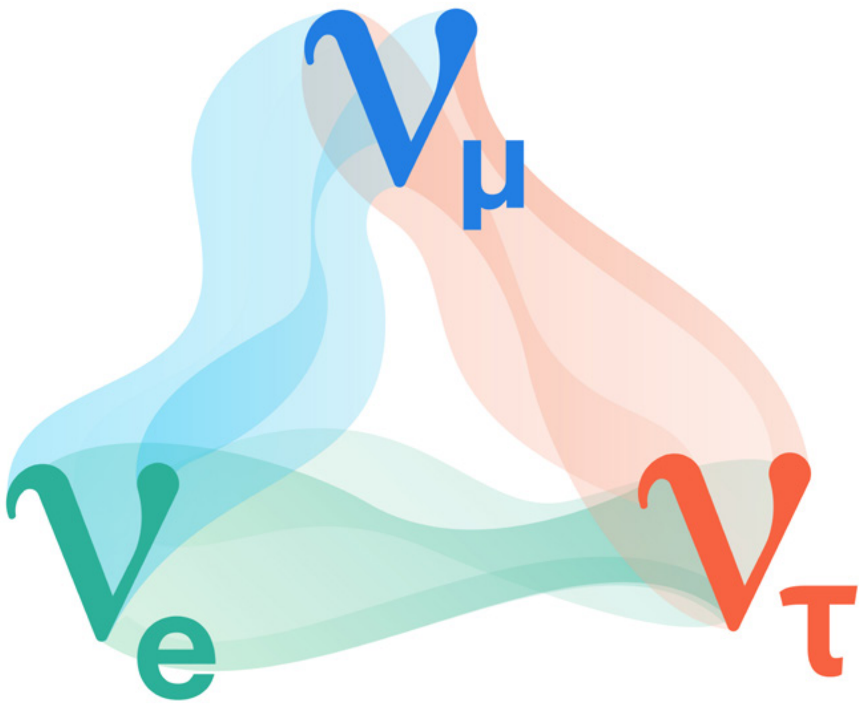
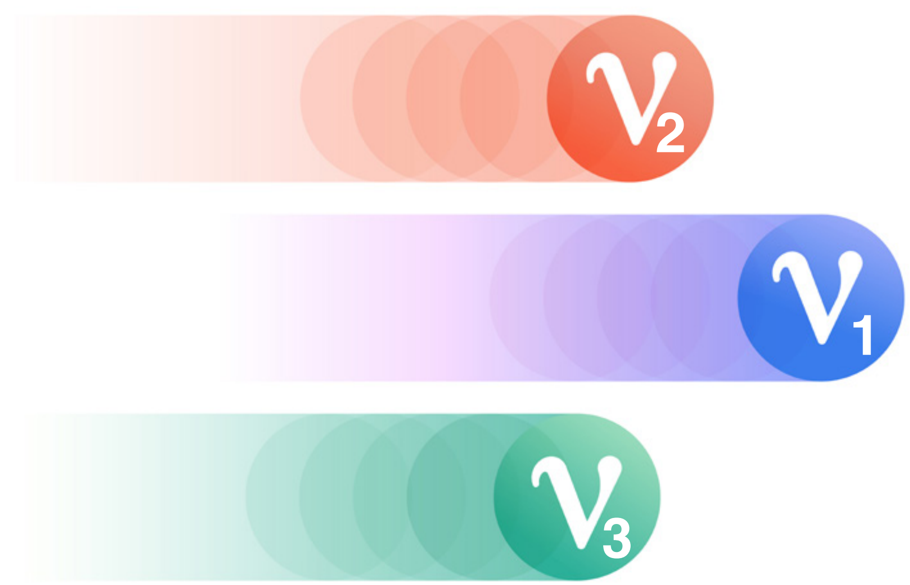
Theoretical Aspects of the Quantum Neutrino

Stephen Parke
Theoretical Physicist
Chicago, USA





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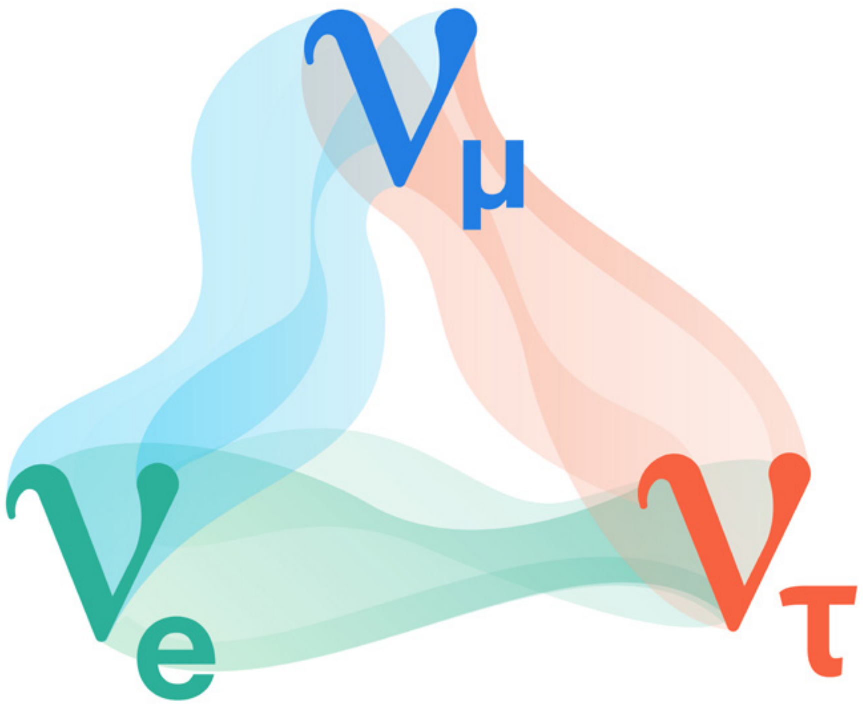

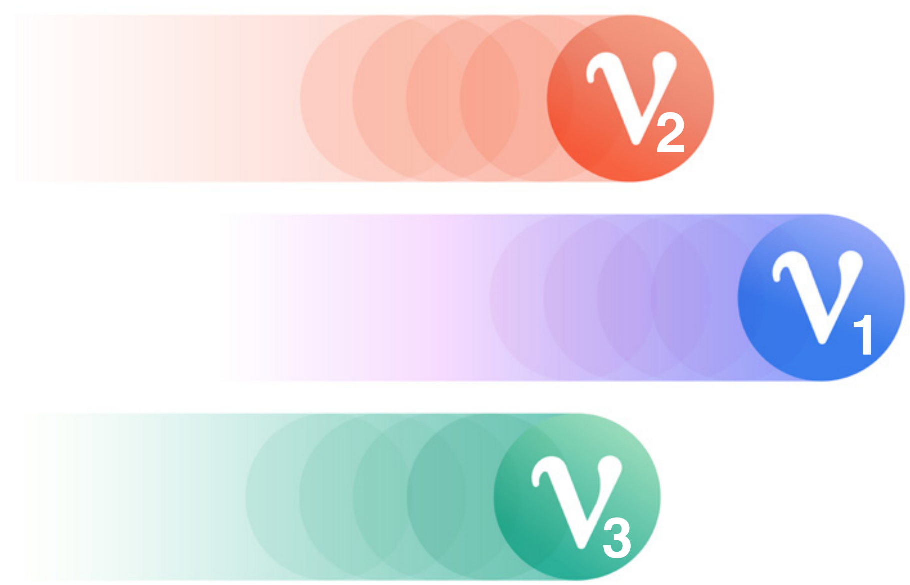

Xu Zhan, Tsinghua

DUALITY AND MULTI-GLUON SCATTERING

Michelangelo MANGANO, Stephen PARKE and Zhan XU[1]

Fermi National Accelerator Laboratory[2], P.O. Box 500, Batavia, IL 60510, USA

Received 13 July 1987

For the *six*-gluon scattering process we give explicit and simple expressions for the amplitude and its square. To achieve this we use an analogy with string theories to identify a unique procedure for writing the multi-gluon scattering amplitudes in terms of a sum of gauge invariant dual sub-amplitudes multiplied by an appropriate color (Chan-Paton) factor. The sub-amplitudes defined in this way are invariant under cyclic permutations, satisfy powerful identities which relate different non-cyclic permutations and factorize in the soft gluon limit, the two-gluon collinear limit and on multi-gluon poles. Also, to leading order in the number of colors these sub-amplitudes sum *incoherently* in the square of the full matrix element. The results contained here are important for Monte Carlo studies of multi-jet processes at hadron colliders as well as for understanding the general structure of QCD.

[1] Permanent address; Dept. of Physics, Tsinghua University, Beijing, The People's Republic of China.

Nuclear Physics B298 (1988) 653–672
North-Holland, Amsterdam

Xu Zhan, Tsinghua

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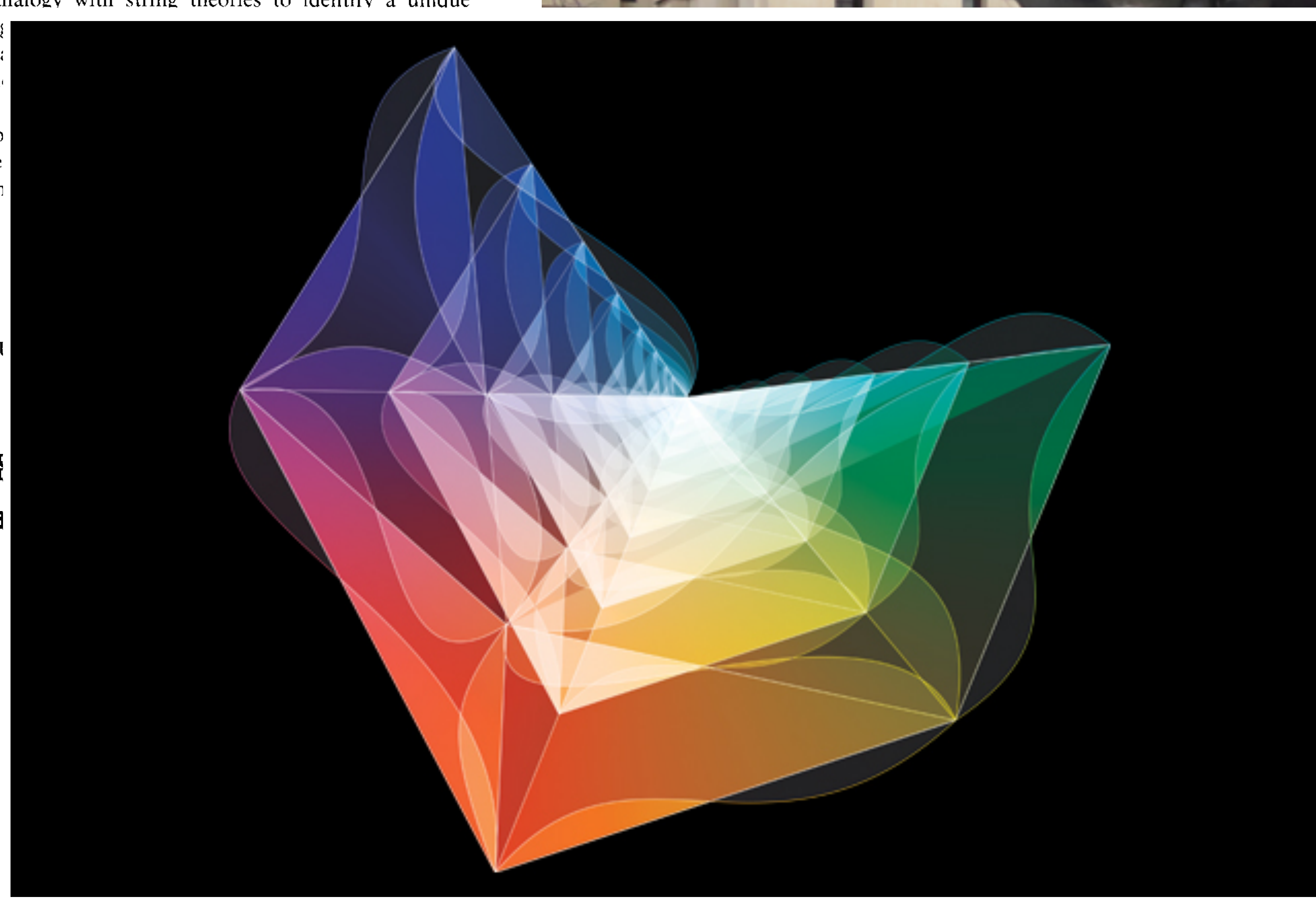

AMPLITUHEDRON

HEP 4 records found Search took 0.31 seconds.

1. **Helicity Amplitudes for Multiple Bremsstrahlung in Massless Nonabelian Gauge Theories**
Zhan Xu, Da-Hua Zhang, Lee Chang (Tsinghua U., Beijing). Jul 1986. 37 pp.
Published in **Nucl.Phys. B291 (1987) 392-428**
TUTP-86/9a
DOI: 10.1016/0550-3213(87)90479-2
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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2. **Helicity Amplitudes For Multiple Bremsstrahlung In Massless Nonabelian Gauge Theory. 2. Decompositi Invariant Subsets**
Zhan Xu, Da-Hua Zhang, Lee Chang (Tsinghua U., Beijing). Mar 1985. 32 pp.
TUTP 84/4
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record

3. **Helicity Amplitudes For Multiple Bremsstrahlung In Massless Nonabelian Gauge Theory. 3. Amplitudes C Processes Involving Gluon Selfcoupling Vertices**
Da-hua Zhang, Zhan Xu, Lee Chang (Tsinghua U., Beijing). Jan 1985. 29 pp.
TUTP-84/5a
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record

4. **Helicity Amplitudes For Multiple Bremsstrahlung In Massless Nonabelian Gauge Theory. 1. New Definitio Formulation Of Amplitudes In Grassmann Algebra**
Zhan Xu, Da-Hua Zhang, Lee Chang (Tsinghua U., Beijing). Dec 1984. 20 pp.
TUTP-84/3-TSINGHUA
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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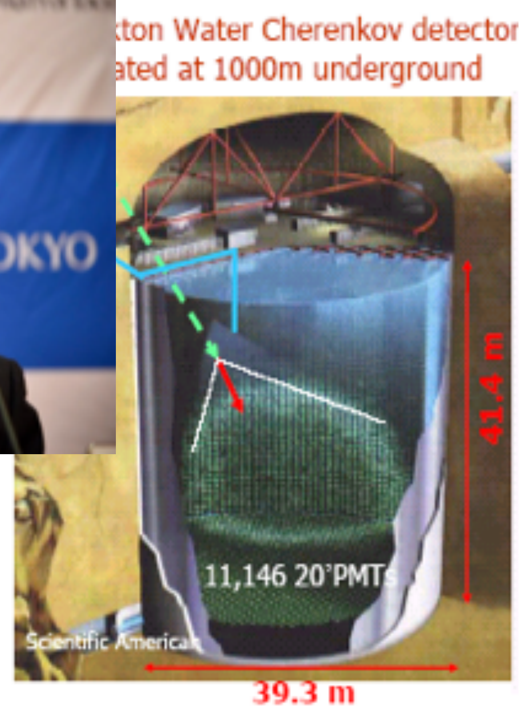
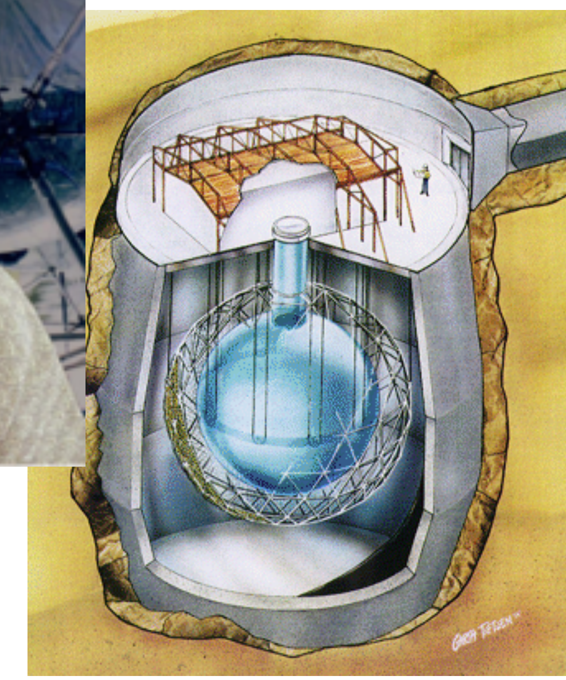
NOBEL 2015

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



Takaaki Kajita
SuperKamiokaNDE



Art McDonald
SNO

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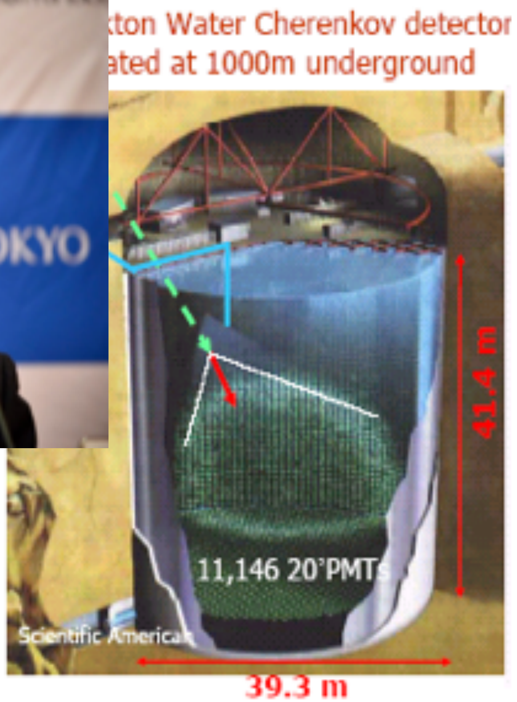

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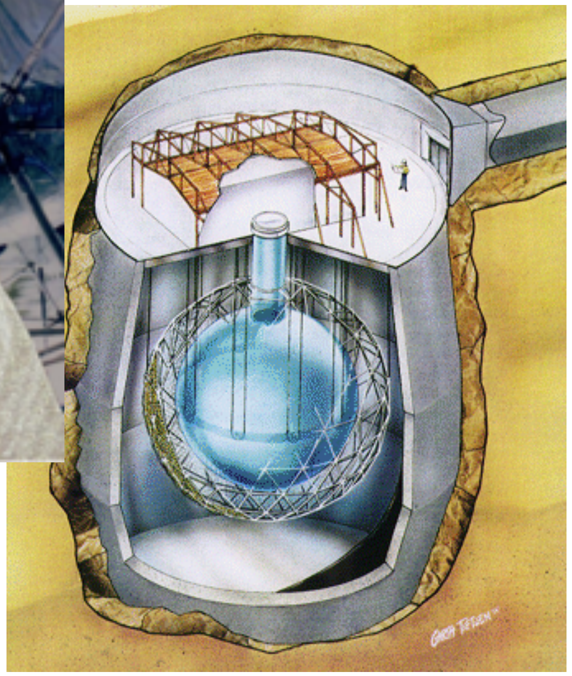

Art McDonald
SNO

~ vacuum oscillations

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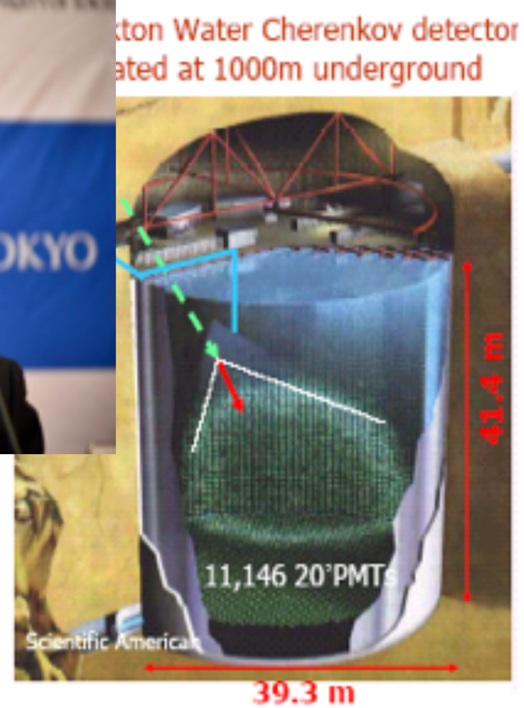

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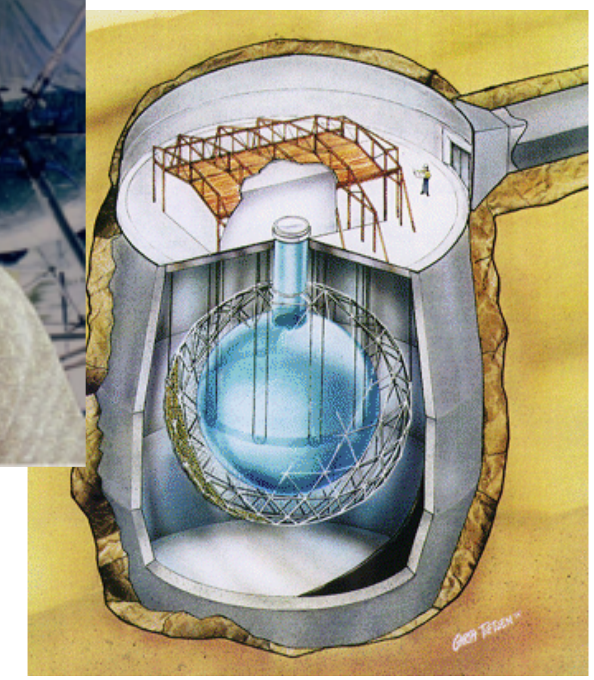

Art McDonald
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~ vacuum oscillations

Wolfenstein matter effects dominant flavor transformations

See Smirnov arXiv:1609.02386

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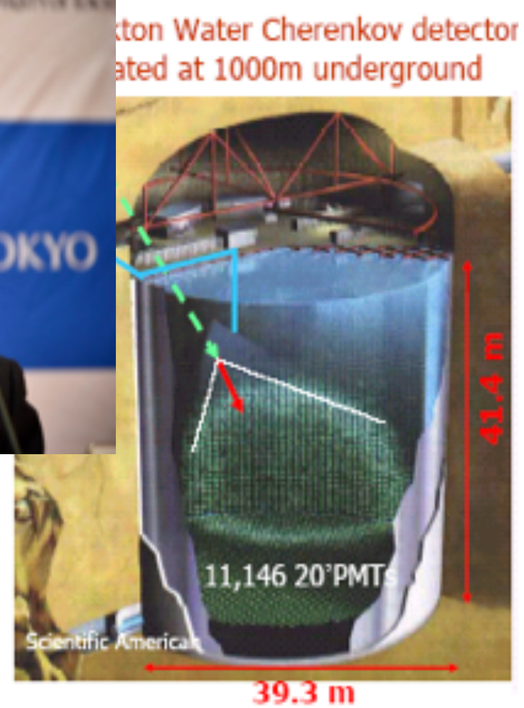

