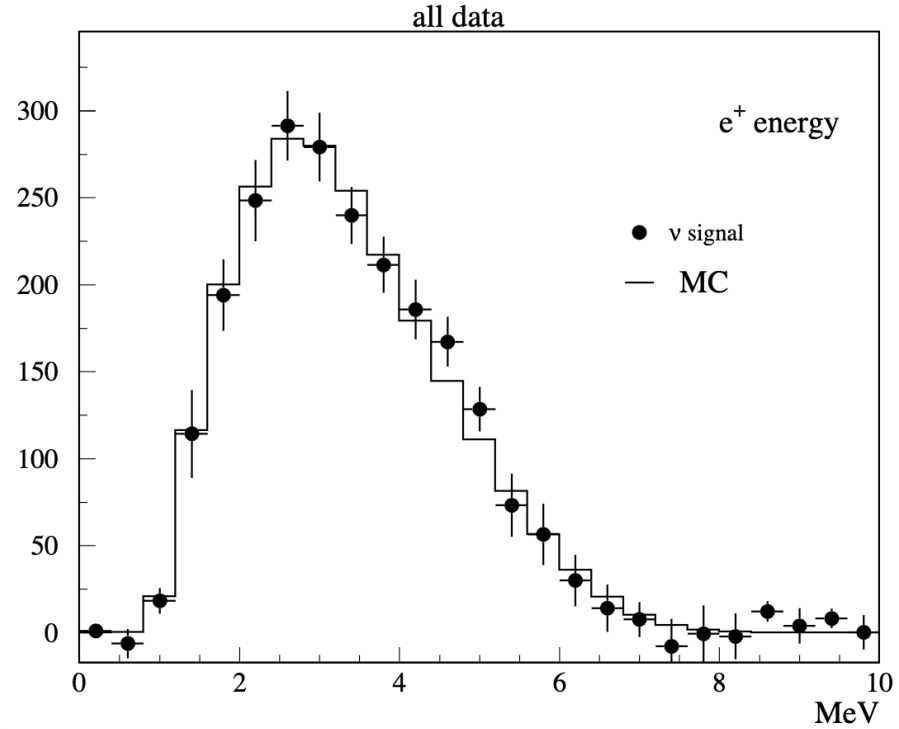
And...

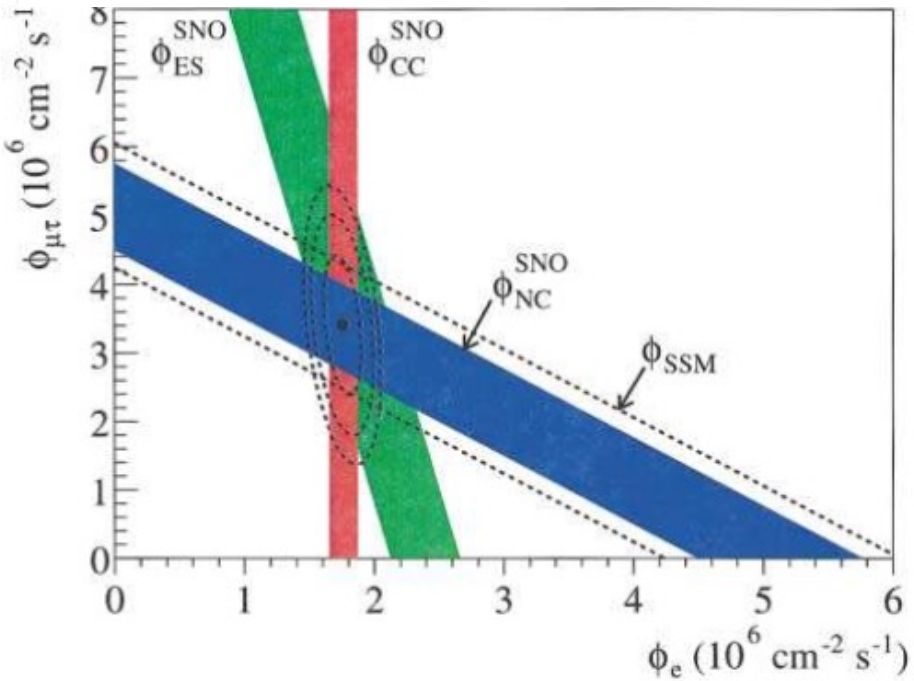
The SNO NC result 2002:

$\phi_{CC} / \phi_{NC} = 0.35 \pm 0.04 \sim 1/3$!

So...

Trimaximal Mixing is Excluded!





Long live Tri(Bi)Maximal Mixing!

Tri-bimaximal mixing and the neutrino oscillation data PLB 530 (2002) 167

“HPS5”
(1651 citations)

Long live Tri(Bi)Maximal Mixing!