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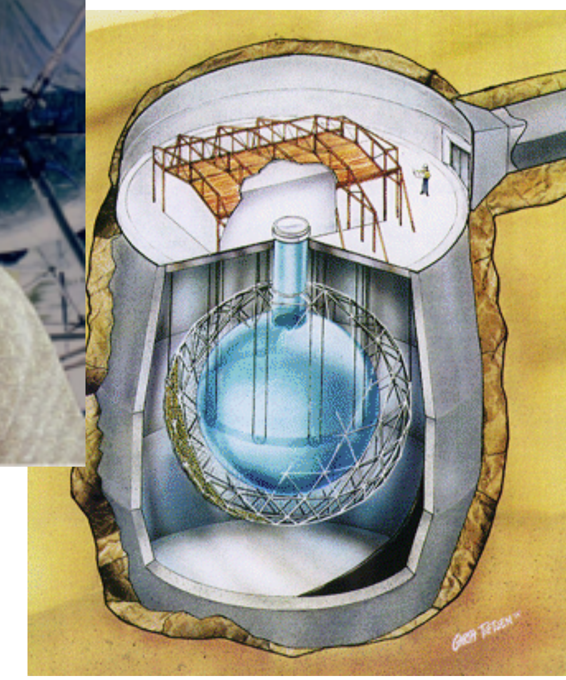

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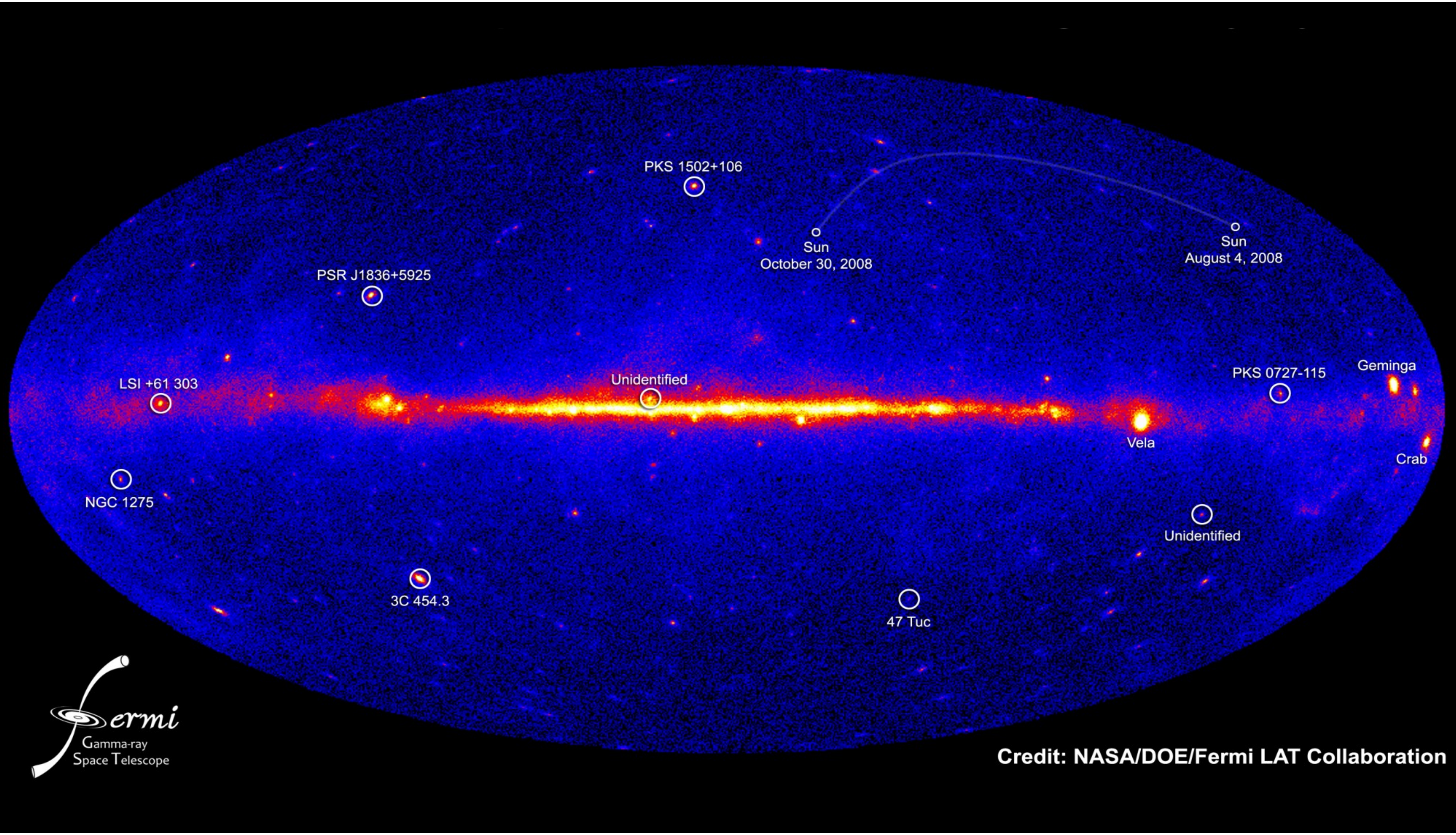
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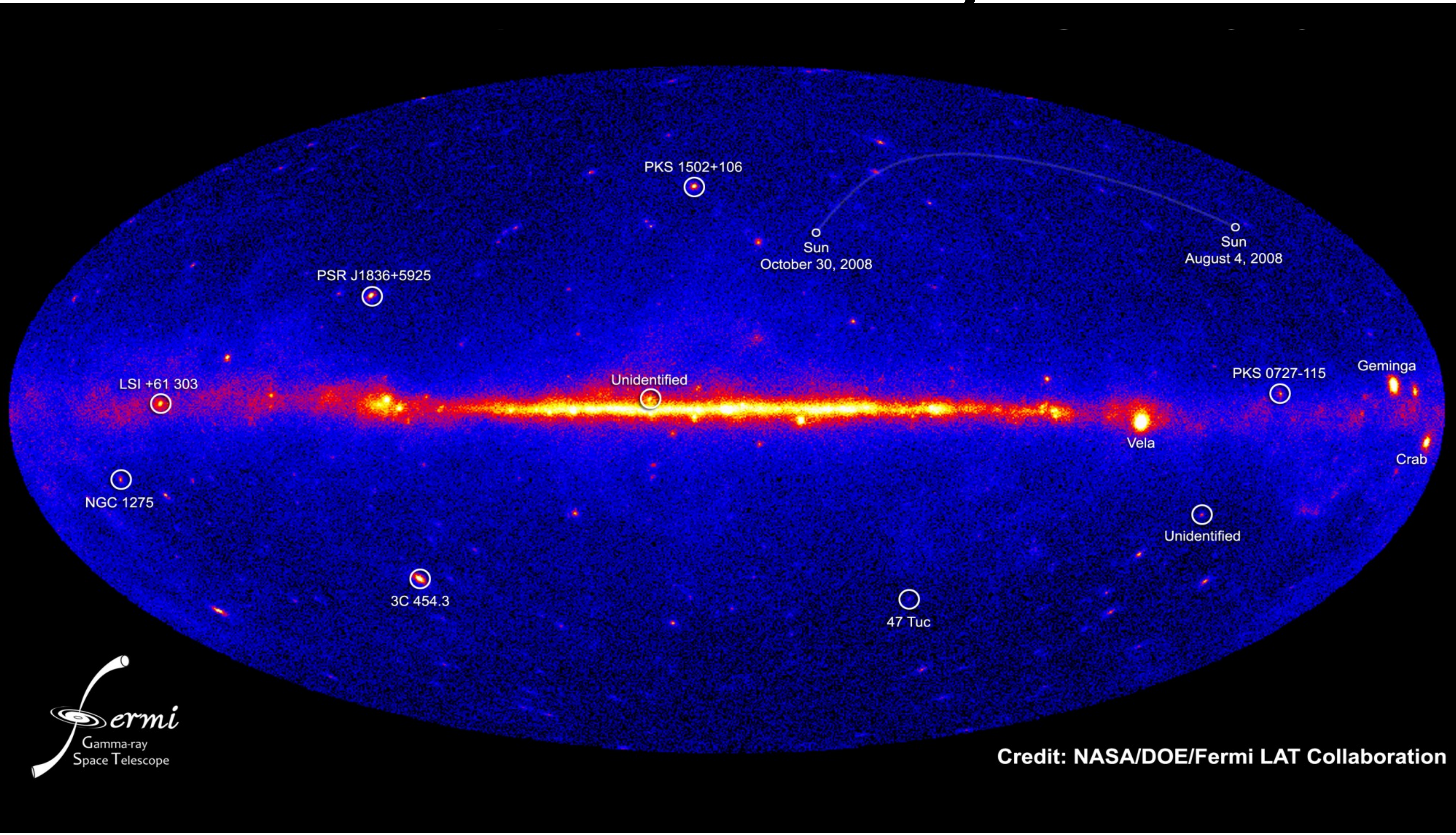
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

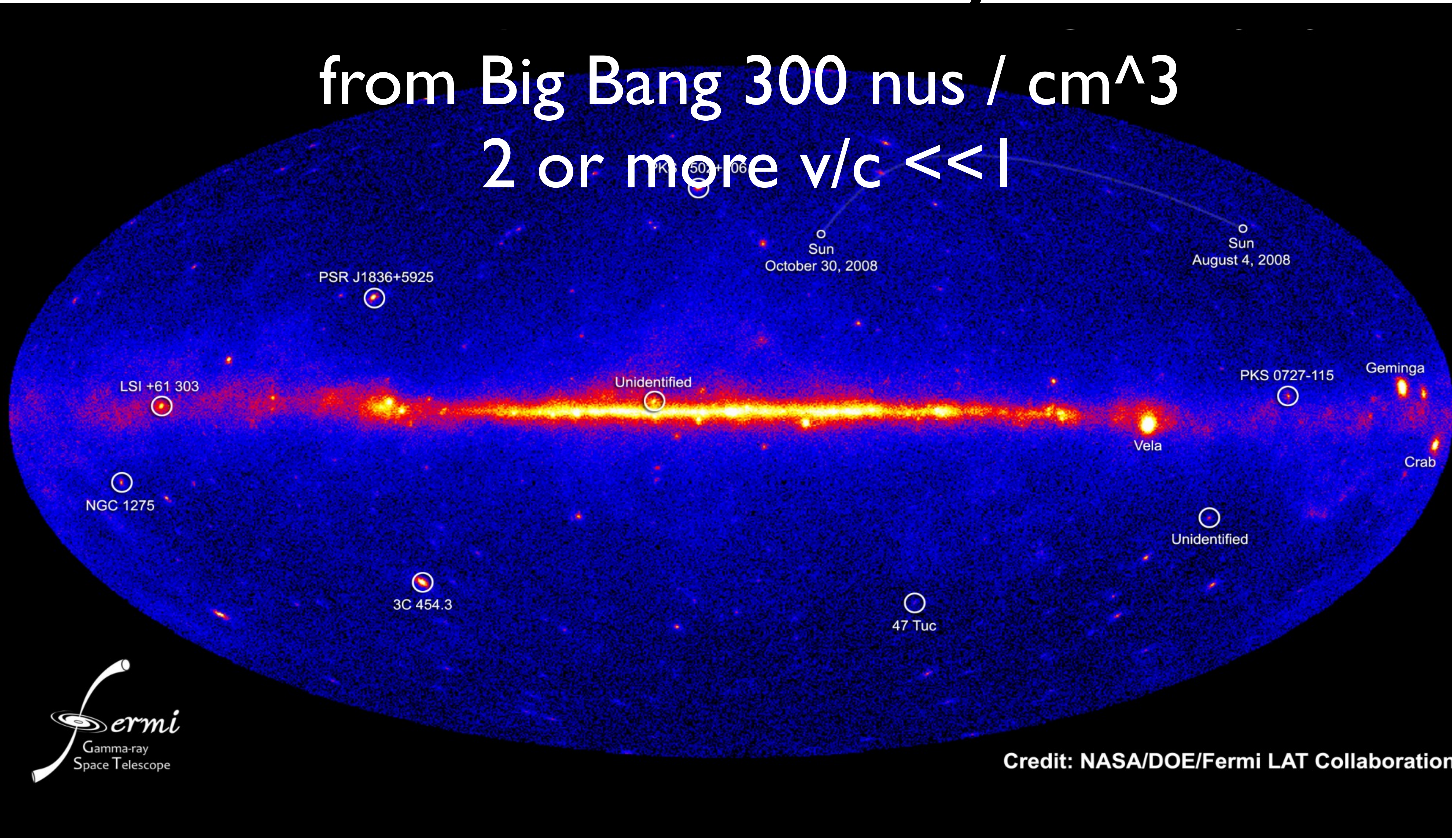
Neutrinos are Everywhere !



Neutrinos are Everywhere !

from Big Bang 300 nus / cm^3

2 or more v/c <<1



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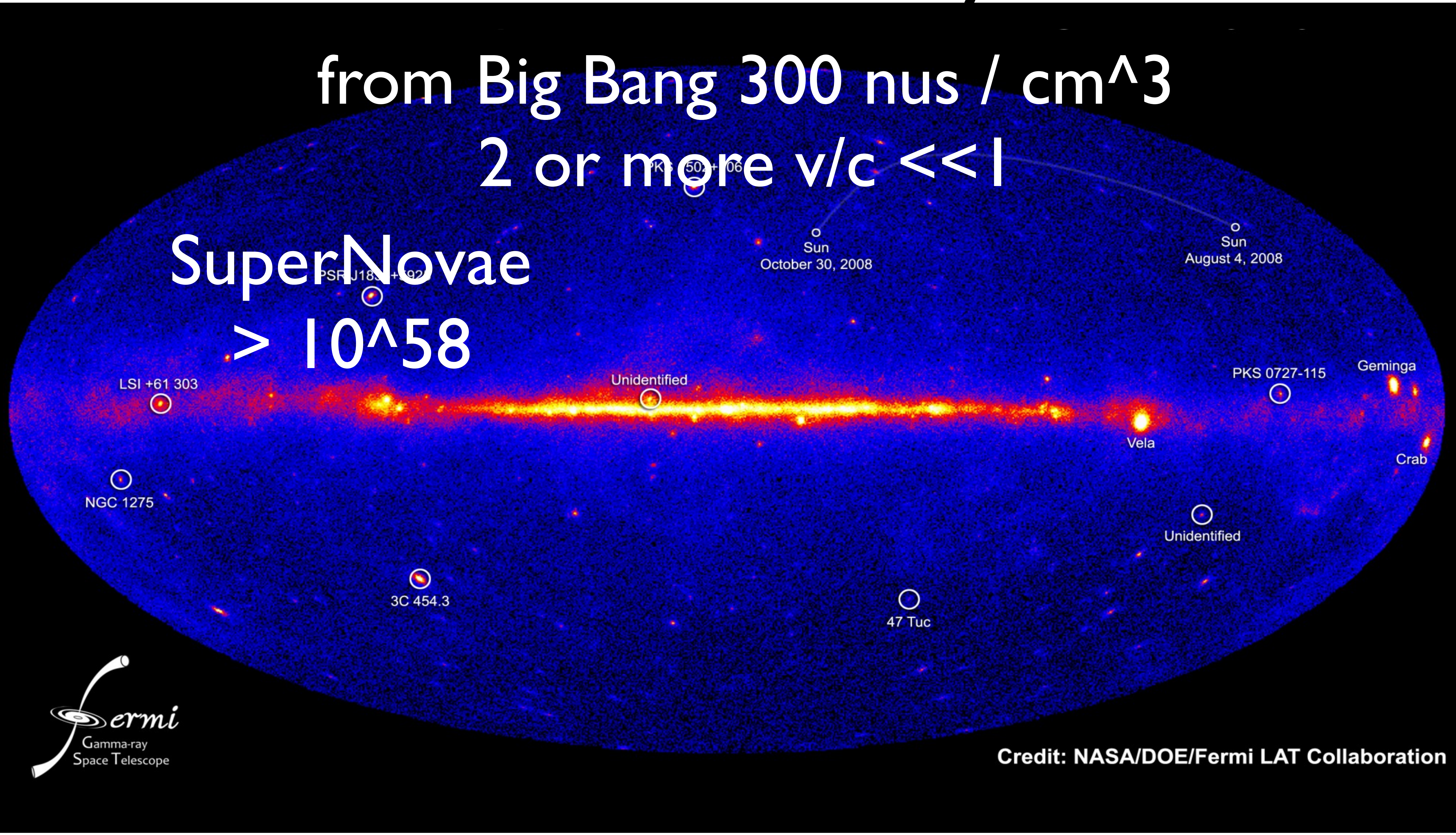

from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

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from Big Bang 300 nus / cm^3

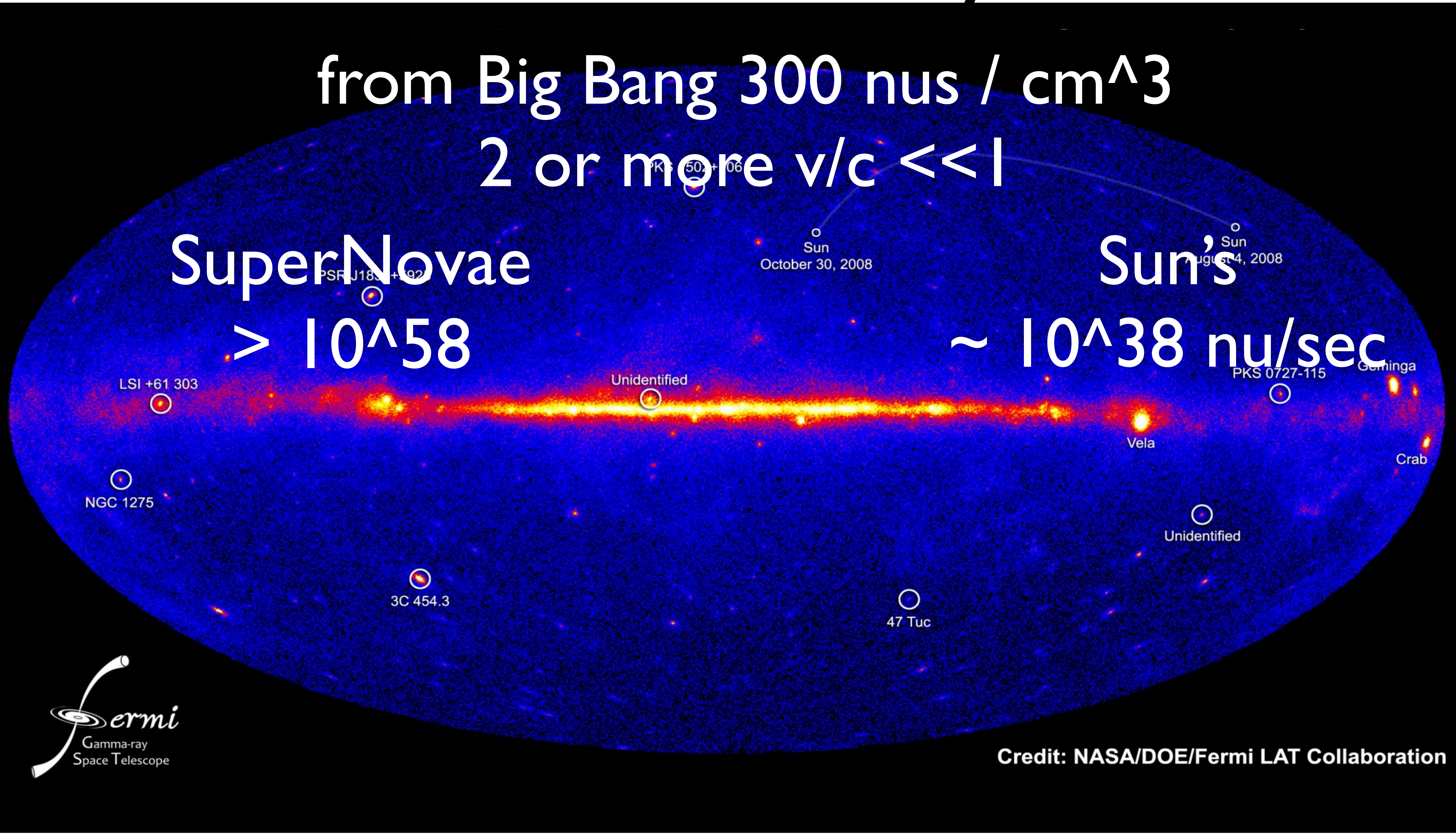
2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec