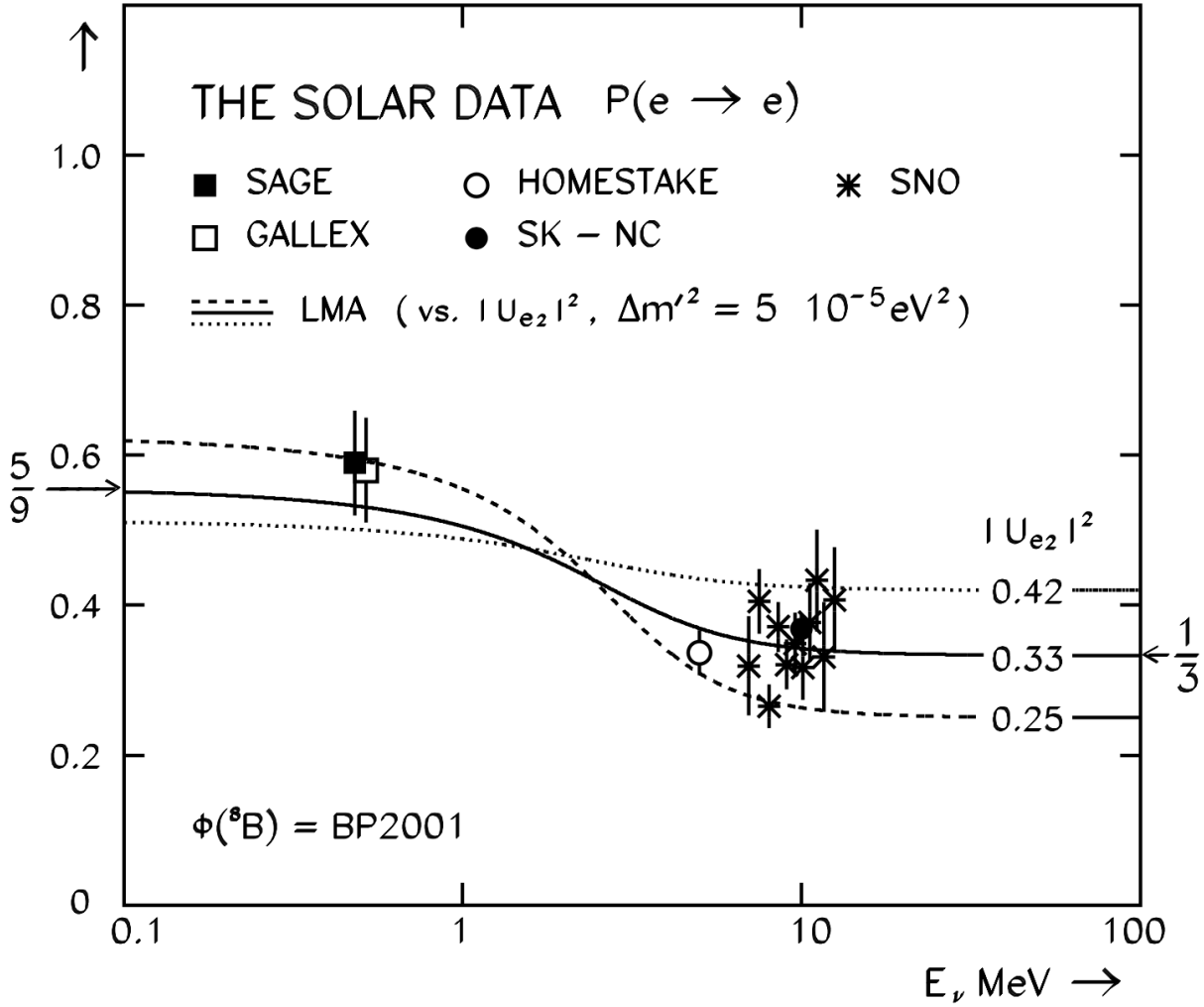
Tri-bimaximal mixing and the neutrino oscillation data PLB 530 (2002) 167

"HPS5" (1651 citations)

Return of the HPS "5/9-1/3-5/9" Bathtub! (this time at the second threshold)

Conclude:

$|U_{e2}|^2 \sim 1/3$



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Tri-bimaximal mixing and the neutrino oscillation data PLB 530 (2002) 167

"HPS5" (1651 citations)