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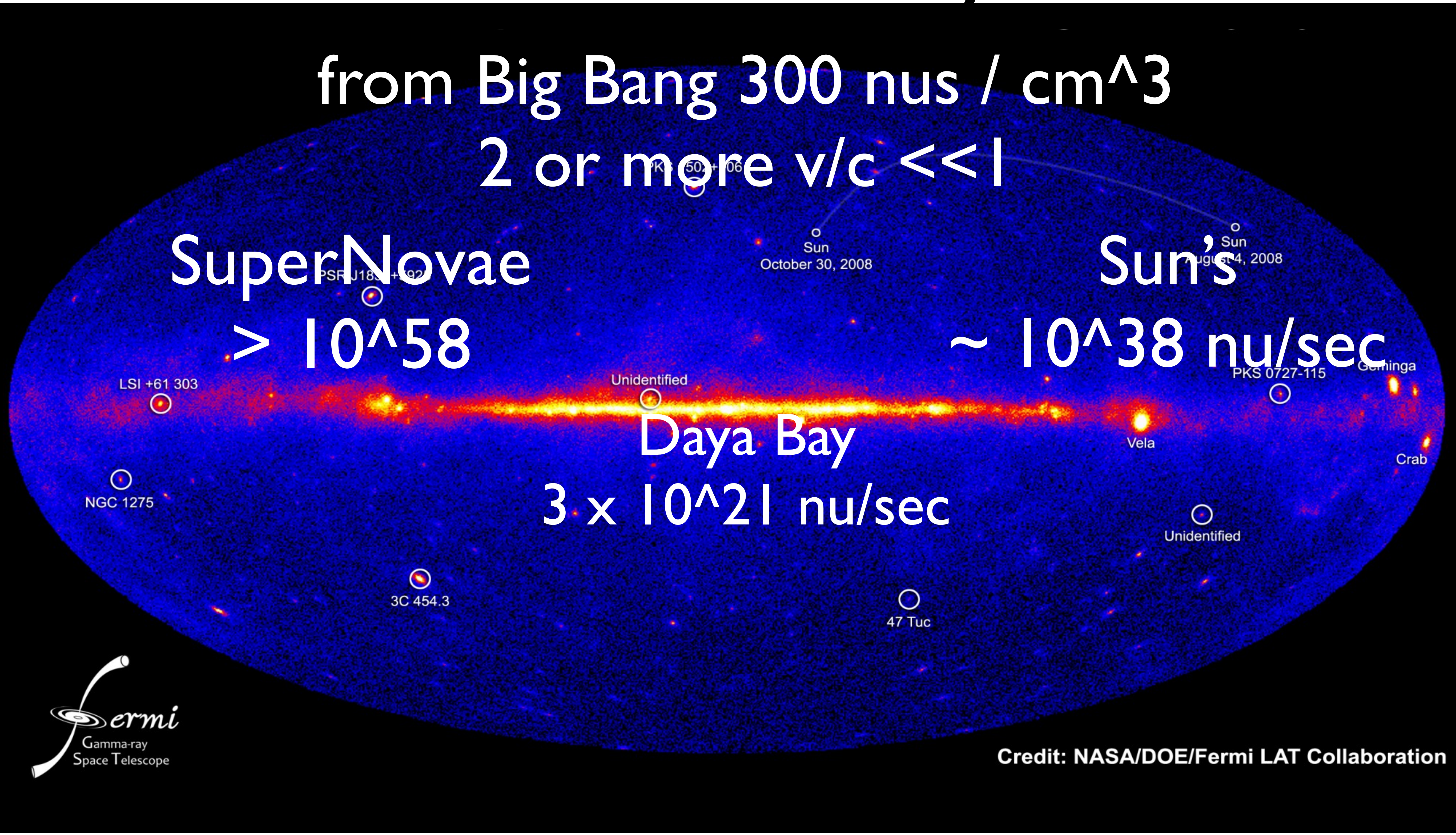
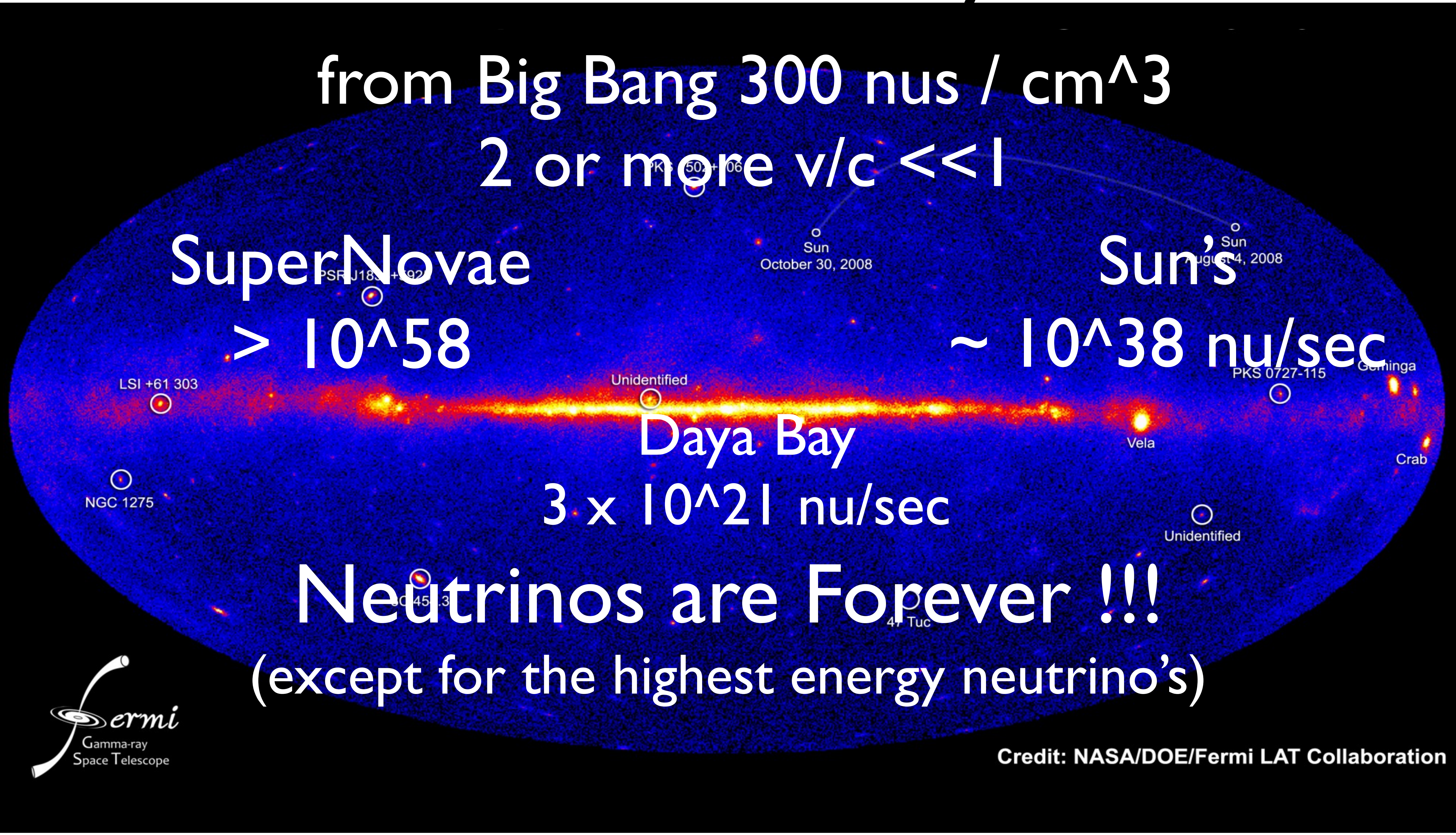
Daya Bay

3 x 10^21 nu/sec



Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

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~ 10^38 nu/sec

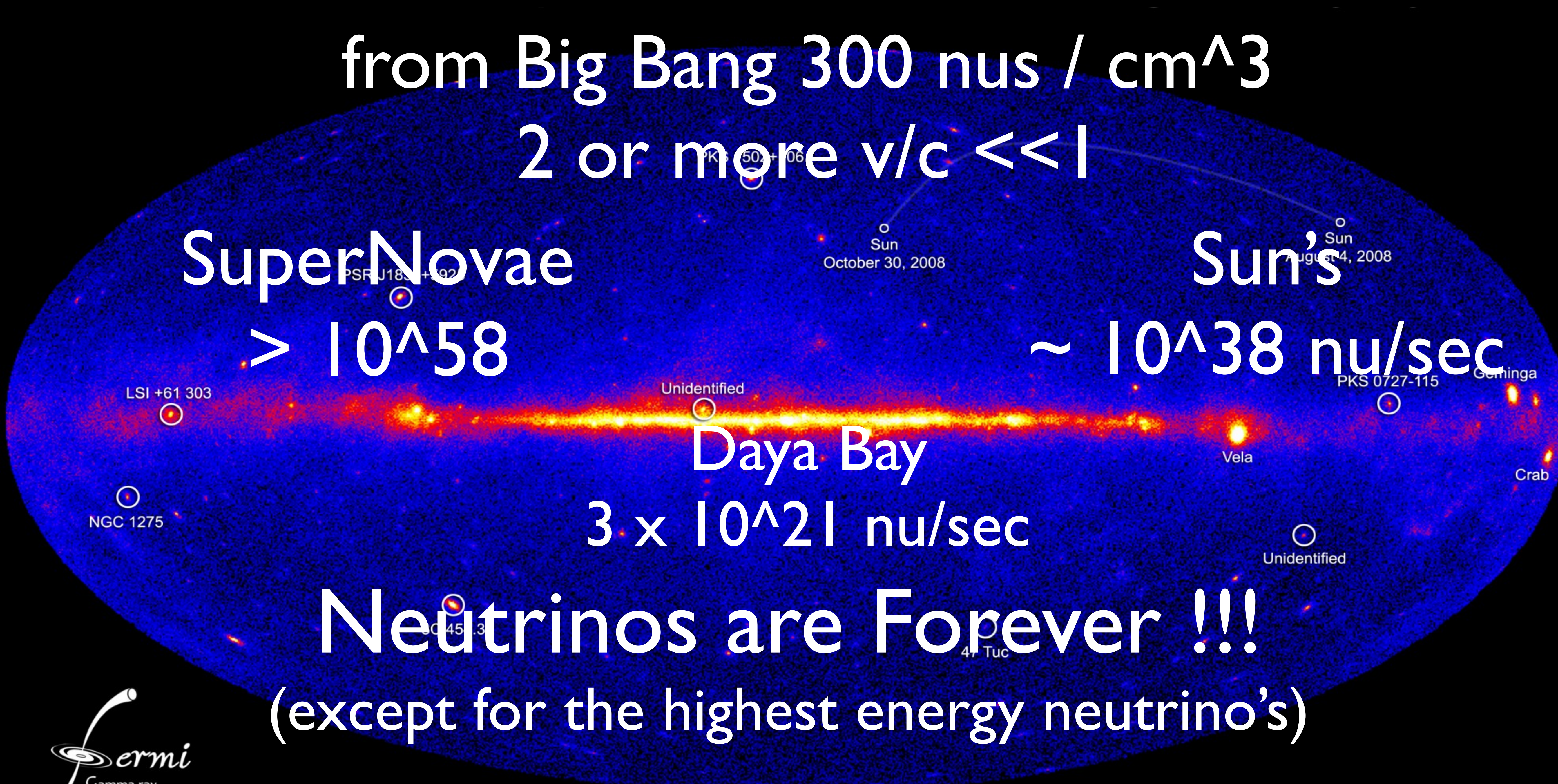
Daya Bay

3 x 10^21 nu/sec

Neutrinos are Forever !!!

(except for the highest energy neutrino's)

Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

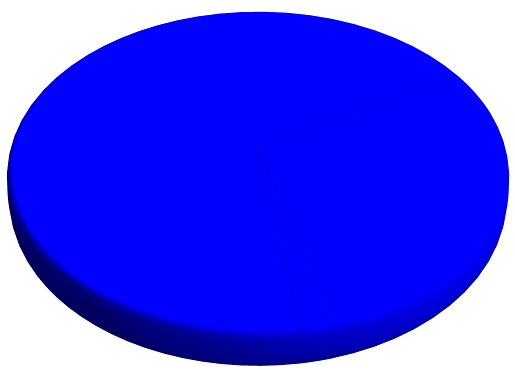
Neutrinos are Forever !!!

(except for the highest energy neutrino's)

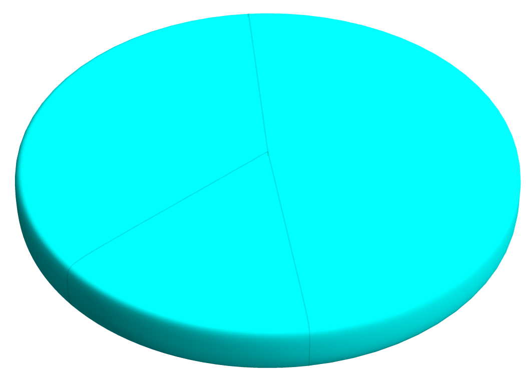
therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Flavor or Interaction States:

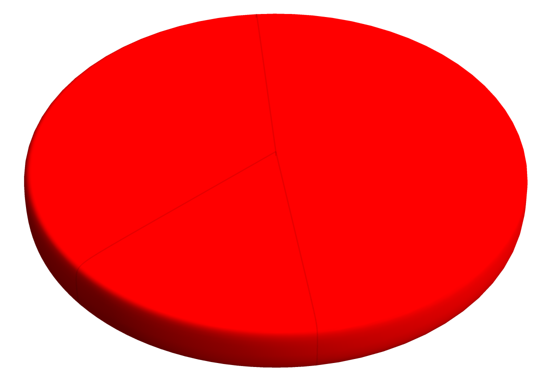
$W^+ \to e^+\nu_e$ | $W^+ \to \mu^+\nu_\mu$ | $W^+ \to \tau^+\nu_\tau$



ν_e



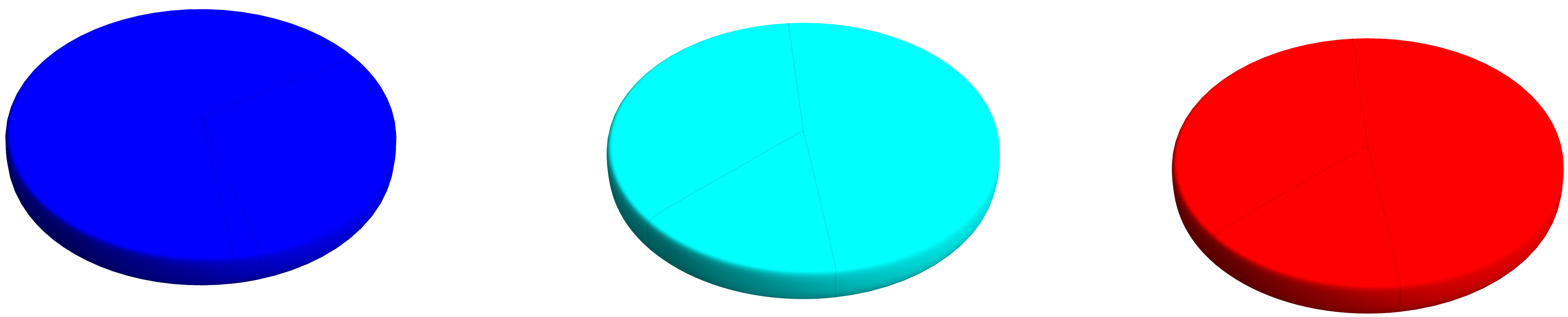
ν_μ



ν_τ

Neutrino Flavor or Interaction States:

$W^+ \to e^+ \nu_e$ $W^+ \to \mu^+ \nu_\mu$ $W^+ \to \tau^+ \nu_\tau$



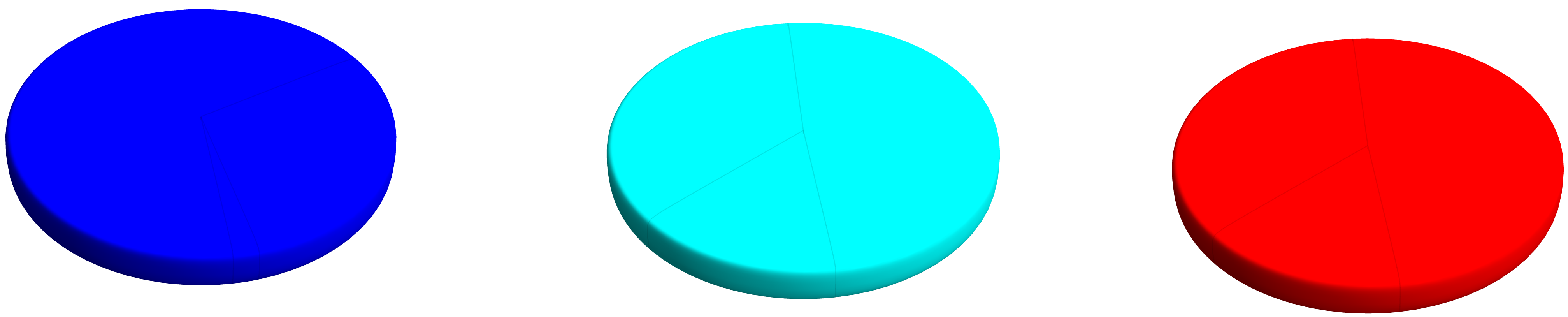
ν_e ν_μ ν_τ

provided $L/E \ll 0.5$ km/MeV $= 500$ km/GeV !!!

$\sim$ 1 picosecond in Neutrino rest frame !!!

Neutrino Flavor or Interaction States:

$W^+ \to e^+ \nu_e$ $\quad$ $W^+ \to \mu^+ \nu_\mu$ $\quad$ $W^+ \to \tau^+ \nu_\tau$



ν_e $\quad$ ν_μ $\quad$ ν_τ

provided $L/E \ll 0.5$ km/MeV $= 500$ km/GeV !!!

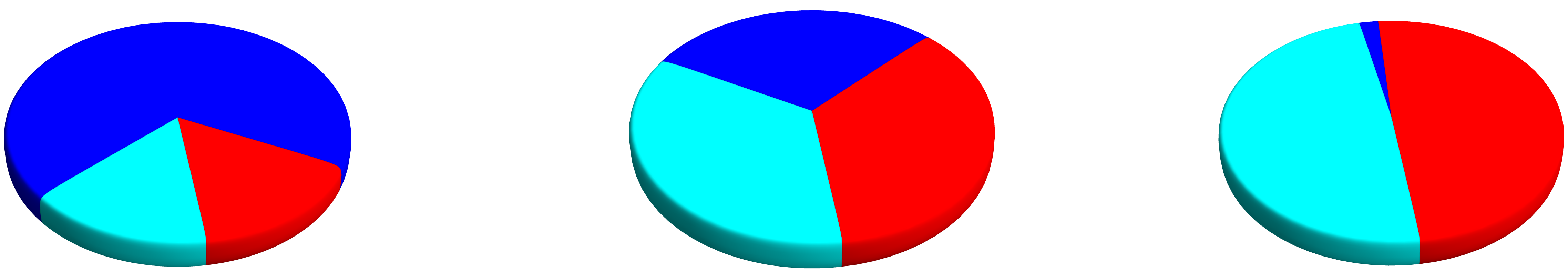
$\sim$ 1 picosecond in Neutrino rest frame !!!

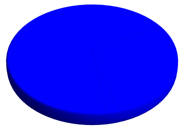
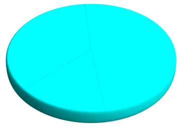
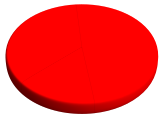
$\approx$ Age of Universe / 10^{26}

Neutrino Mass EigenStates or Propagation States:

$$\text{Propagator } \nu_j \rightarrow \nu_k \; = \boldsymbol{\delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}}$$

$\boldsymbol{\nu_1}$ most ν_e | $\boldsymbol{\nu_2}$ | $\boldsymbol{\nu_3}$ least ν_e

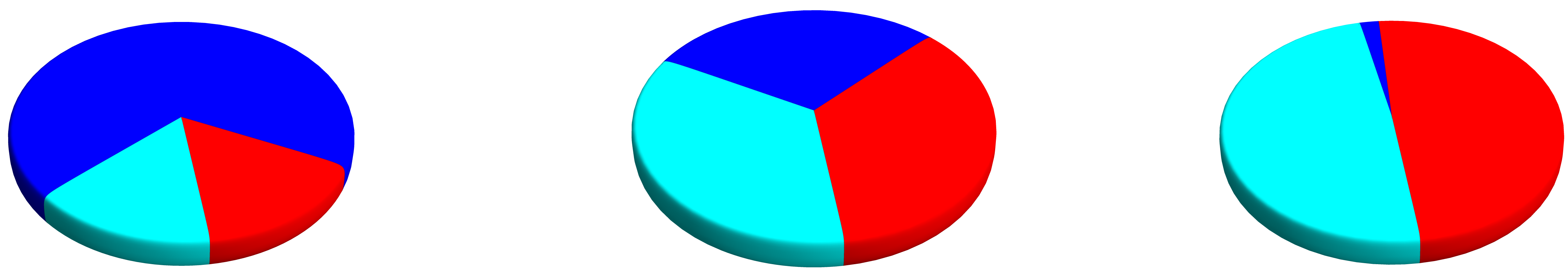


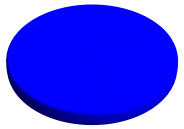
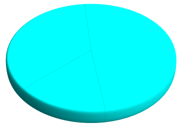
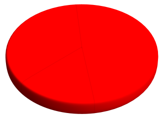
$\boldsymbol{\nu_e} =$  $\boldsymbol{\nu_\mu} =$  $\boldsymbol{\nu_\tau} =$ 

Neutrino Mass EigenStates or Propagation States:

$$\text{Propagator } \nu_j \rightarrow \nu_k \;=\; \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$

ν_1 most ν_e — ν_2 — ν_3 least ν_e



$\nu_e =$  $\nu_\mu =$  $\nu_\tau =$ 

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

Neutrino Mass EigenStates or Propagation States:

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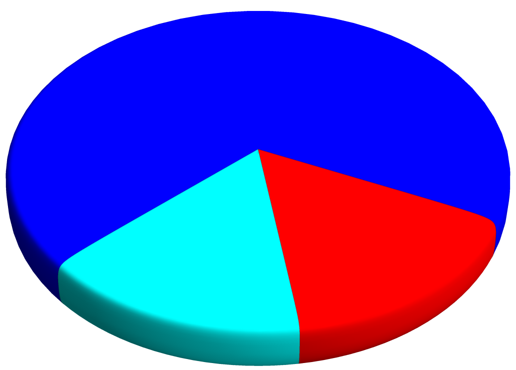
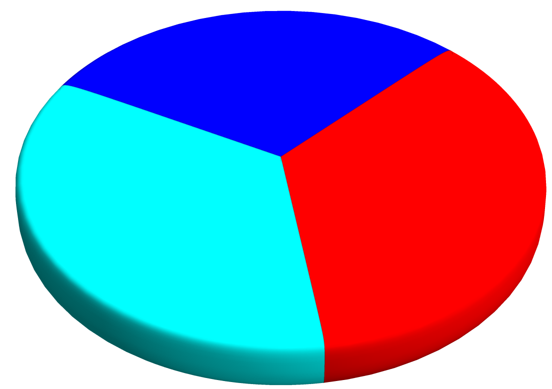
$\boldsymbol{\nu_1}$

most ν_e

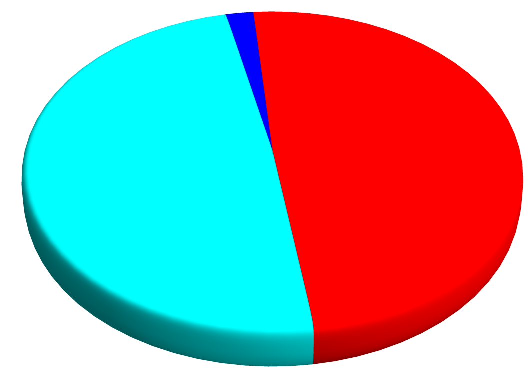


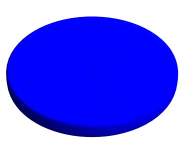
$\boldsymbol{\nu_2}$



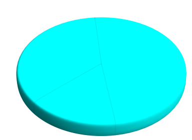
$\boldsymbol{\nu_3}$

least ν_e

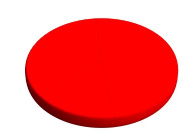


$\boldsymbol{\nu_e =}$ 

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\boldsymbol{\nu_\mu =}$ 

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\boldsymbol{\nu_\tau =}$ 

Neutrino Mass EigenStates or Propagation States:

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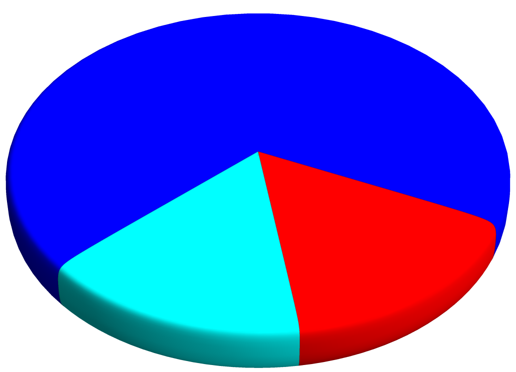
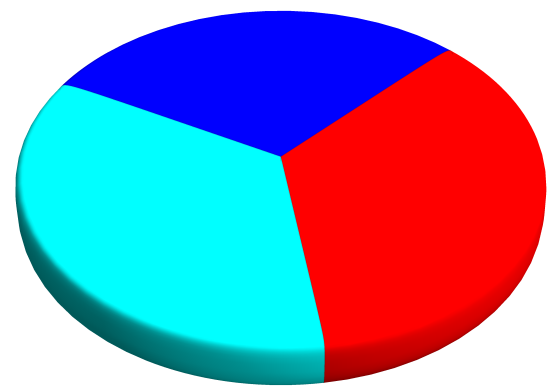
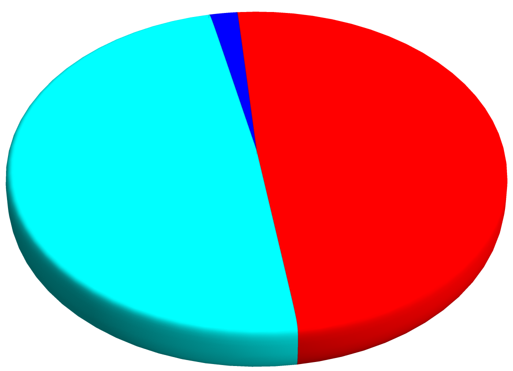
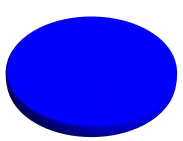
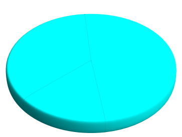
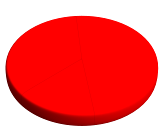
ν_1	ν_2	ν_3
most ν_e		least ν_e
		

$\boldsymbol{\nu_e} =$ 

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ 

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\boldsymbol{\nu_\tau} =$ 

Unitarity
SK, Opera
ICECUBE ?