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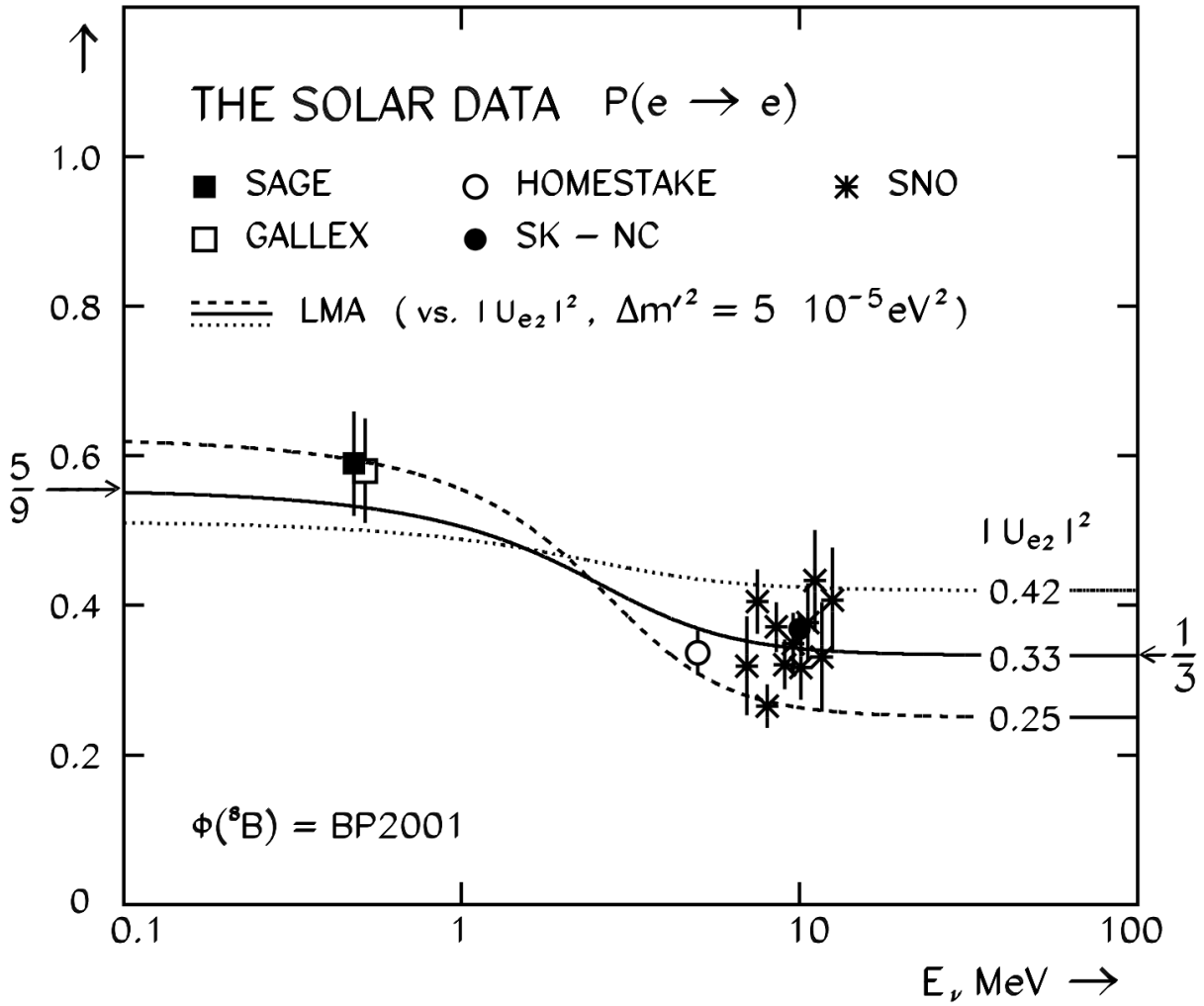
Conclude: $|U_{e2}|^2 \sim 1/3$

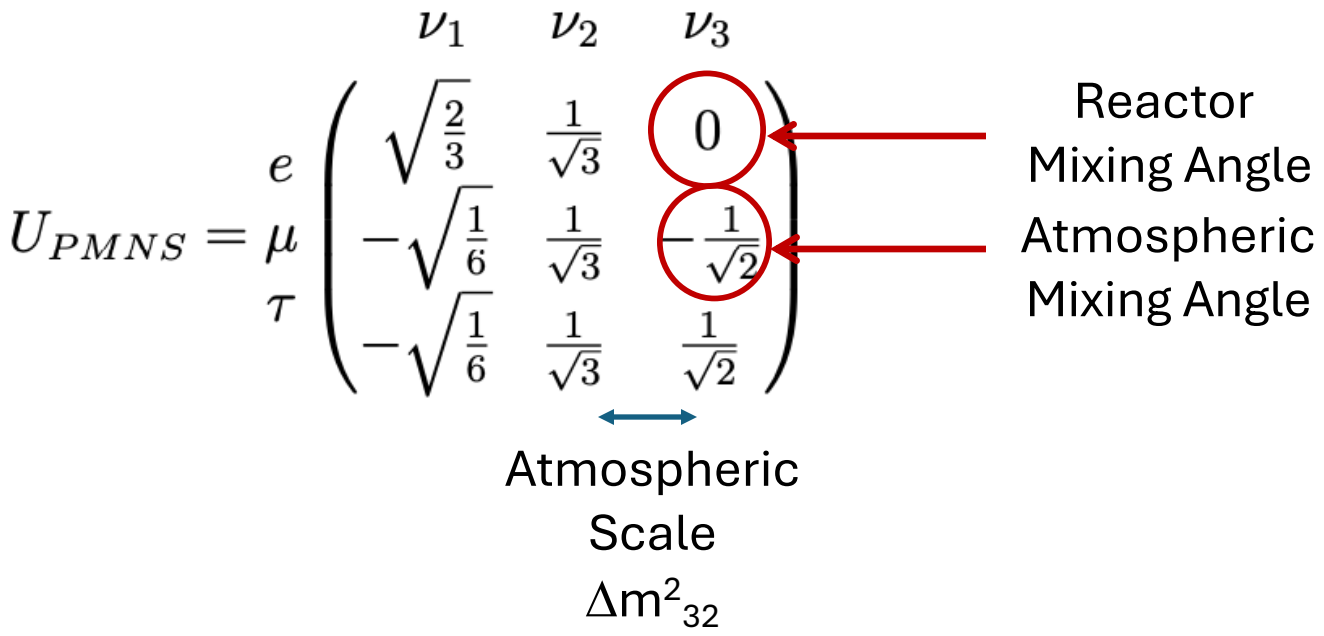
Also… **SUPERK Atmospheric neutrino results pointing strongly to twofold maximal $\nu_\mu - \nu_\tau$ mixing"**