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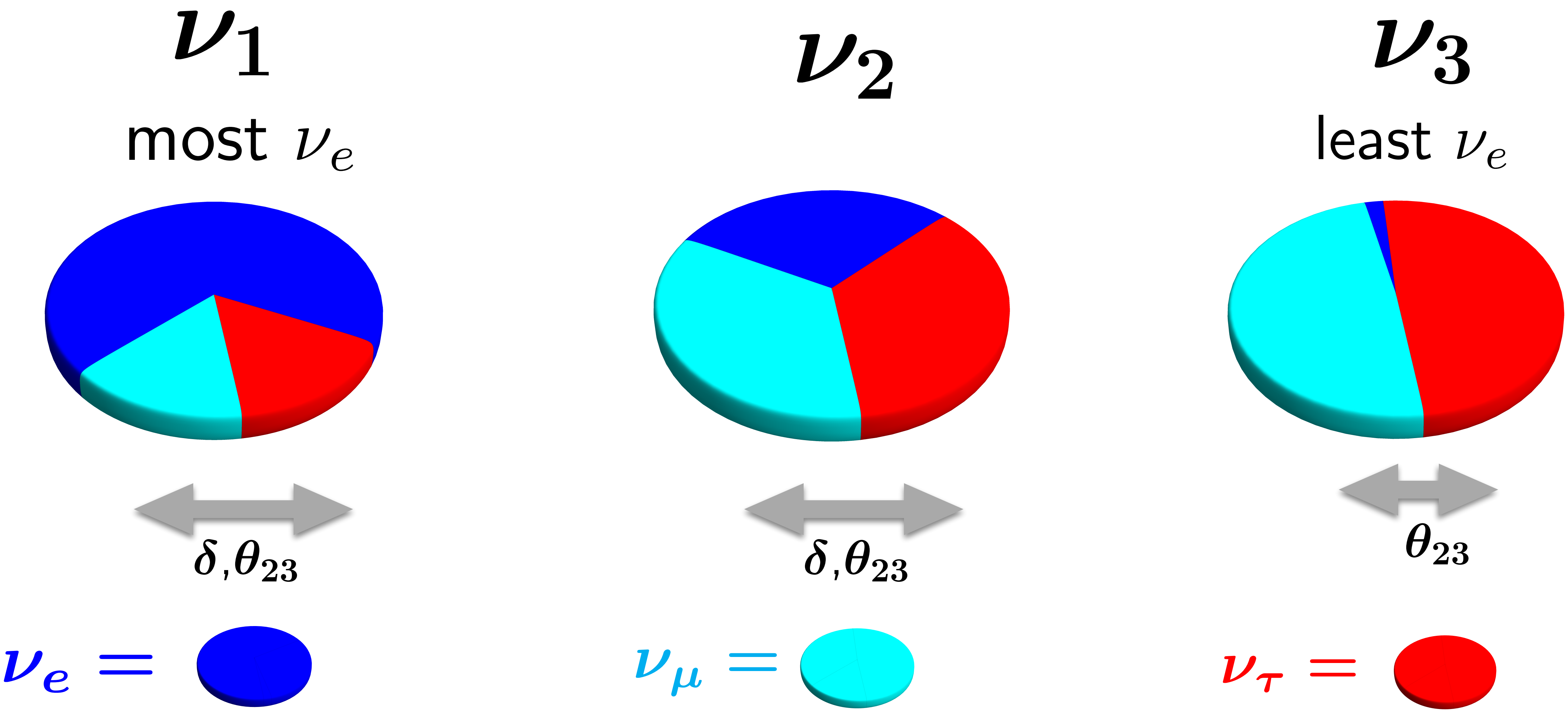
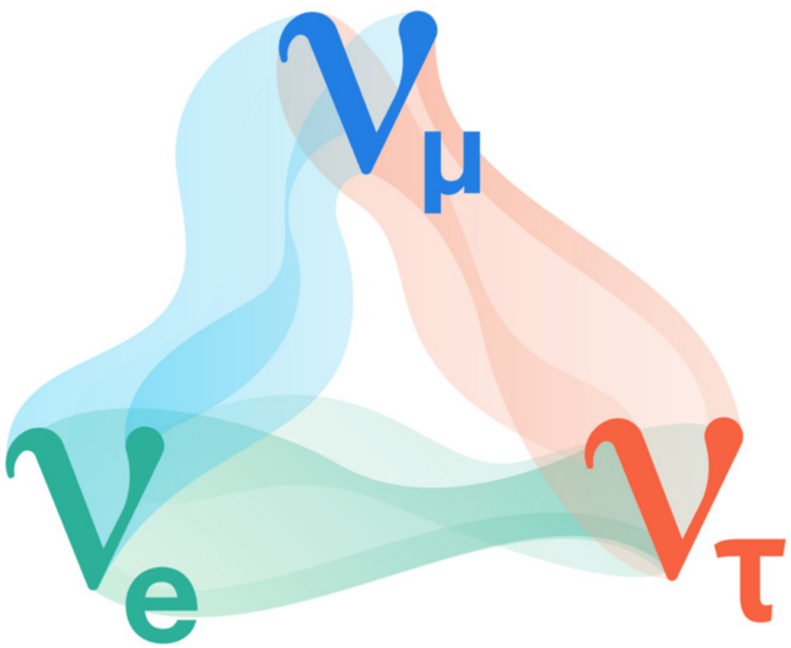


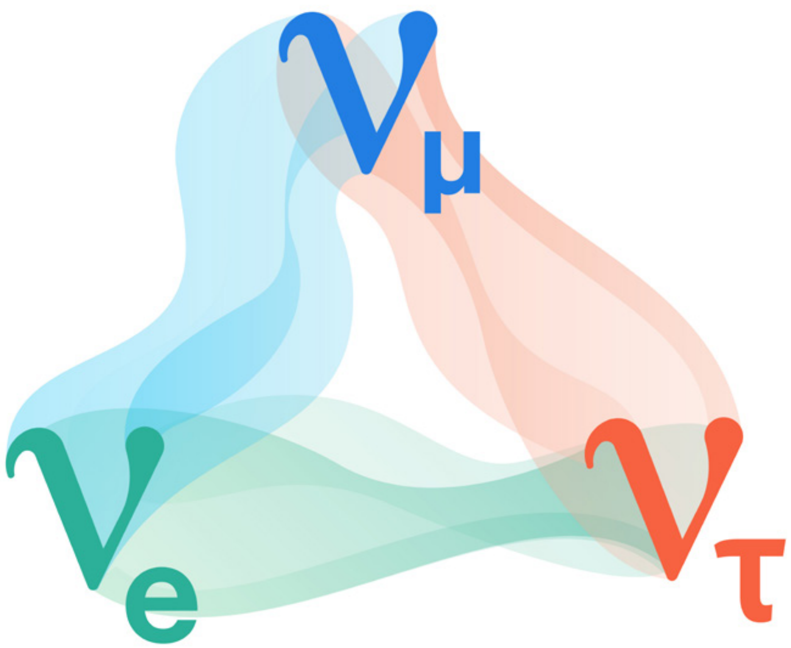
Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

Unitarity
SK, Opera
ICECUBE ?



ν μ
ν e
ν τ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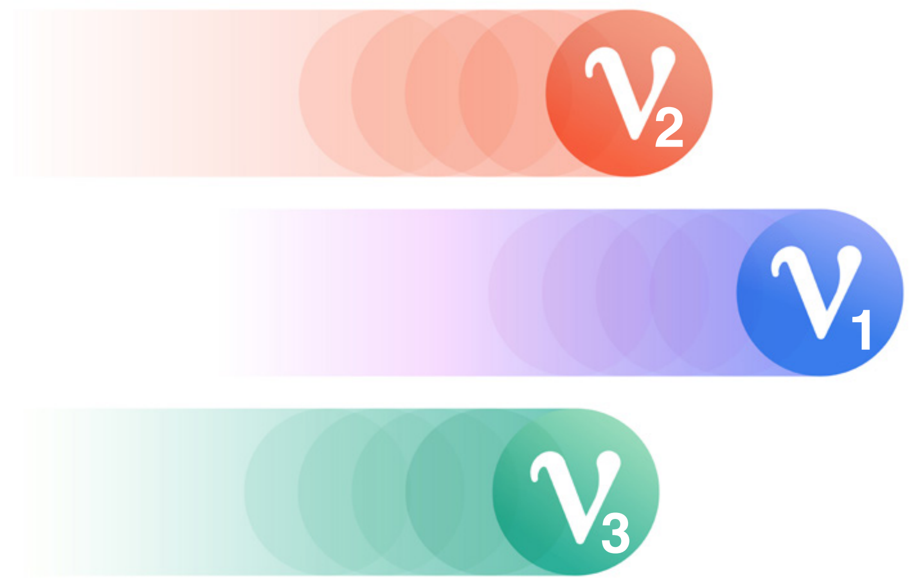
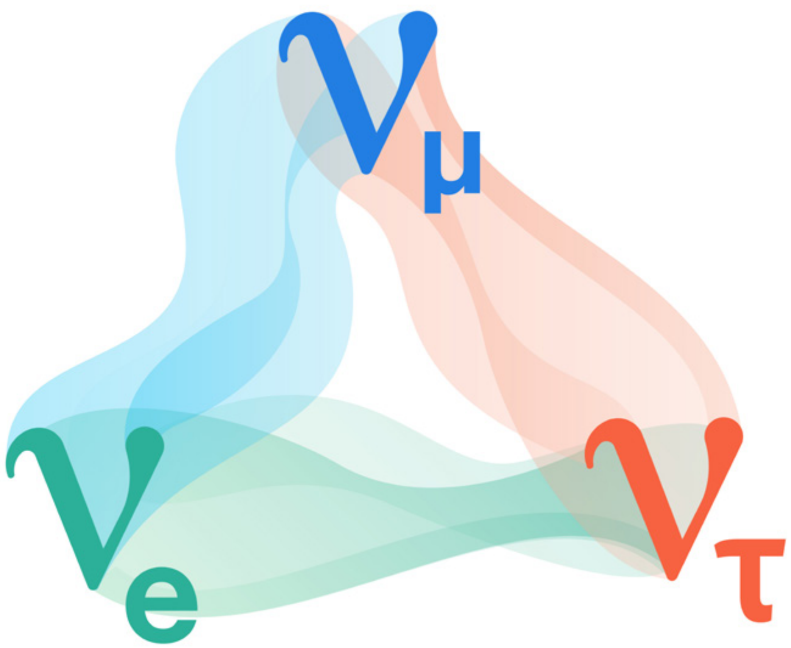
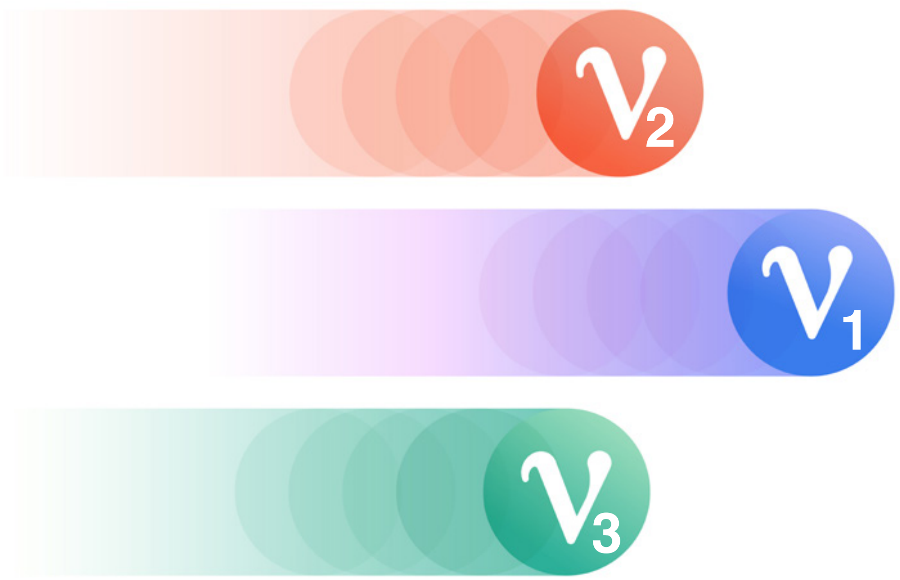

ν_2
ν_1
ν_3

Interactions:

simple



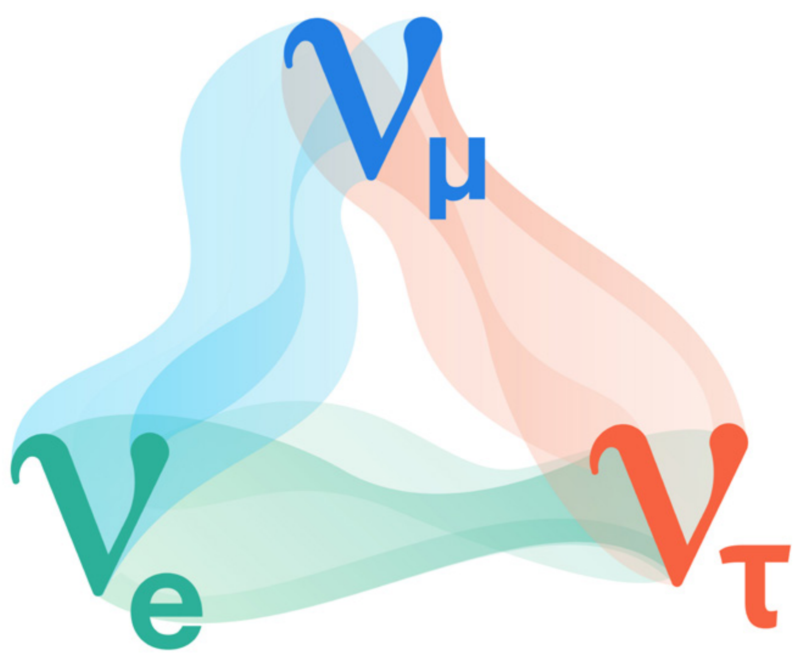
complicated

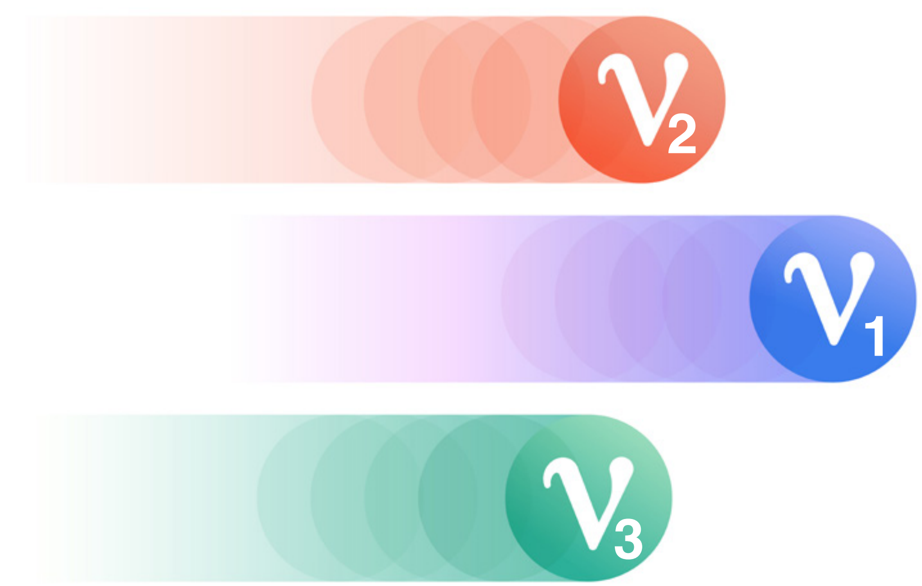


Interactions:

simple

complicated





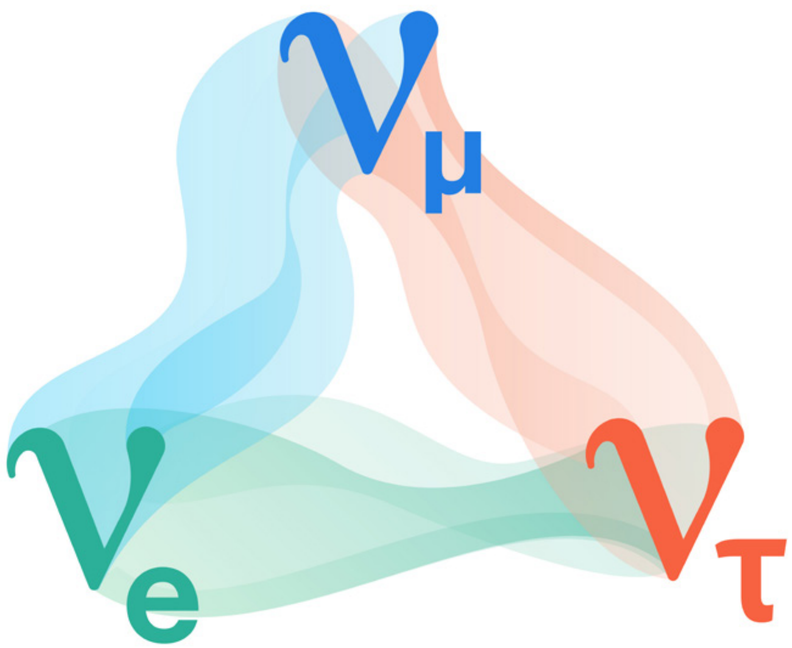
complicated

simple

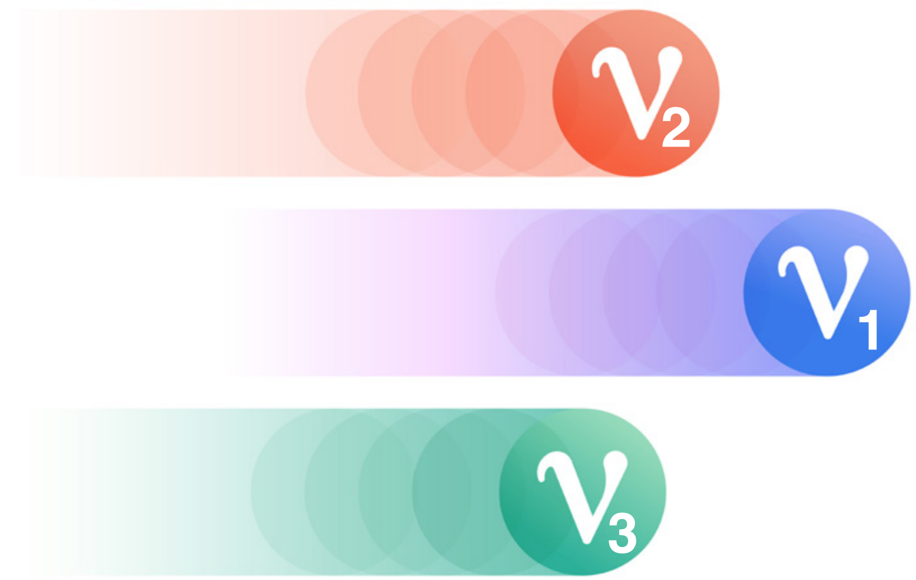
Propagation:

Interactions:

simple complicated



$= U$

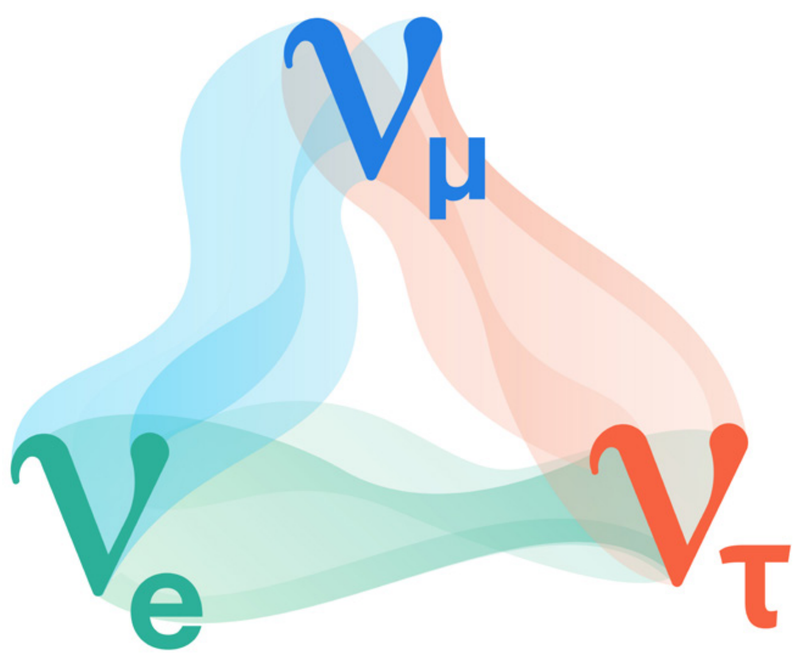


complicated simple

Propagation:

Interactions:

simple | complicated



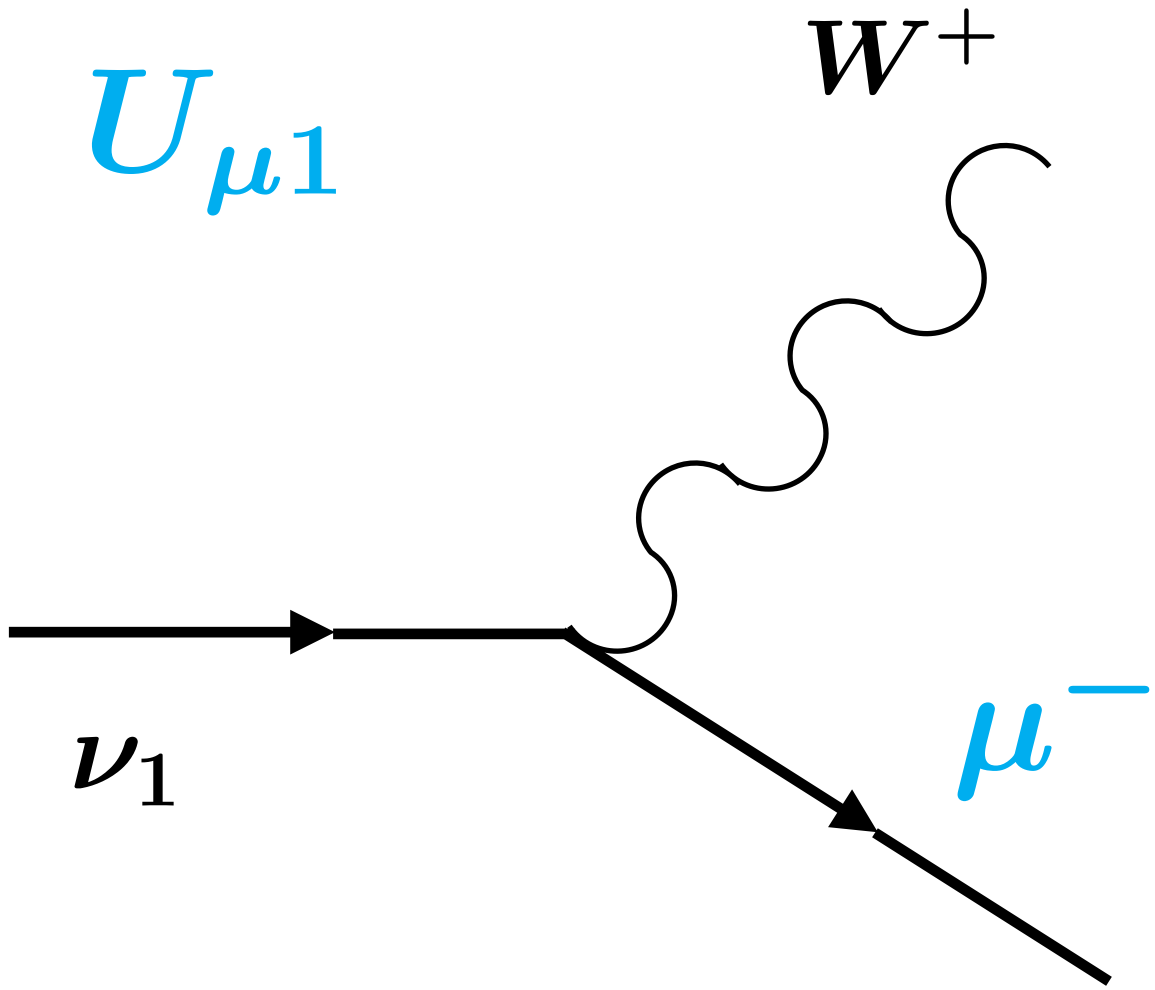
=U

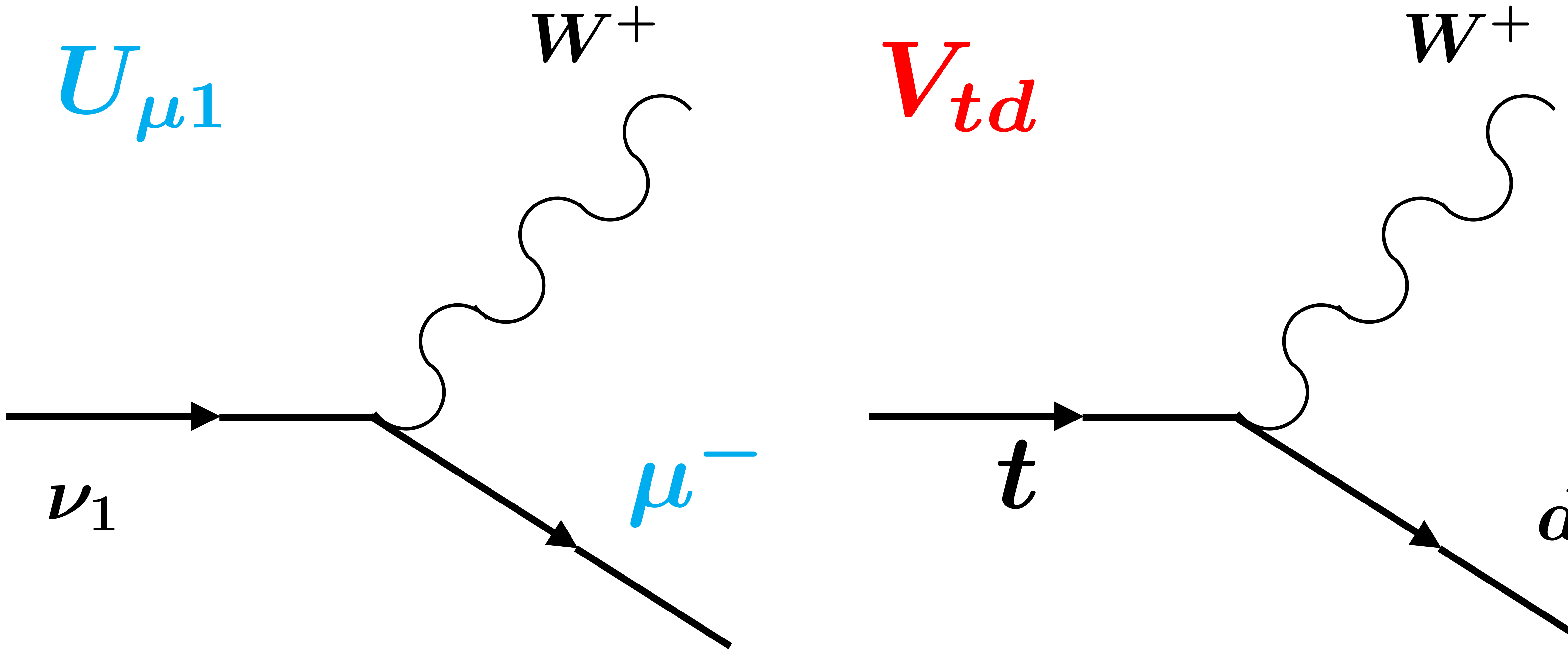
unitary matrix ?

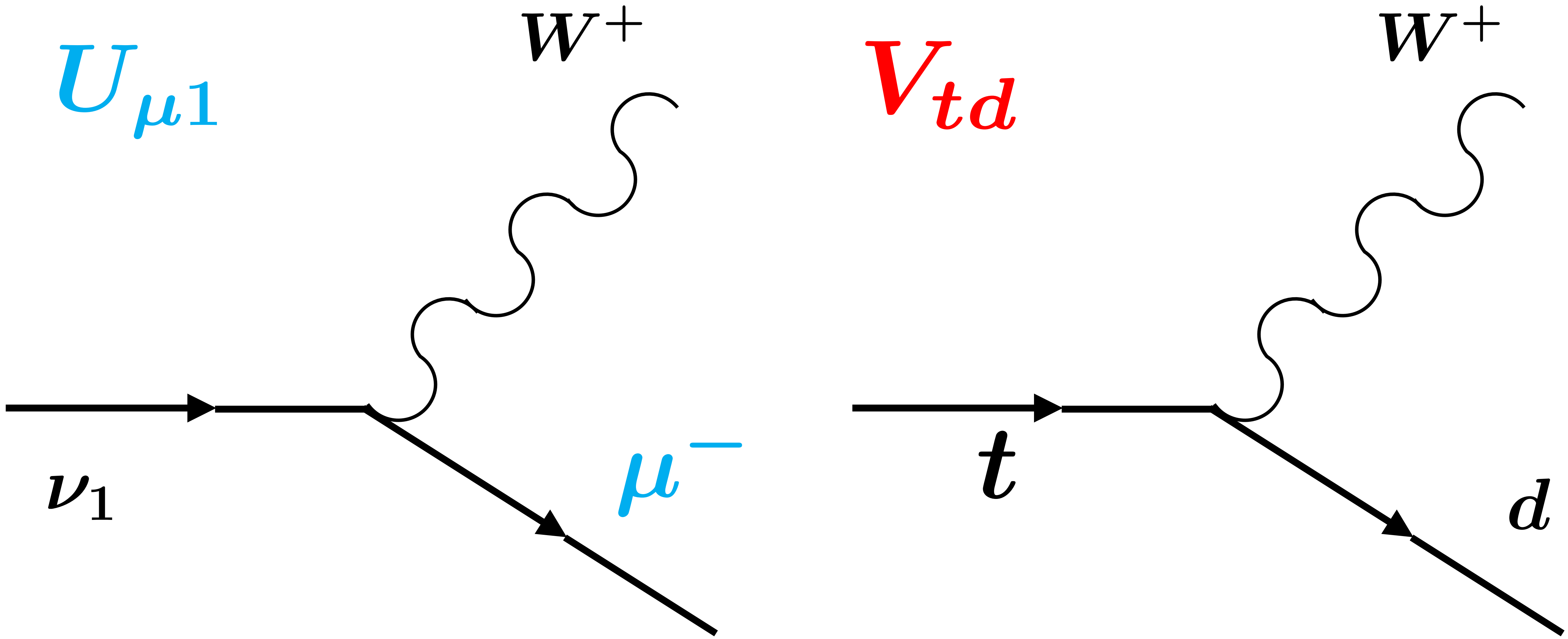
complicated | simple

masses ?

Propagation:


$U_{\mu 1}$
W^+
ν_1
μ^-


$U_{\mu 1}$
W^+
ν_1
μ^-
V_{td}
W^+
t
d



Rates: $|U_{\mu 1}|^2$ & $|V_{td}|^2$

unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$U_{PMNS} = U_{23}(\theta_{23}, 0)\ U_{13}(\theta_{13}, \delta)\ U_{12}(\theta_{12}, 0)$$

Why this order ???

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{+i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$

$$\times\ \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$$

unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$U_{PMNS} = U_{23}(\theta_{23}, 0)\, U_{13}(\theta_{13}, \delta)\, U_{12}(\theta_{12}, 0)$$

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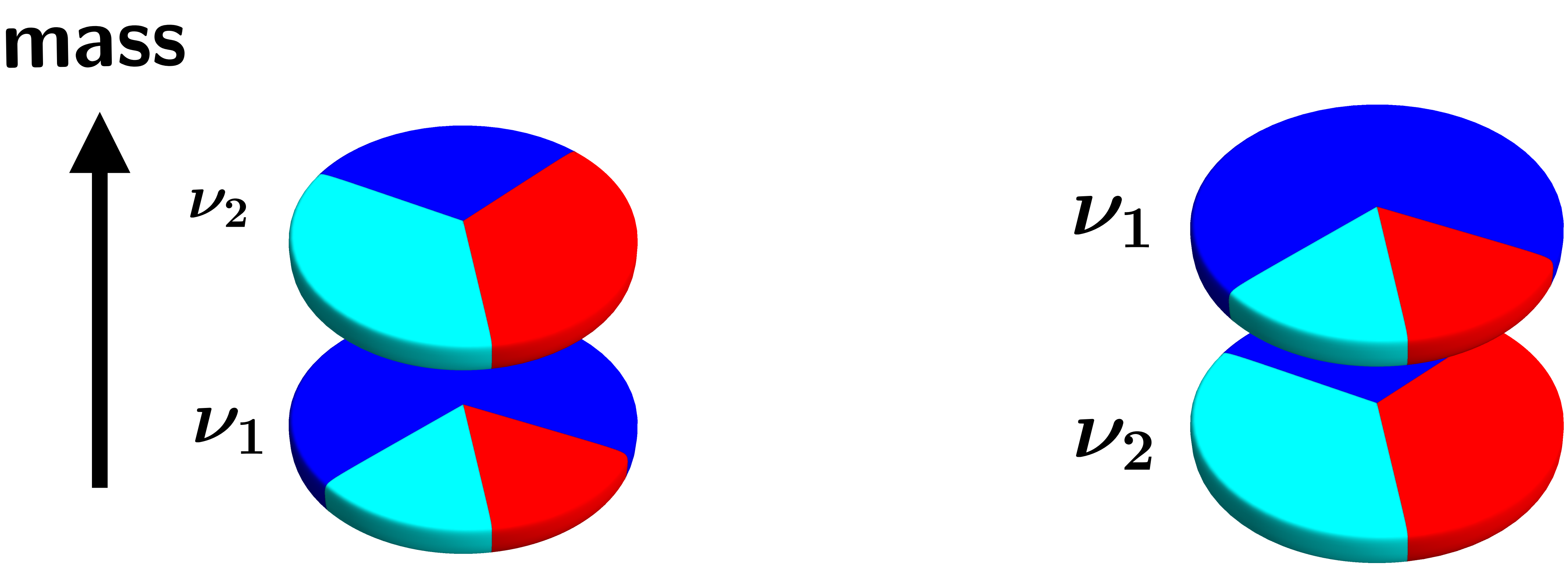
$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij} \qquad \times\, \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$$

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$\nu_1, \;\; \nu_2$ Mass Ordering:

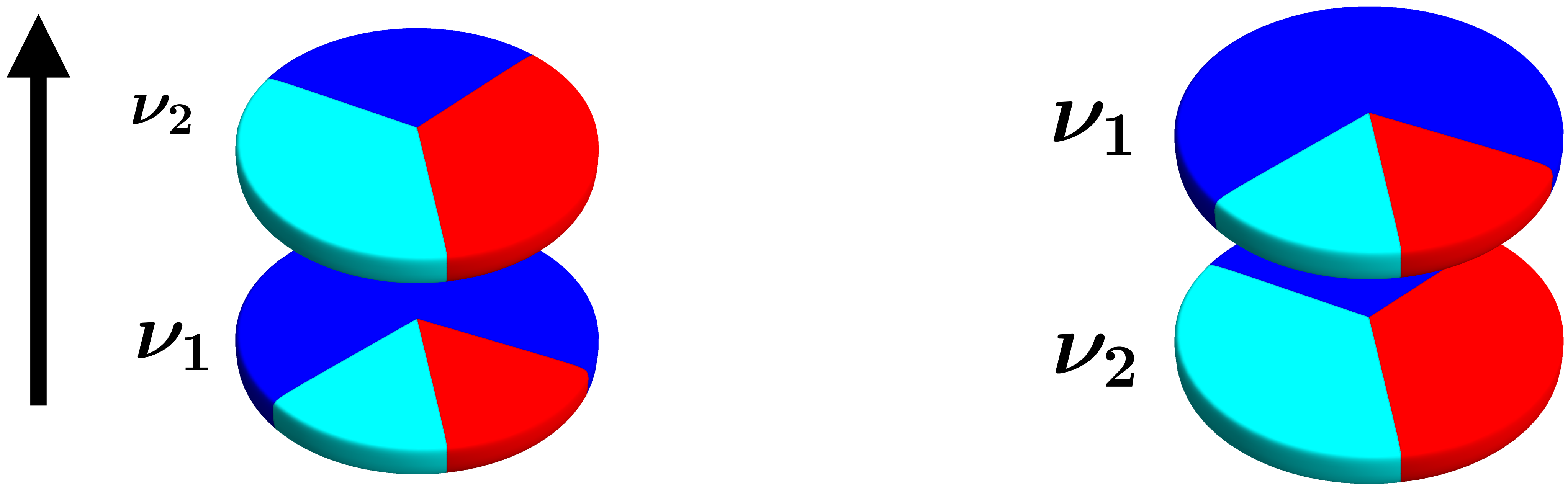
–solar mass ordering



$\nu_1, \ \nu_2$ Mass Ordering:

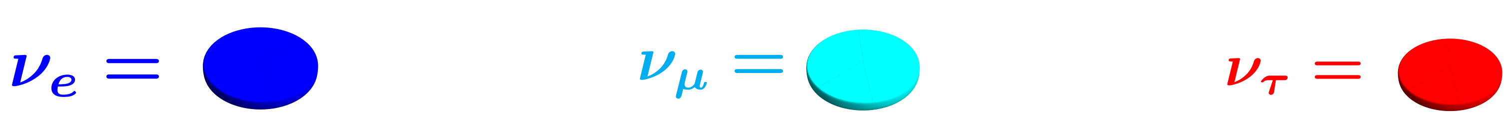
–solar mass ordering

mass



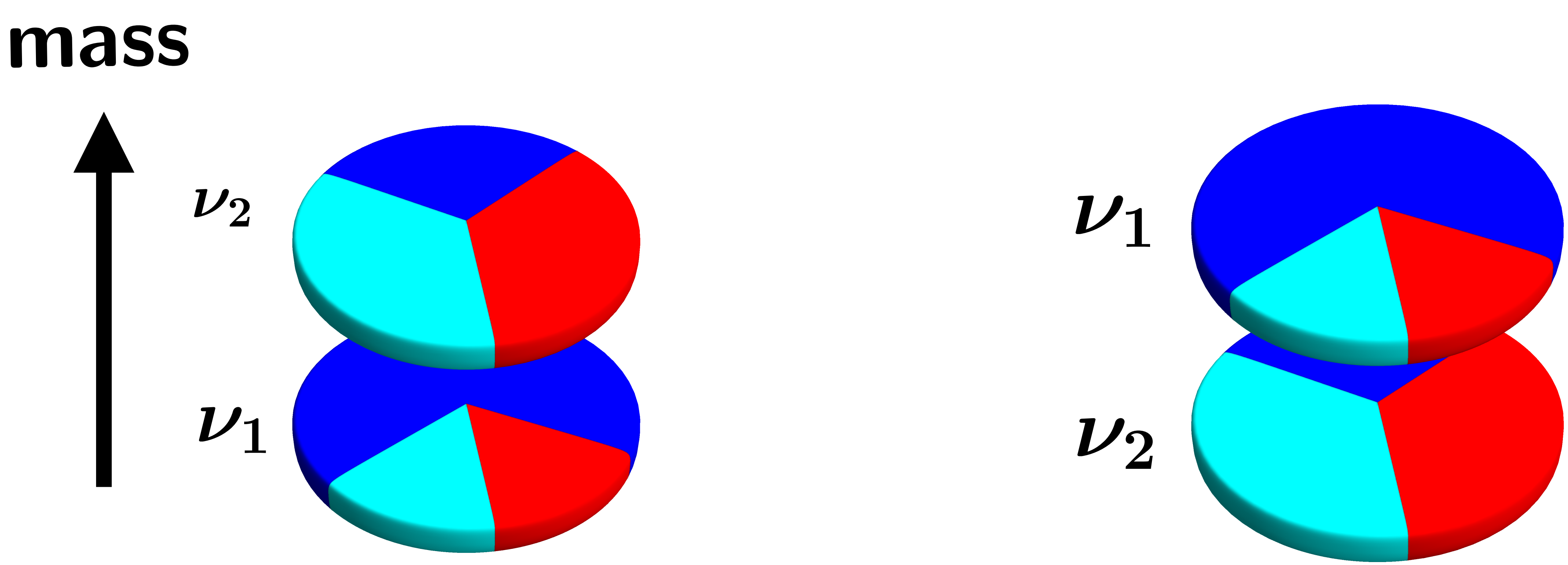
$$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5} \text{ eV}^2$$

$$L/E = 15 \text{ km/MeV} = 15,000 \text{ km/GeV}$$



$\nu_1, \ \nu_2$ Mass Ordering:

–solar mass ordering



$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5} \ \mathrm{eV}^2$

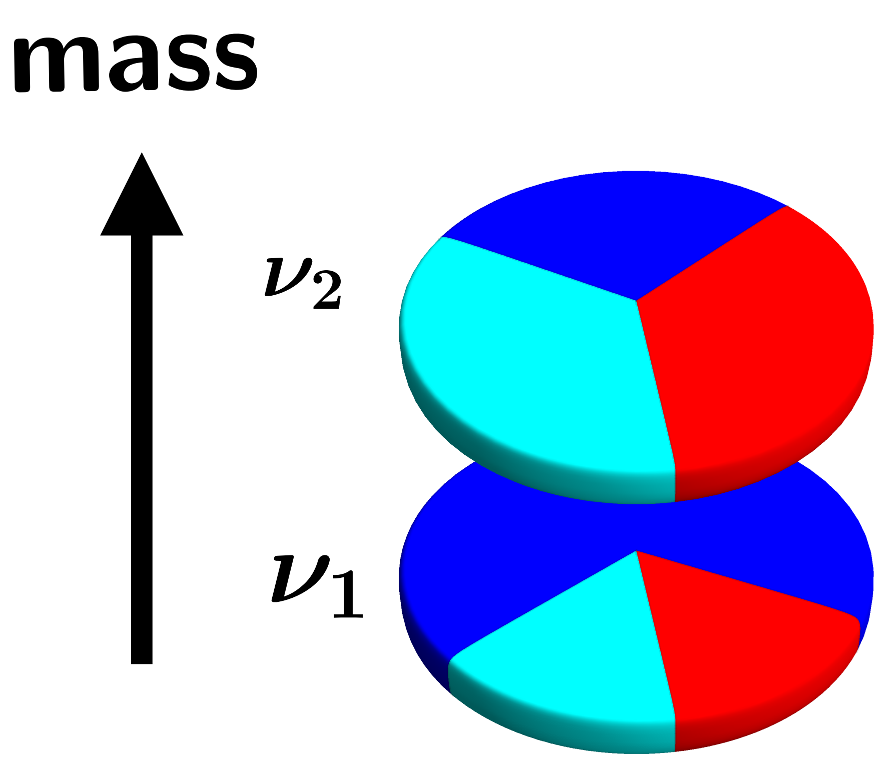
$L/E = 15 \ \mathrm{km/MeV} = 15,000 \ \mathrm{km/GeV}$