Conclude: $|U_{\mu 3}|^2 \sim |U_{\tau 3}|^2 \sim 1/2$



HPS5 (cond.)

The trend of the data now pointing strongly towards another specific form for the lepton mixing matrix:



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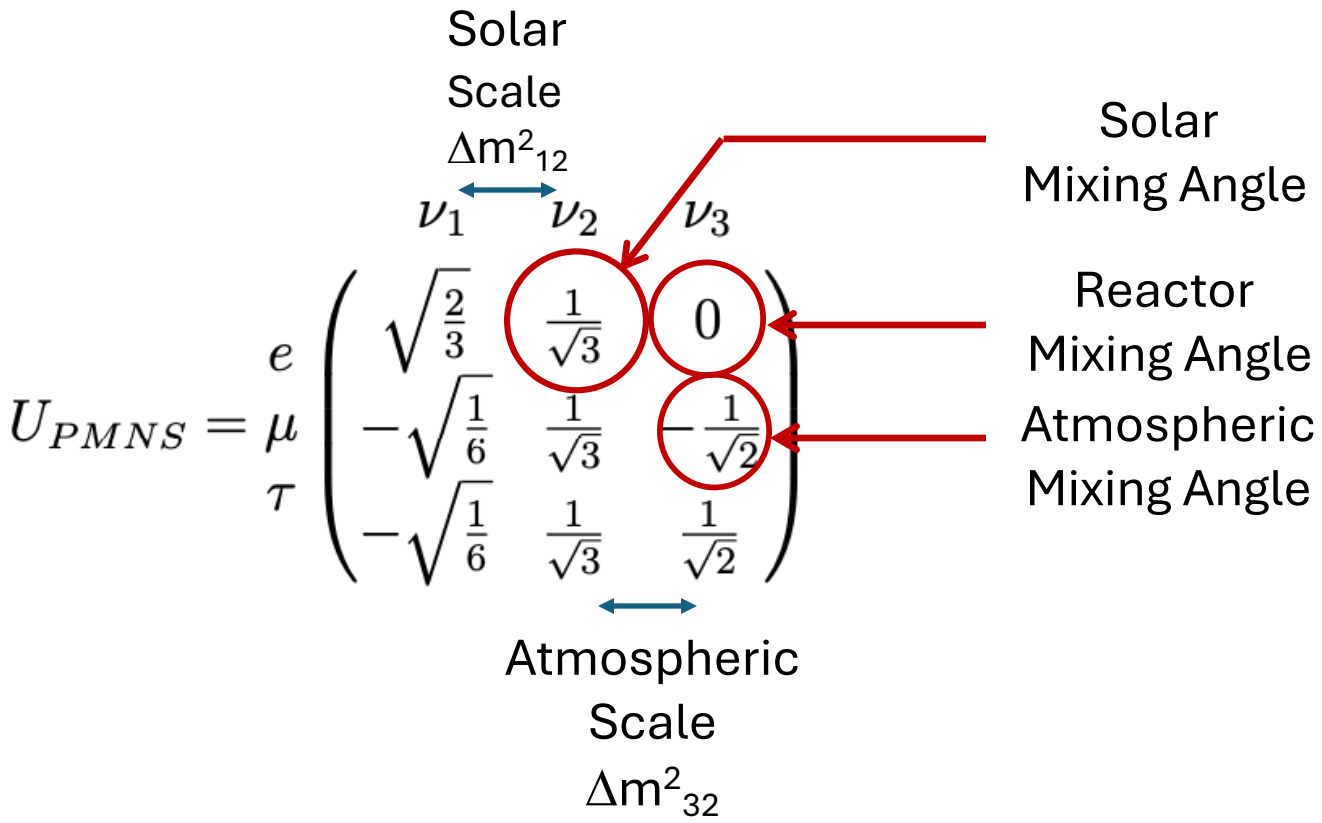