SNO $m_2 > m_1$

$\nu_e =$ $\nu_\mu =$ $\nu_\tau =$

$\nu_1, \ \nu_2$ Mass Ordering:

–solar mass ordering



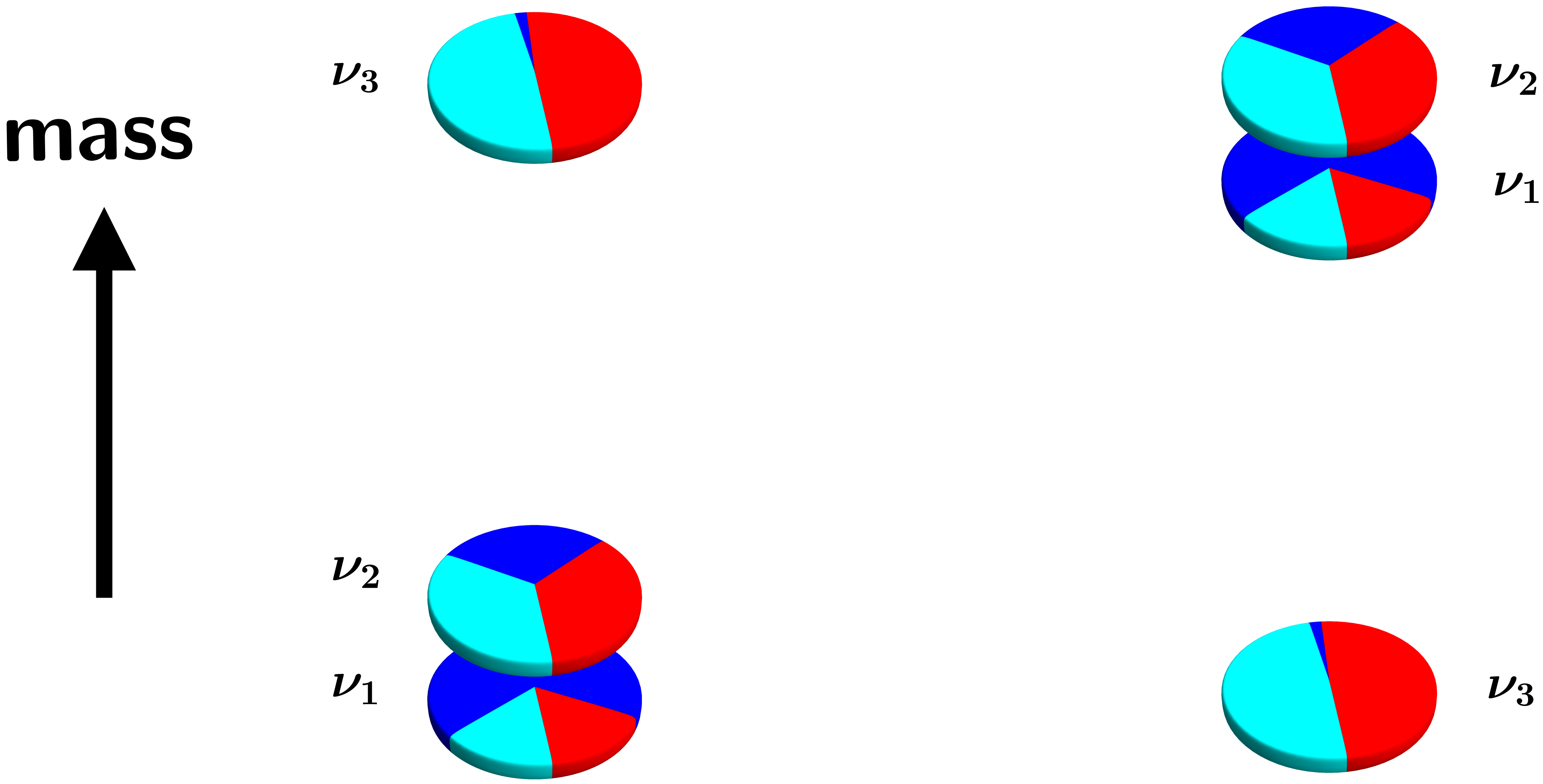
$$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = \mathbf{7.5} \times \mathbf{10^{-5}}\ \mathrm{eV}^2 \qquad \boldsymbol{L/E} = \mathbf{15}\ \mathrm{km/MeV} = \mathbf{15,000}\ \mathrm{km/GeV}$$

SNO $\quad m_2 > m_1$

$\nu_e =$ $\qquad \nu_\mu =$ $\qquad \nu_\tau =$

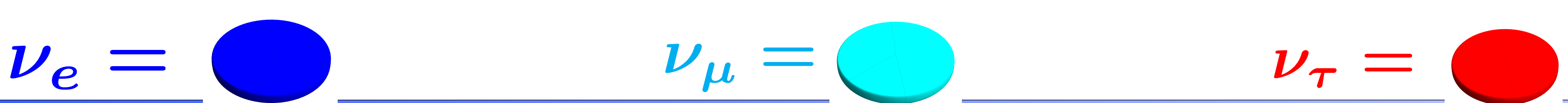
ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering



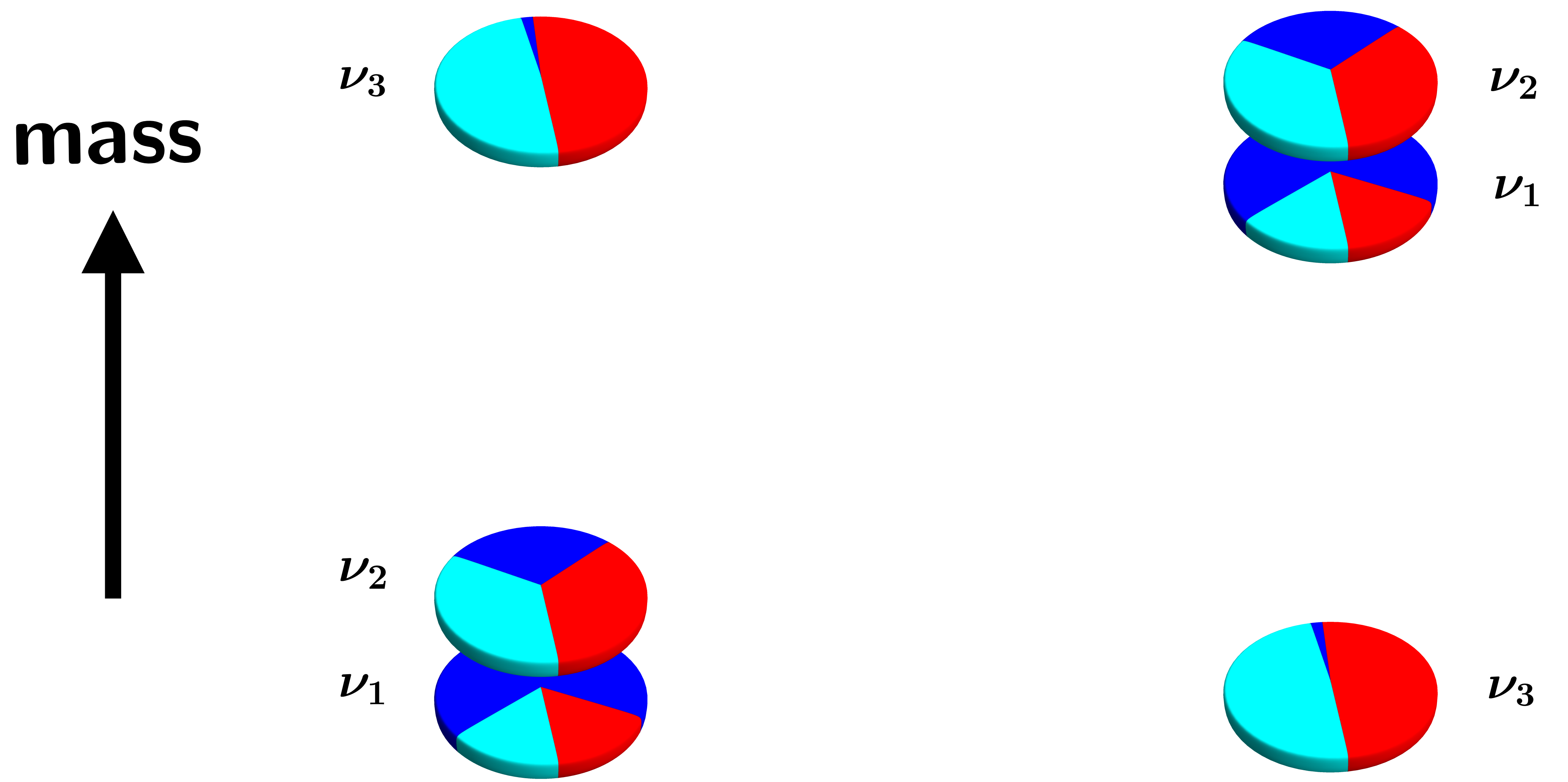
$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$L/E = 0.5\ \mathrm{km/MeV} = 500\ \mathrm{km/GeV}$



ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering



$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \text{eV}^2$ $\quad$ $L/E = 0.5$ km/MeV $= 500$ km/GeV

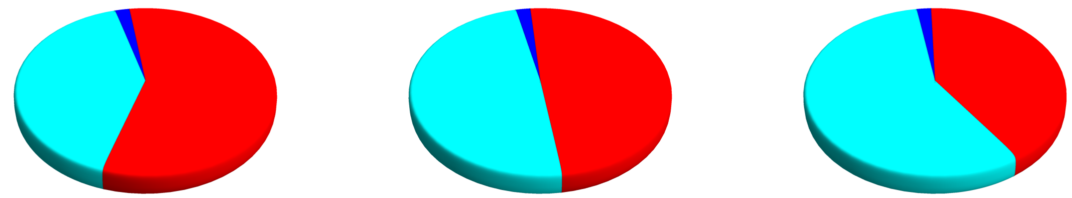
Unknown: NOνA, JUNO, ICECUBE, DUNE, T2HKK....

$\nu_e =$ $\quad$ $\nu_\mu =$ $\quad$ $\nu_\tau =$

Summary: Octant of θ_{23}

$\sin^2\theta_{23}$ **0.40** **0.50** **0.60**

ν_3



0

δ $\pm\pi/2$

$\nu_e =$

$\nu_\mu =$ π

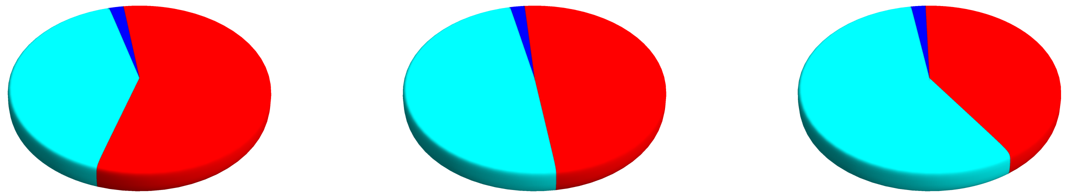
$\nu_\tau =$

Summary:

Octant of θ_{23}

$\sin^2\theta_{23}$ **0.40** **0.50** **0.60**

ν_3



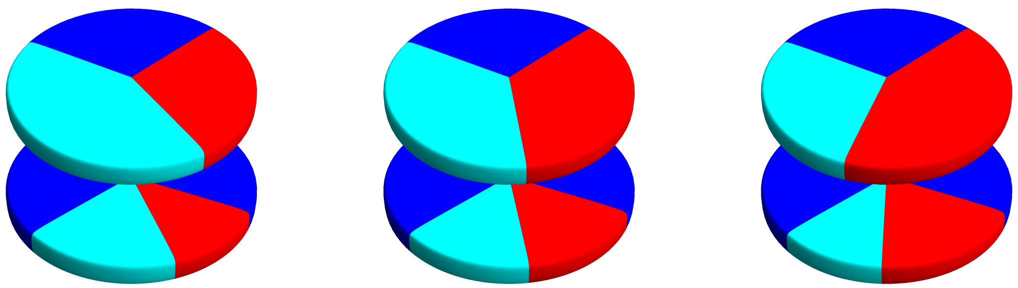
δ

0

$\pm\pi/2$

ν_2

ν_1



π

$\nu_e =$

$\nu_\mu =$

$\nu_\tau =$

Summary:

Octant of θ_{23}

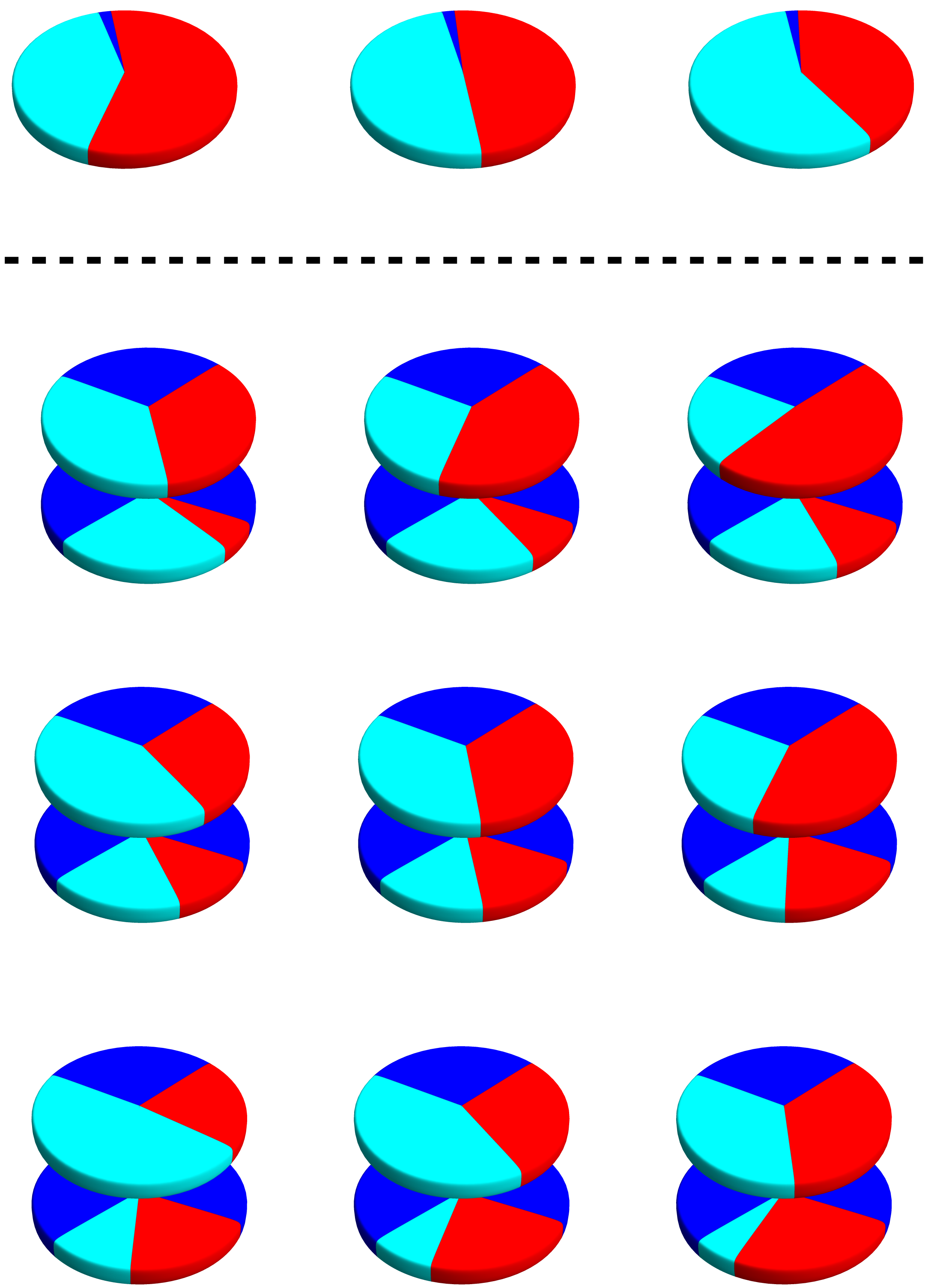
$\sin^2\theta_{23}$	0.40	0.50	0.60

ν_3

δ: 0 — ν_2, ν_1

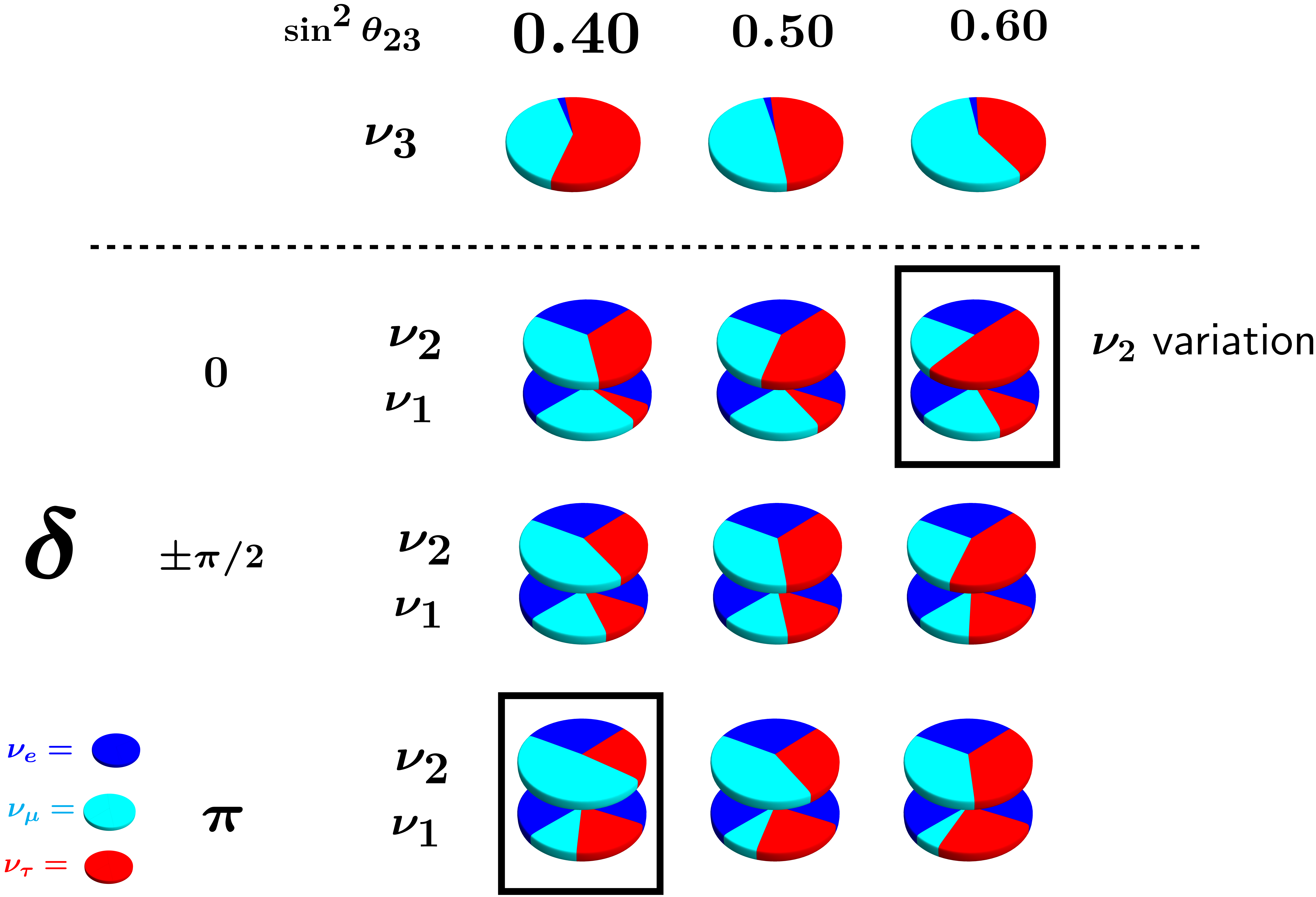
$\pm\pi/2$ — ν_2, ν_1

π — ν_2, ν_1



$\nu_e =$ (blue)
$\nu_\mu =$ (cyan)
$\nu_\tau =$ (red)

Summary: Octant of θ_{23}



Summary:

Octant of θ_{23}

$\sin^2\theta_{23}$ **0.40** **0.50** **0.60**

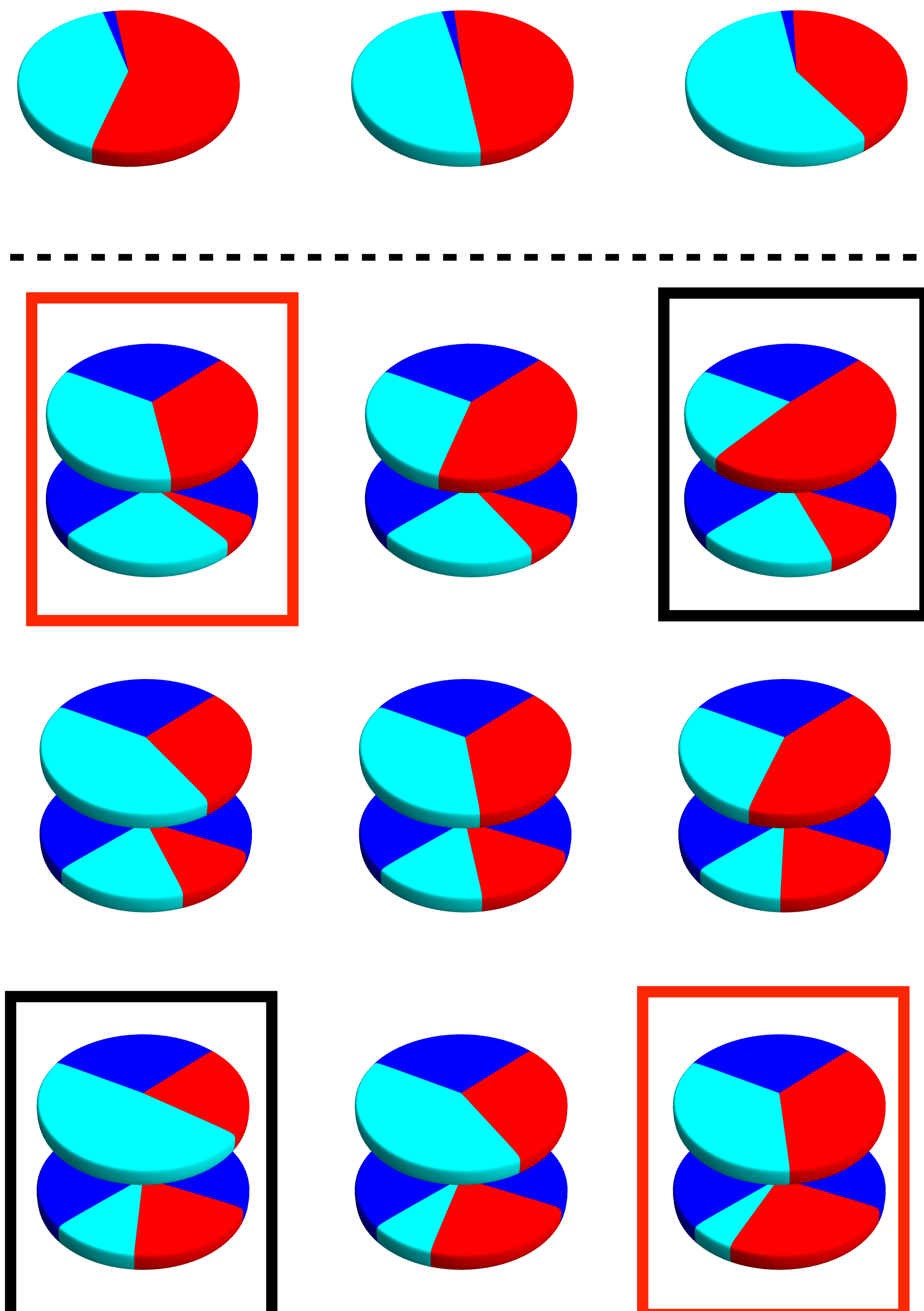
ν_3

δ

0: ν_2 / ν_1

$\pm\pi/2$: ν_2 / ν_1

π: ν_2 / ν_1



ν_2 variation

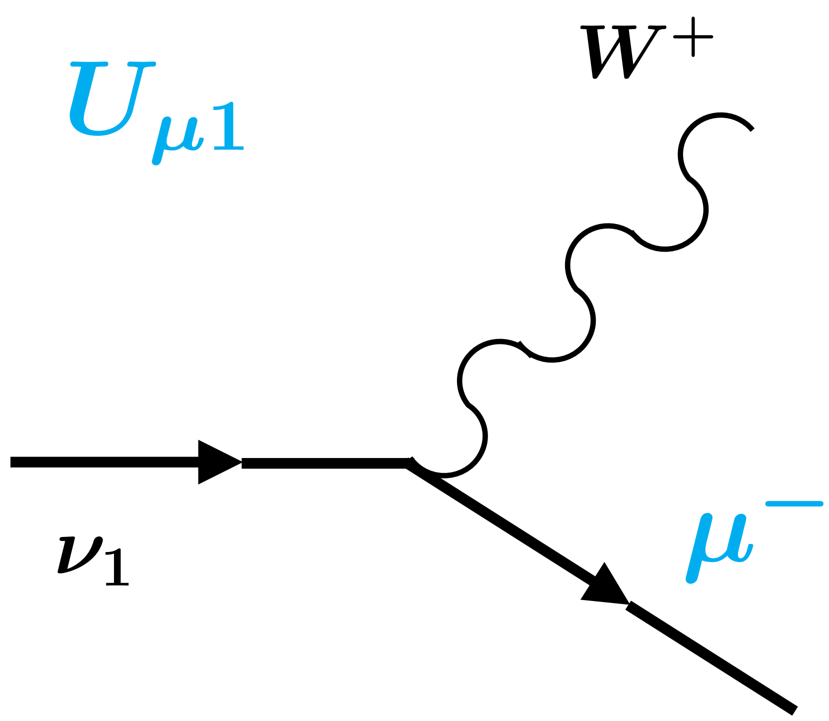
ν_1 variation

$\nu_e =$

$\nu_\mu =$

$\nu_\tau =$

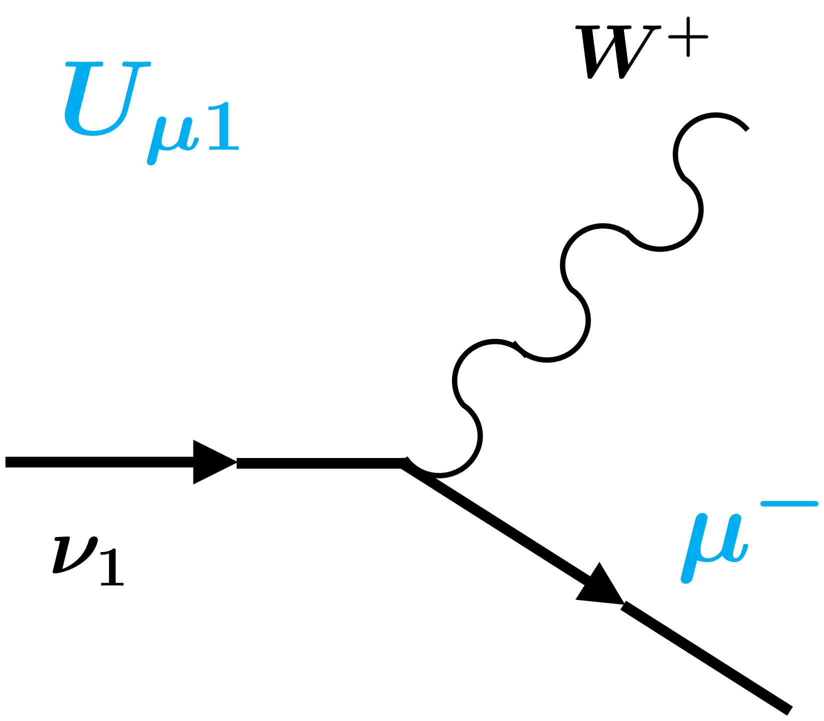
Leptons:



$$0.08 < |U_{\mu 1}|^2 < 0.24$$

variation in δ only !

Leptons:



$$0.08 < |U_{\mu 1}|^2 < 0.24$$

variation in δ only !

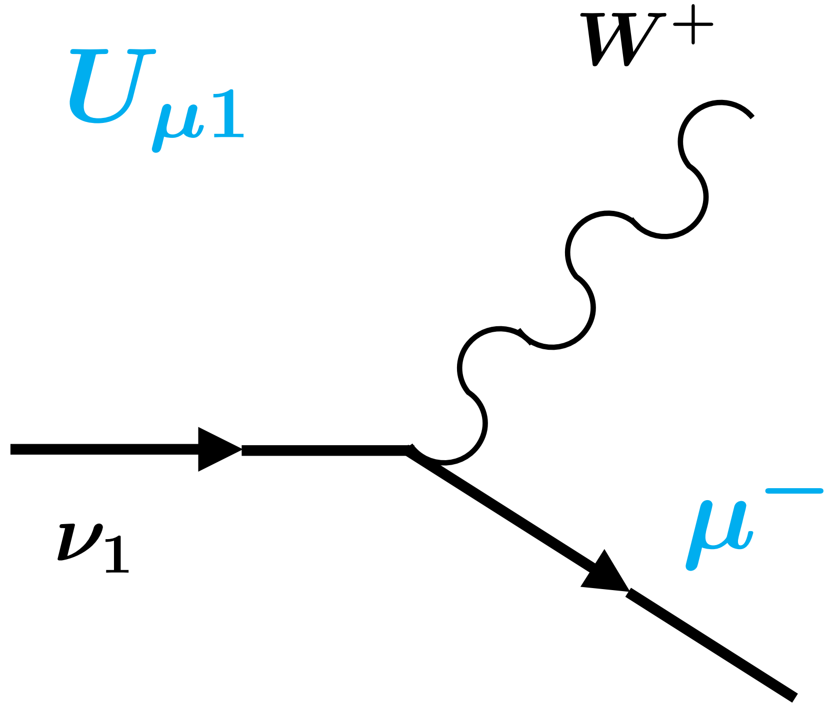
factor of 3 diff.

$$|U_{\mu 3}|^2 = 0.4 - 0.6$$
$$|U_{\mu 2}|^2 = 0.26 - 0.41$$
$$|U_{\mu 1}|^2 = 0.08 - 0.24$$

Leptons:

Quarks:

$|V_{ij}|^2$ essentially independent of δ_q !



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Leptons:

Quarks:

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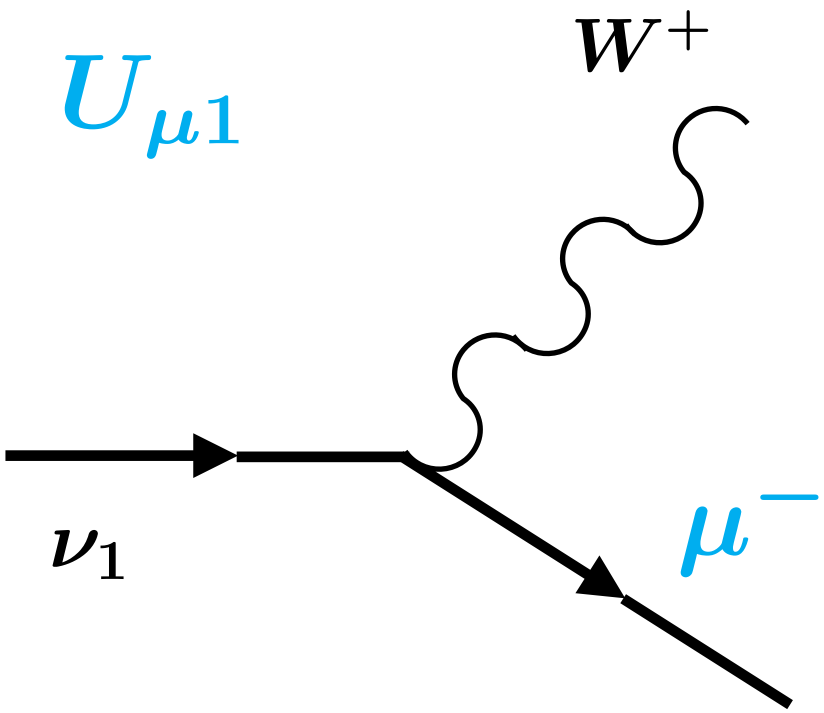
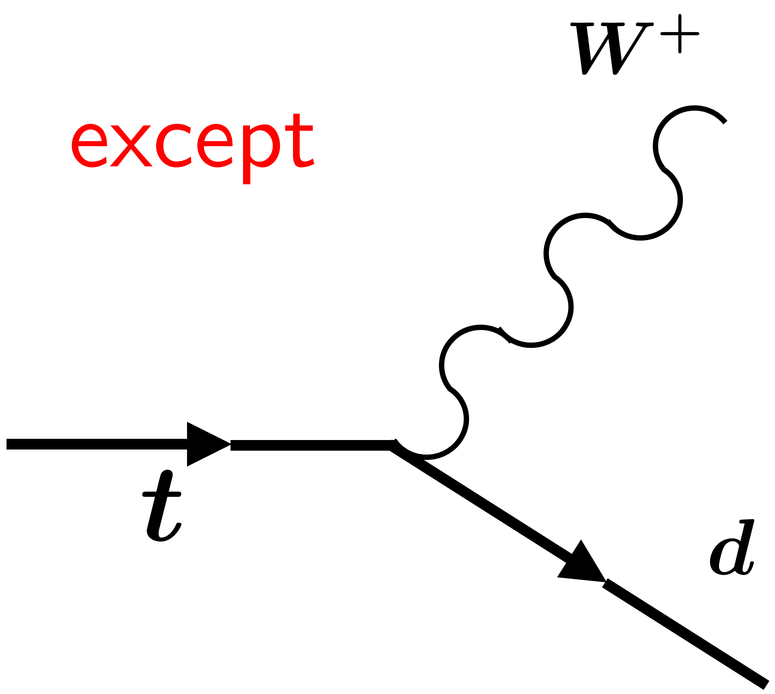
$U_{\mu 1}$



except



$$0.08 < |U_{\mu 1}|^2 < 0.24$$

variation in δ only !

$$V_{td} \approx A\lambda^3(1 - 0.37 e^{i\delta_q})$$

$$|V_{td}|^2 \approx 10^{-4}$$

factor of 3 diff.

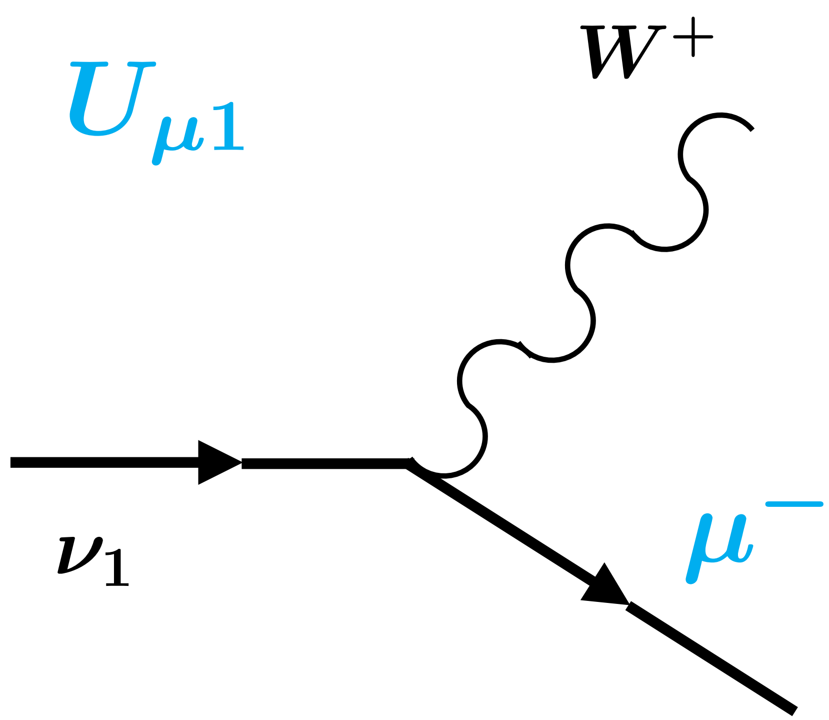
$$|U_{\mu 3}|^2 = 0.4 - 0.6$$
$$|U_{\mu 2}|^2 = 0.26 - 0.41$$
$$|U_{\mu 1}|^2 = 0.08 - 0.24$$

Leptons:

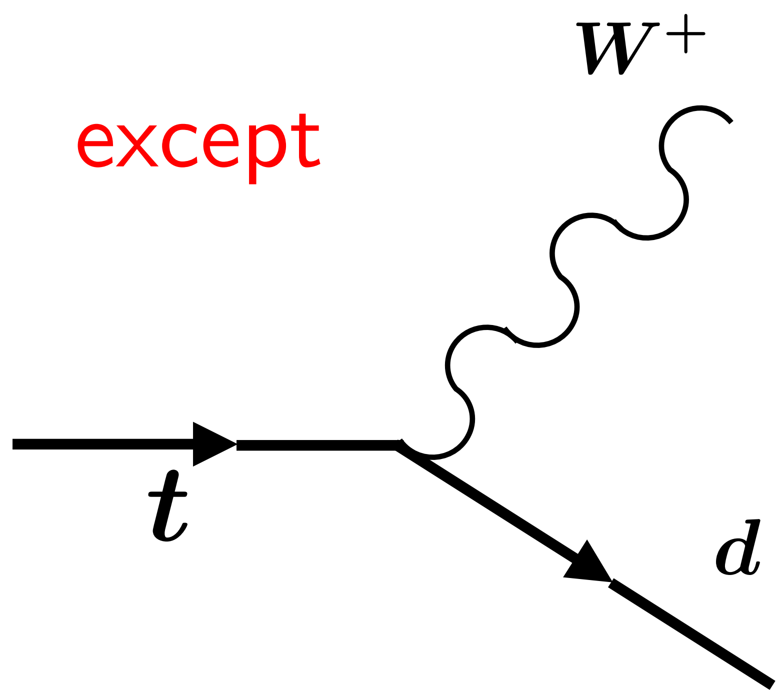
Quarks:

$|V_{ij}|^2$ essentially independent of δ_q !

$U_{\mu 1}$



except



$$0.08 < |U_{\mu 1}|^2 < 0.24$$

variation in δ only !

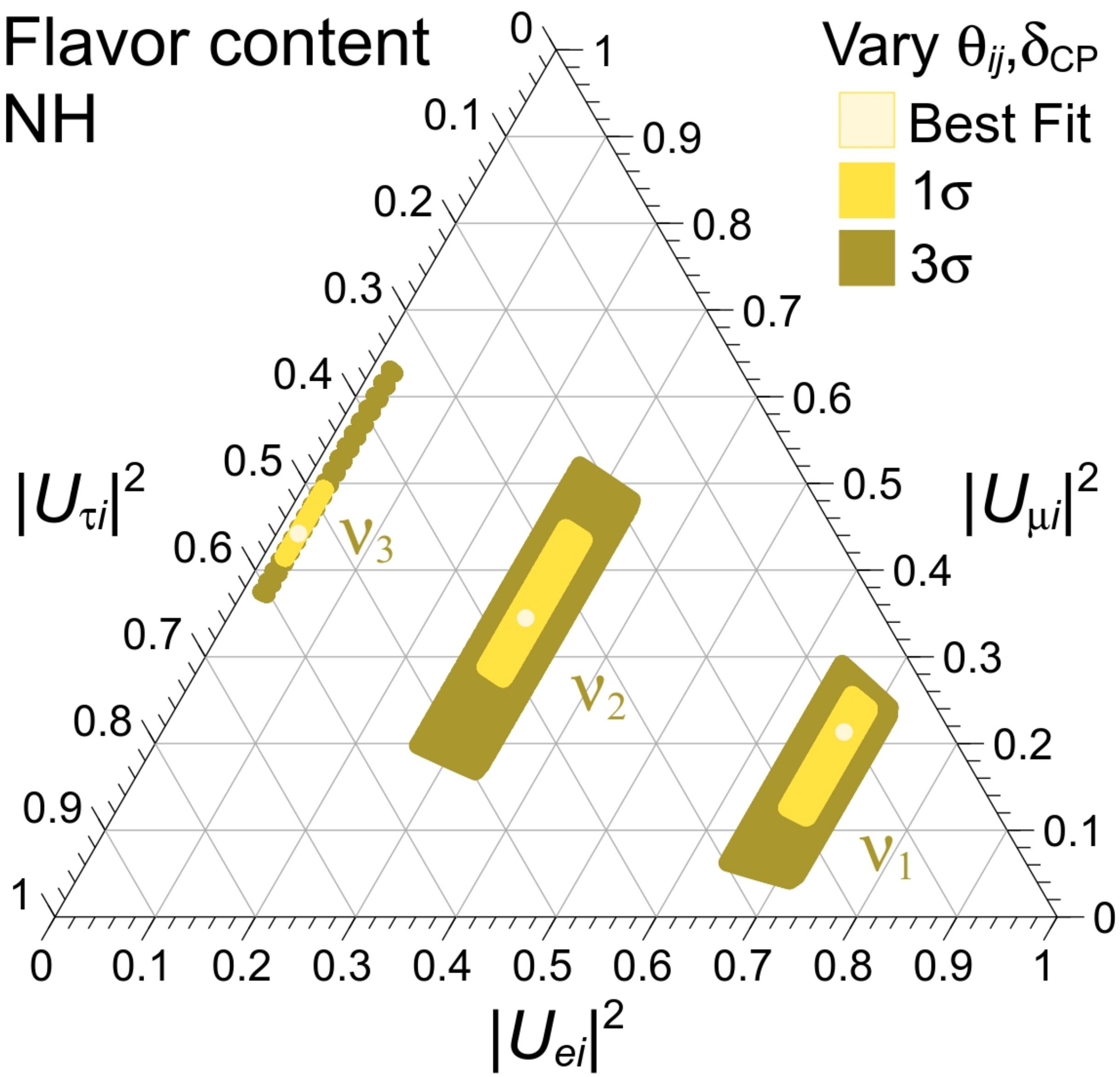
$$V_{td} \approx A\lambda^3(1 - 0.37 e^{i\delta_q})$$

$$|V_{td}|^2 \approx 10^{-4}$$

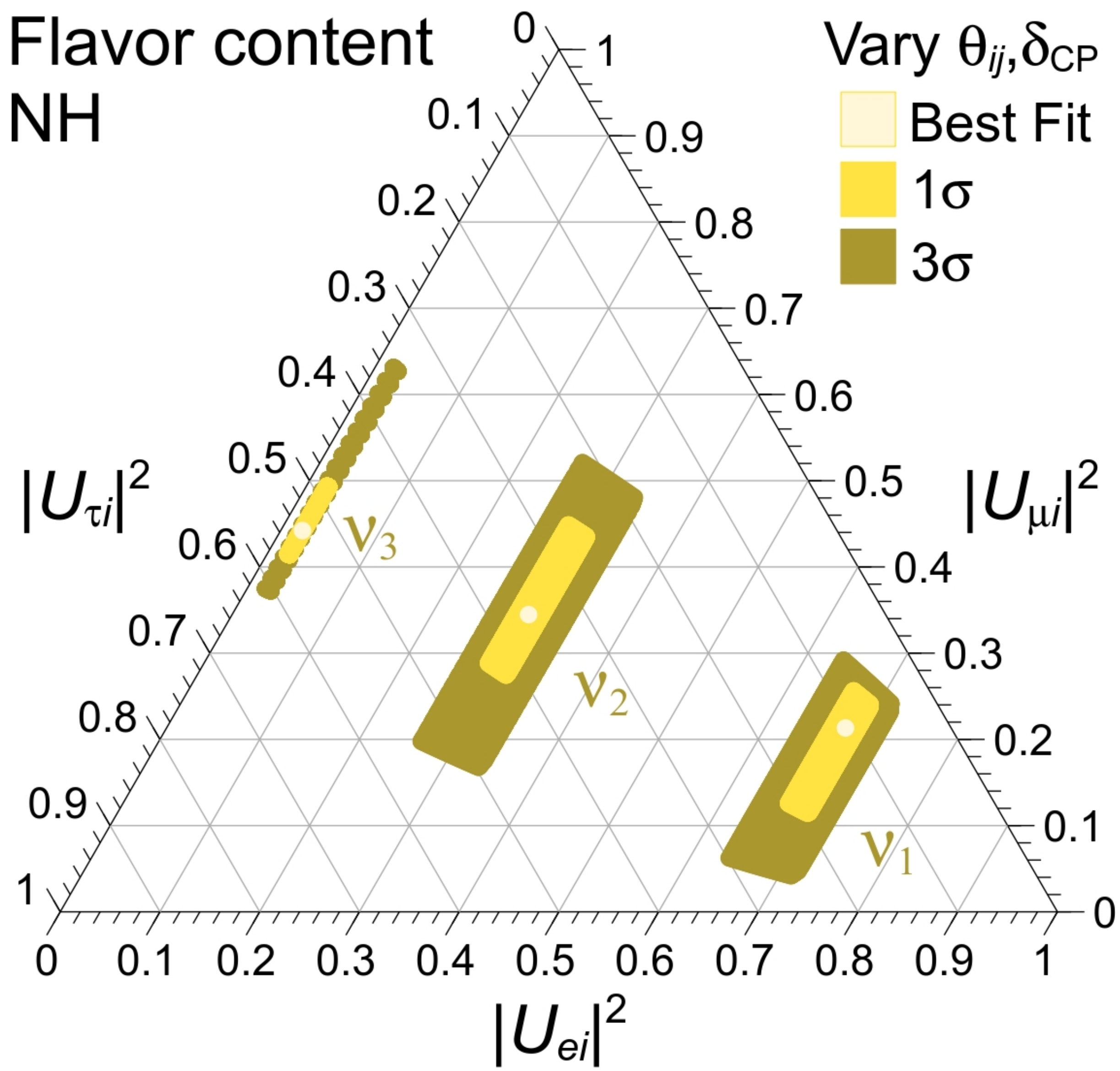
factor of 3 diff.