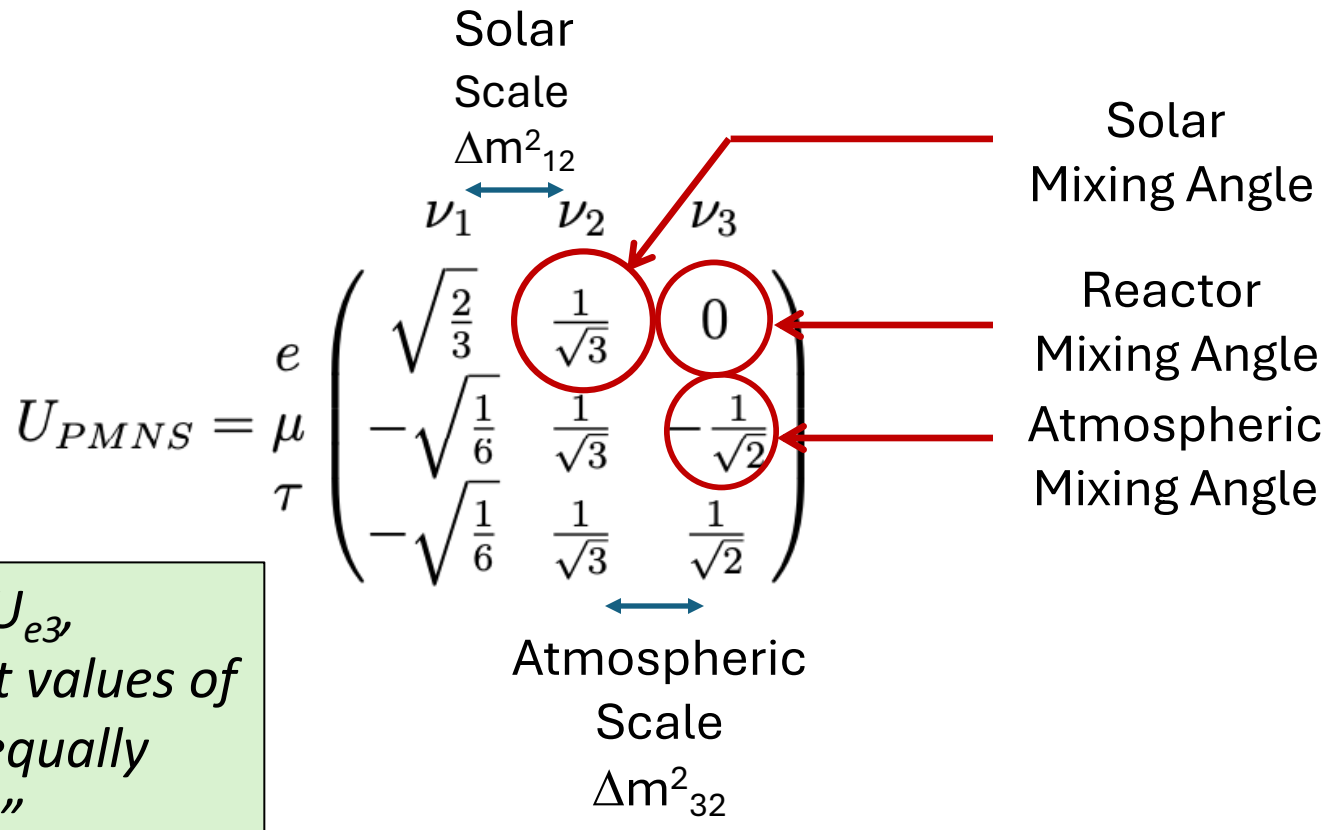


HPS5 (cond.)

The trend of the data now pointing strongly towards another specific form for the lepton mixing matrix:



"Small non-zero values of U_{e3}, and/or somewhat different values of $|U_{\mu 3}|^2$... are more-or-less equally acceptable experimentally."

Symmetries of TBM

As is well-known, mixing matrix arises as a result of different forms for the two mass matrices

Here

$$M_l^2 = \begin{pmatrix} a & b & b^* \\ b^* & a & b \\ b & b^* & a \end{pmatrix} \quad \textbf{and} \quad M_\nu^2 = \begin{pmatrix} x & 0 & y \\ 0 & z & 0 \\ y & 0 & x \end{pmatrix}$$

$$\textbf{=>} \quad U_{PMNS} = \begin{matrix} \\ e \\ \mu \\ \tau \end{matrix} \begin{pmatrix} \frac{1}{\sqrt{3}} & \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} \\ \frac{\omega}{\sqrt{3}} & \sqrt{\frac{1}{3}} & \frac{\bar{\omega}}{\sqrt{3}} \\ \frac{\bar{\omega}}{\sqrt{3}} & \sqrt{\frac{1}{3}} & \frac{\omega}{\sqrt{3}} \end{pmatrix} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \\ \\ \\ \\ \end{matrix} \begin{pmatrix} \sqrt{\frac{1}{2}} & 0 & -\sqrt{\frac{1}{2}} \\ 0 & 1 & 0 \\ \sqrt{\frac{1}{2}} & 0 & \sqrt{\frac{1}{2}} \end{pmatrix} \sim \begin{matrix} \\ e \\ \mu \\ \tau \end{matrix} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \\ \\ \\ \\ \end{matrix} \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\frac{1}{\sqrt{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

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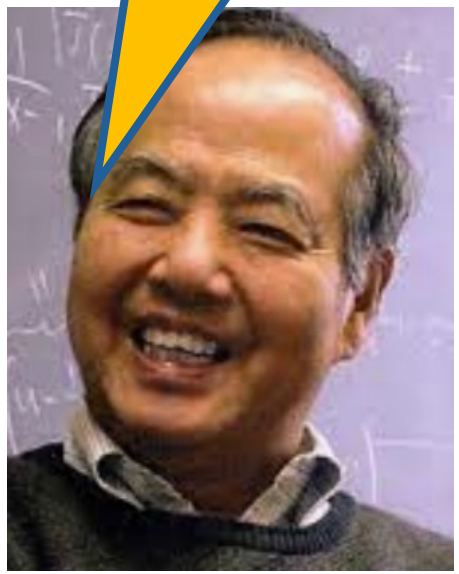
“It’s a tremendous achievement”



T.D. Lee
CERN Colloquium
30th Aug 2007
(re. TBM In HPS5)

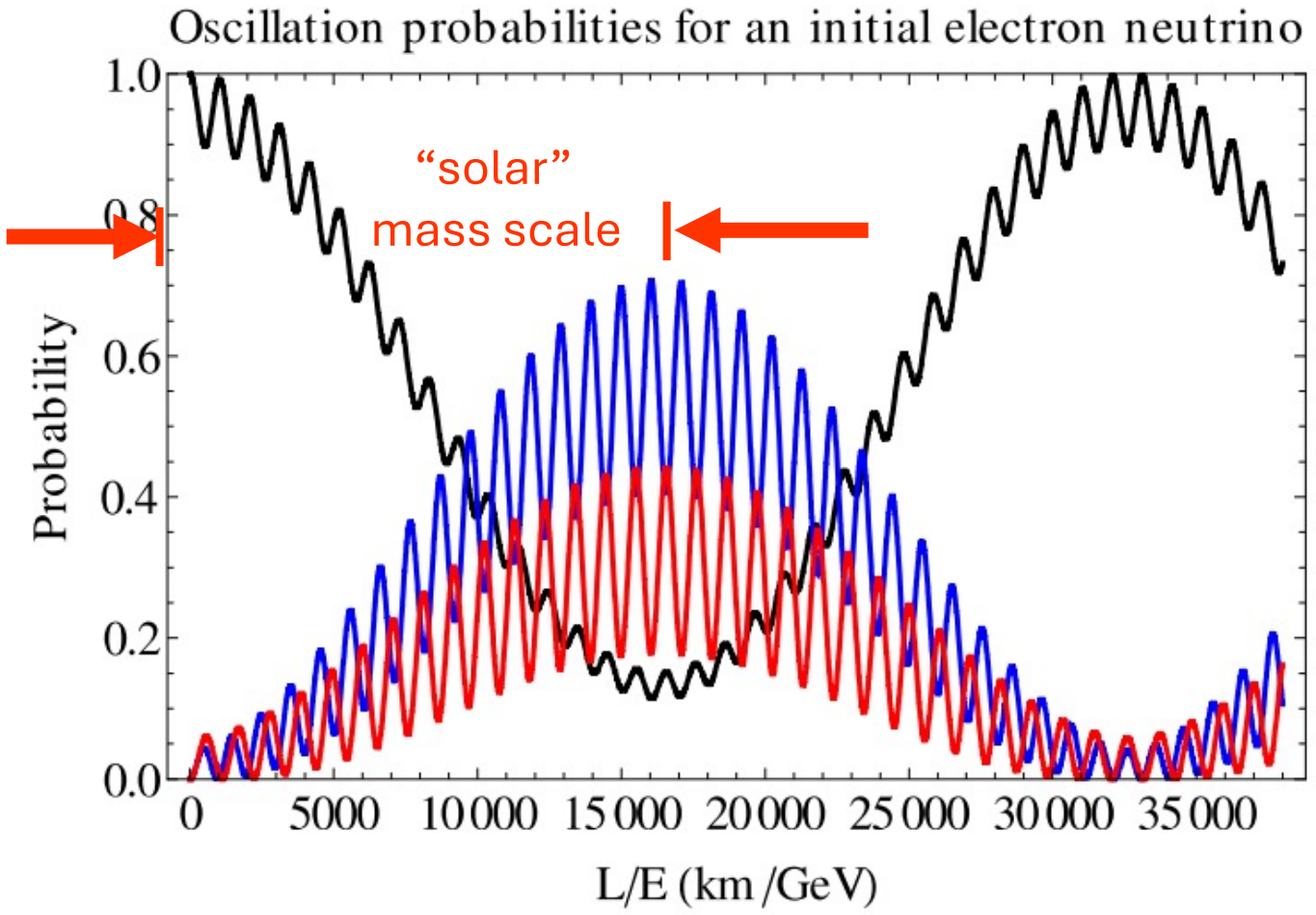
The Future

JUNO 2024 - .....

L_{JUNO} ~ 50 km
c.f. L_{CHOOZ} ~ 1.5 km

Plan to measure U_{e2}, Δm^2_{21} and Δm^2_{32}, with resolutions ⇠ ±1% by 2030.

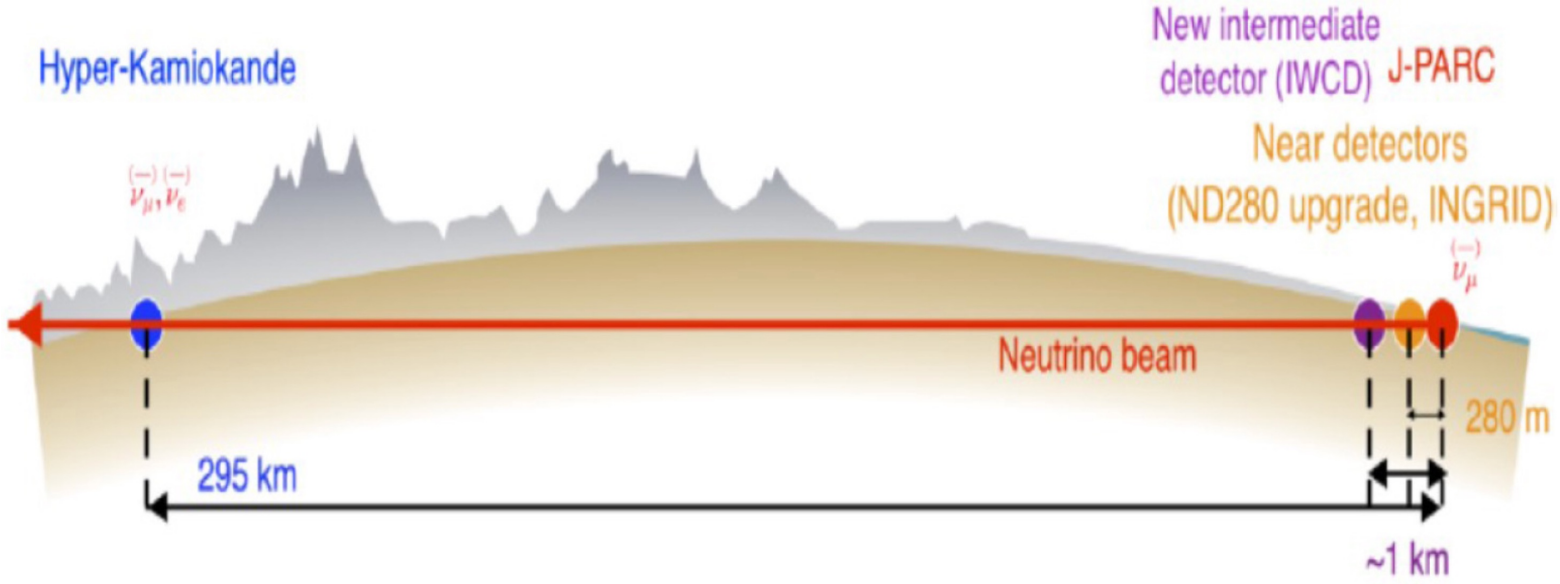
Could resolve the question of the neutrino mass ordering at 3σ.



Leptonic CP Violation?

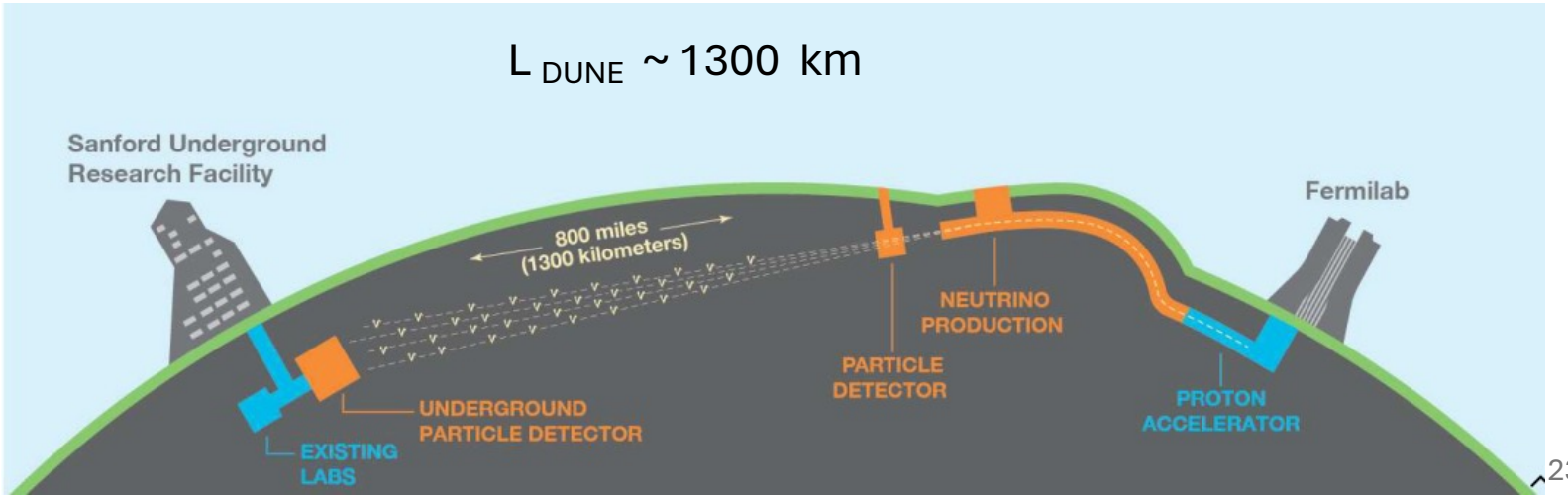
HyperK (~2027)

Plan to confirm at the 5σ level if CP is violated in oscillations for 57% of possible δ_{CP} values with ~10 years' running.



DUNE (~2030)

Similarly expect 5 σ sensitivity to non-zero CPV over ~57% of possible range after ~10 yrs



Legacy

Don decided to leave HPS on a high, making HPS5 his last paper with us.

TBM was finally excluded 10 years later since (as anticipated) $U_{e3} = 0$ was incompatible with new results from the Daya Bay and RENO reactor experiments (2012) and later the T2K accelerator experiment (2013).

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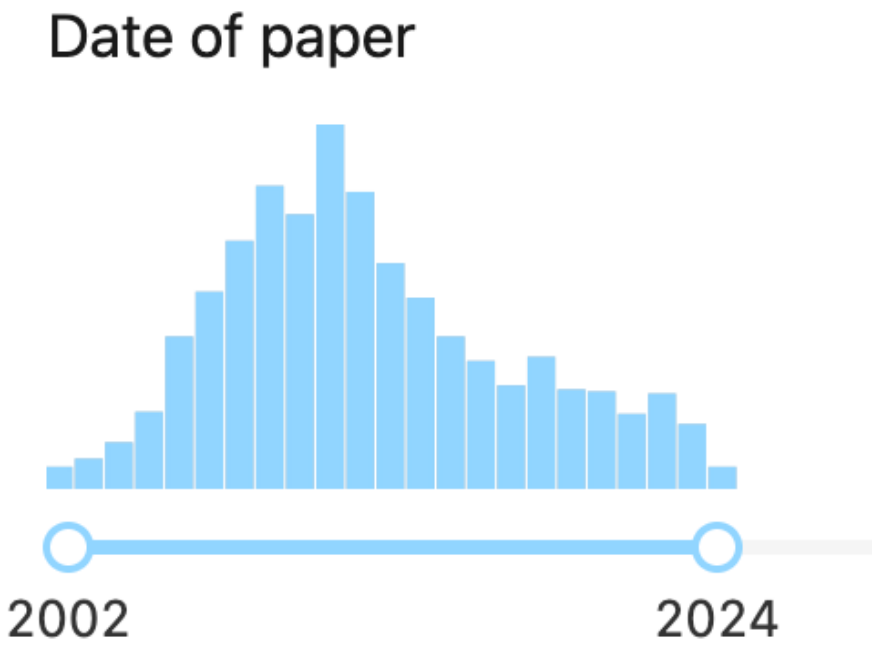
Over 1500 phenomenology papers have cited HPS5.

Our proposed symmetric forms of the mass matrices are suggestive of deeper symmetries, and are exploited in building BSM models of lepton masses and mixing.

Cites per year from INSPIRE



Legacy (Cont.)

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H&S published 25 further papers together on topics descended from the work with Don, several highly-cited.

Currently, $|U_{e3}|^2 \sim 0.02$. Thus TBM remains a useful zeroth-order approximation to U_{PMNS}, while allowing the exciting prospect that CP violation may be accessible in the future.