$$|U_{\mu 3}|^2 = 0.4 - 0.6$$
$$|U_{\mu 2}|^2 = 0.26 - 0.41$$
$$|U_{\mu 1}|^2 = 0.08 - 0.24$$

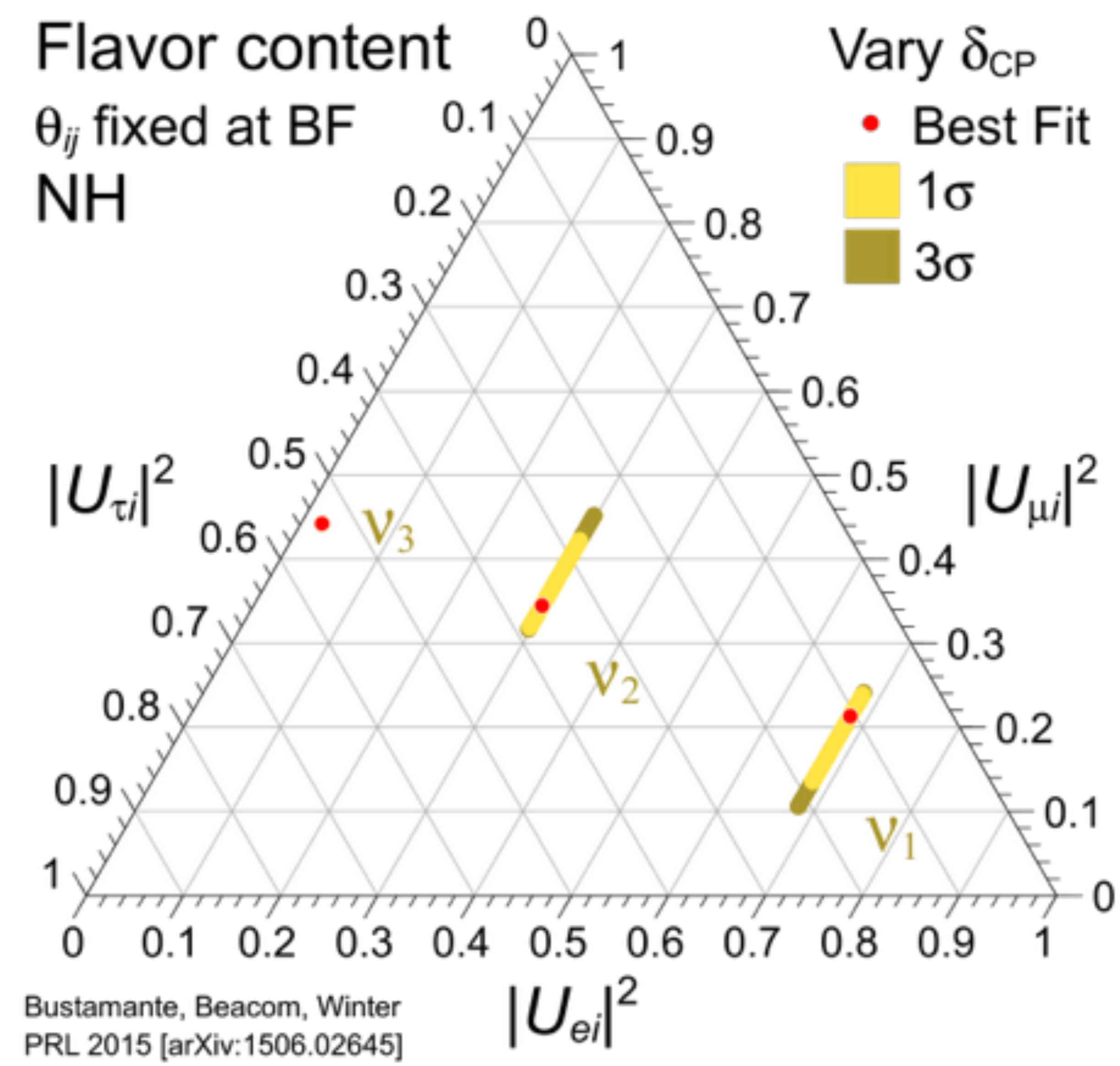
$$|V_{tb}|^2 \approx 1$$
$$|V_{ts}|^2 \sim \lambda^4 \approx 2 \times 10^{-3}$$
δ_q → $$|V_{td}|^2 \sim \lambda^6 \approx 8 \times 10^{-5}$$



δ & θ_{23} uncertainty



δ & θ_{23} uncertainty



no θ_{23} uncertainty

WHY?

Precision Neutrino Measurements:

WHY?

Precision Neutrino Measurements:

To discover neutrino BSM,
one needs precision predictions for nuSM

WHY?

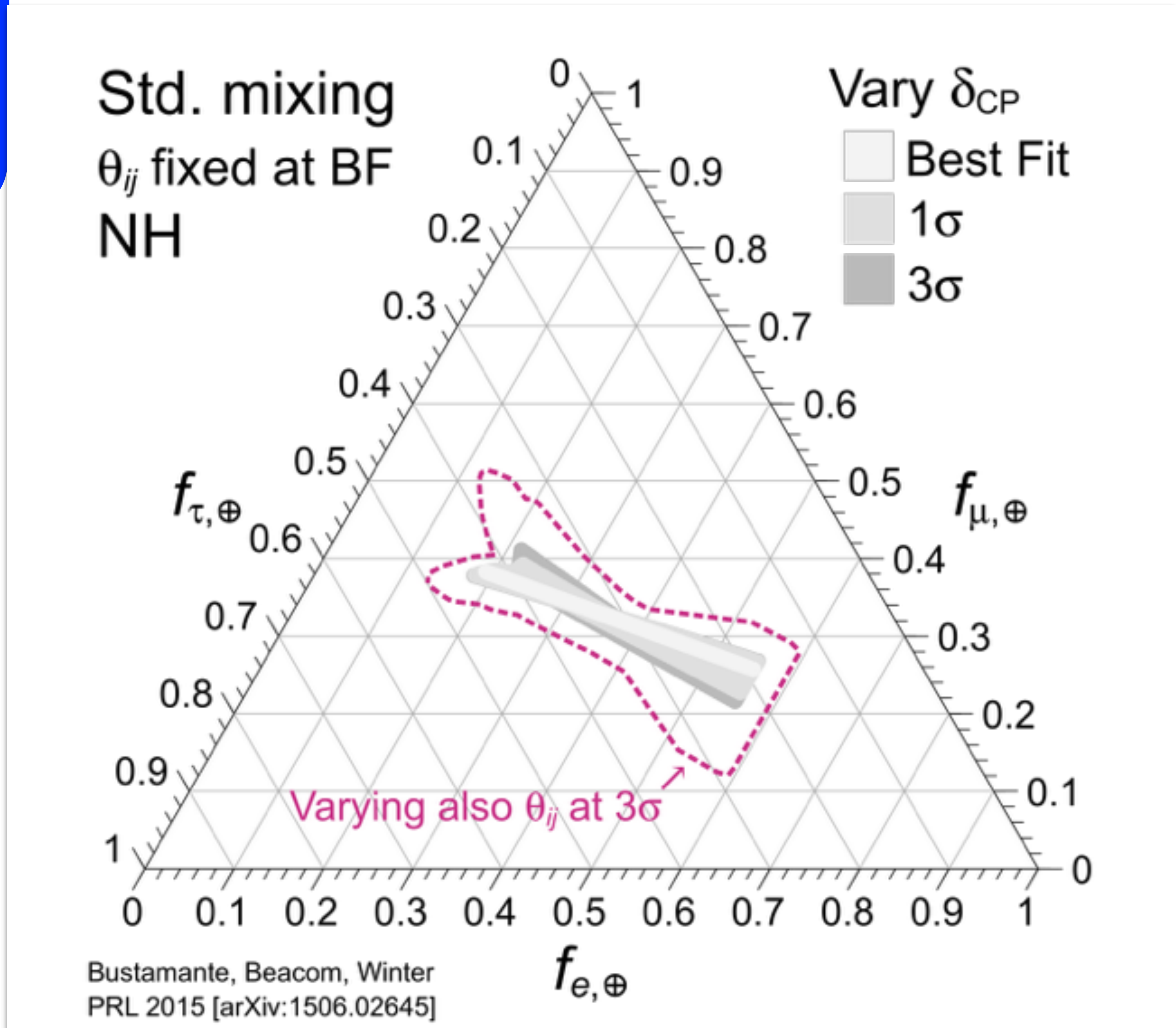
Determine flavor fractions of neutrino mass states

Precision Neutrino Measurements:

To discover neutrino BSM, one needs precision predictions for nuSM

Determine flavor fractions of neutrino mass states

Precision Predictions for flavor ratios at ICECUBE.



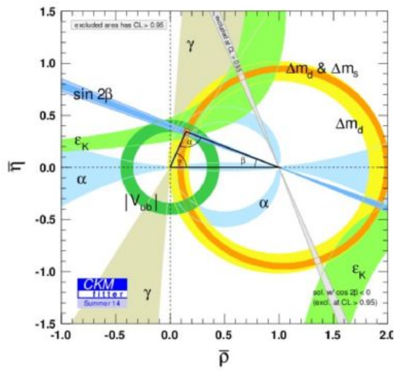
WHY?

Determine flavor fractions of neutrino mass states

Stress Test Neutrino paradigm search for new physics

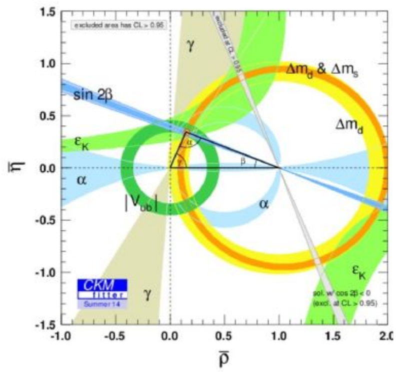
Precision Neutrino Measurements:

Quark



Stress Test
Neutrino paradigm
search for new physics

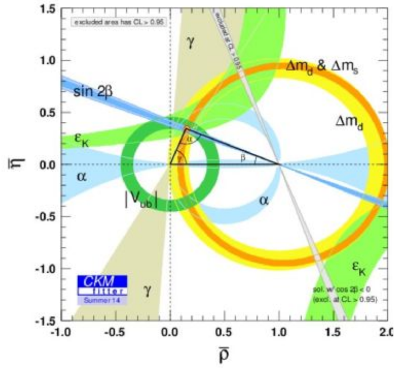
Quark



$A\lambda^3$

Stress Test
Neutrino paradigm
search for new physics

Quark



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Stress Test
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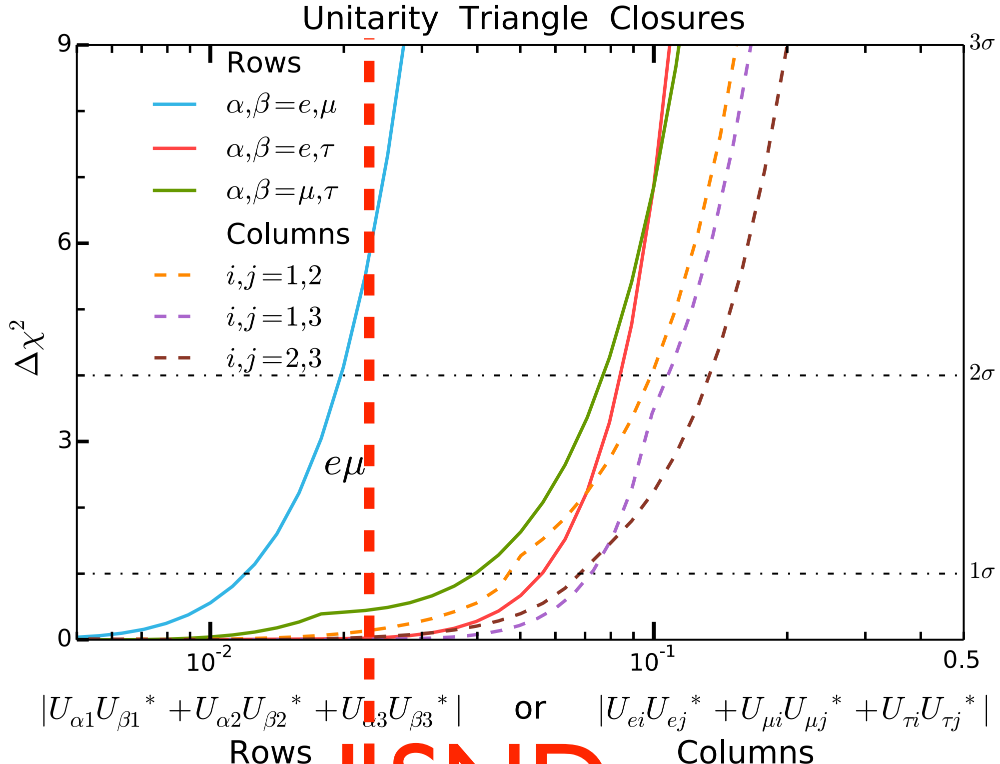
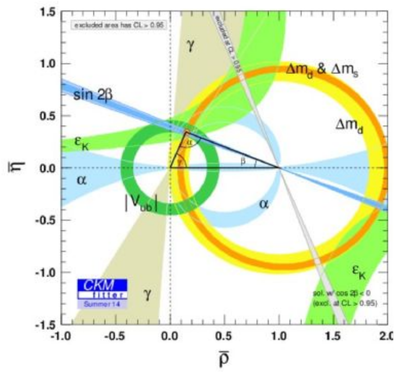


LSND

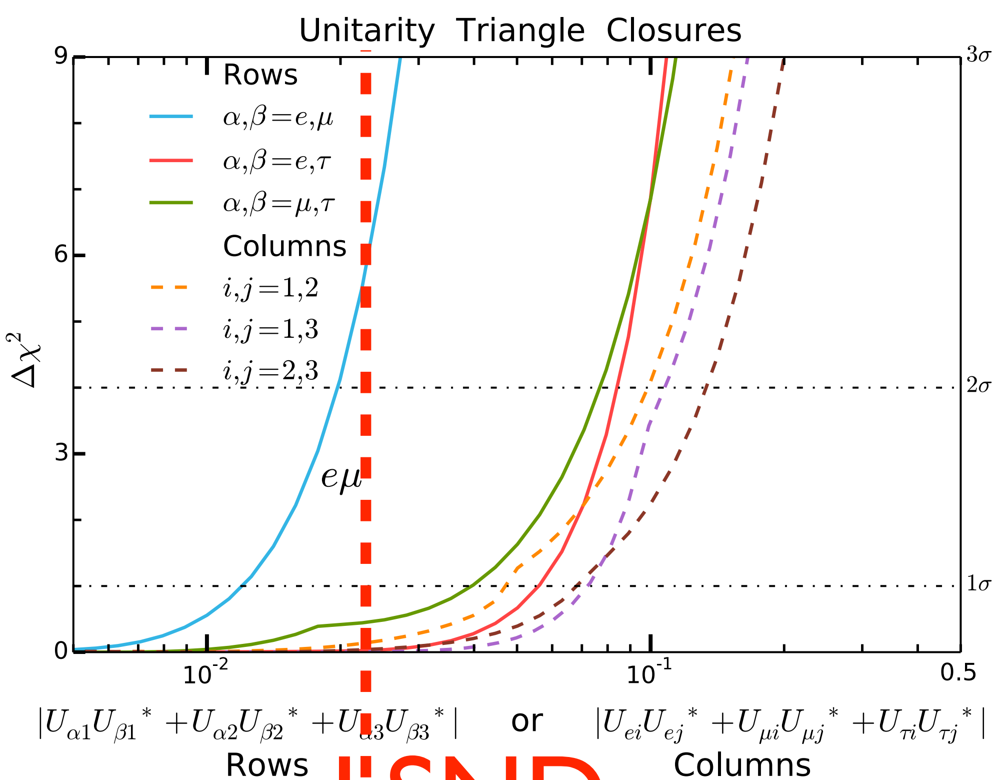
M. Ross-Lonergan + SP
arXiv:1508.05095

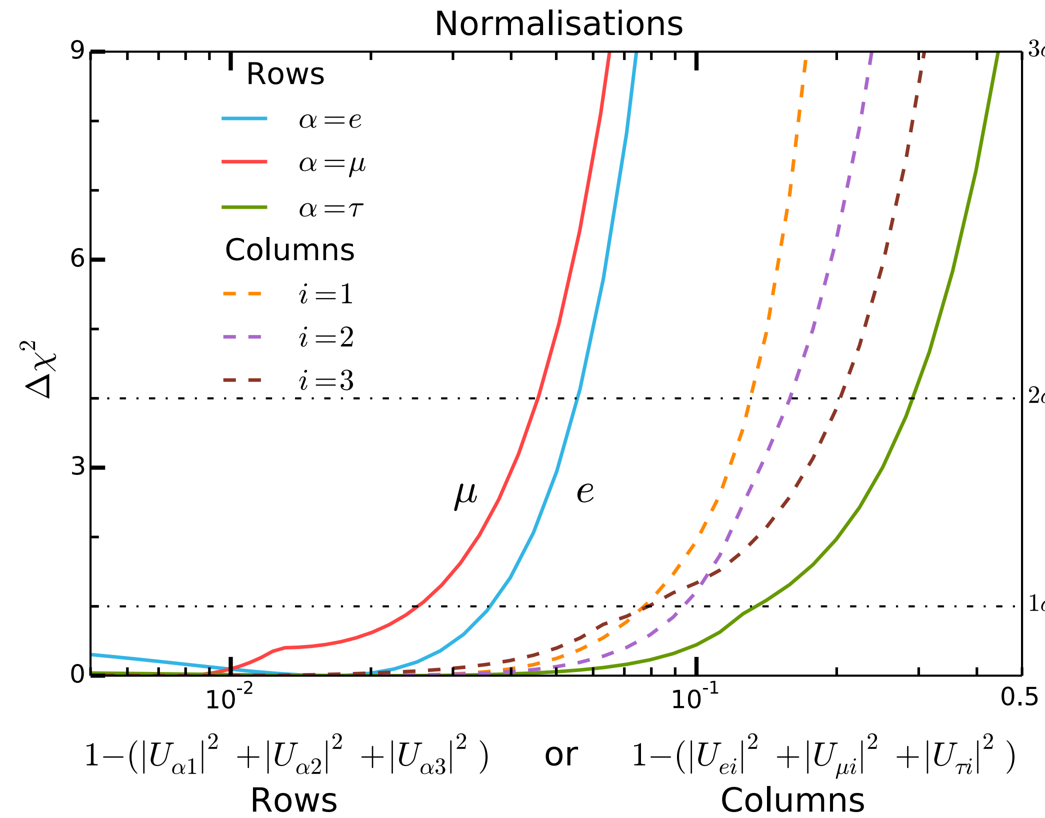
Quark



$A\lambda^3$

Stress Test
Neutrino paradigm
search for new physics





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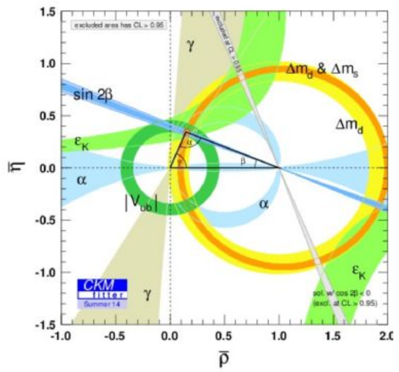
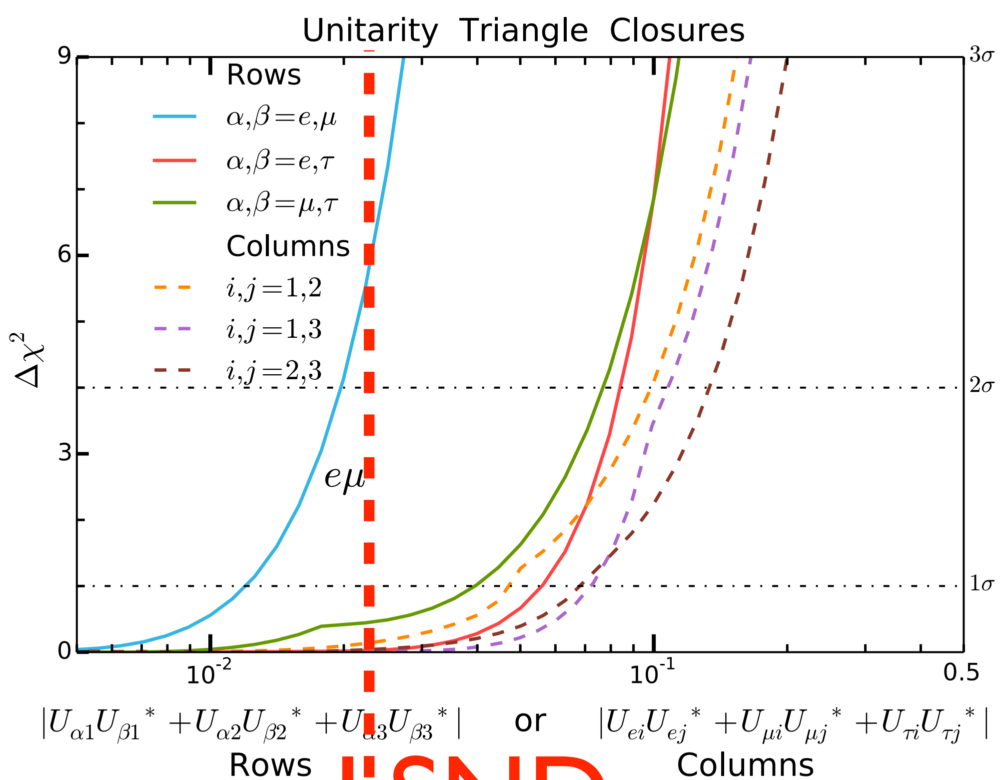


$A\lambda^3$

Stress Test
Neutrino paradigm
search for new physics



LSND

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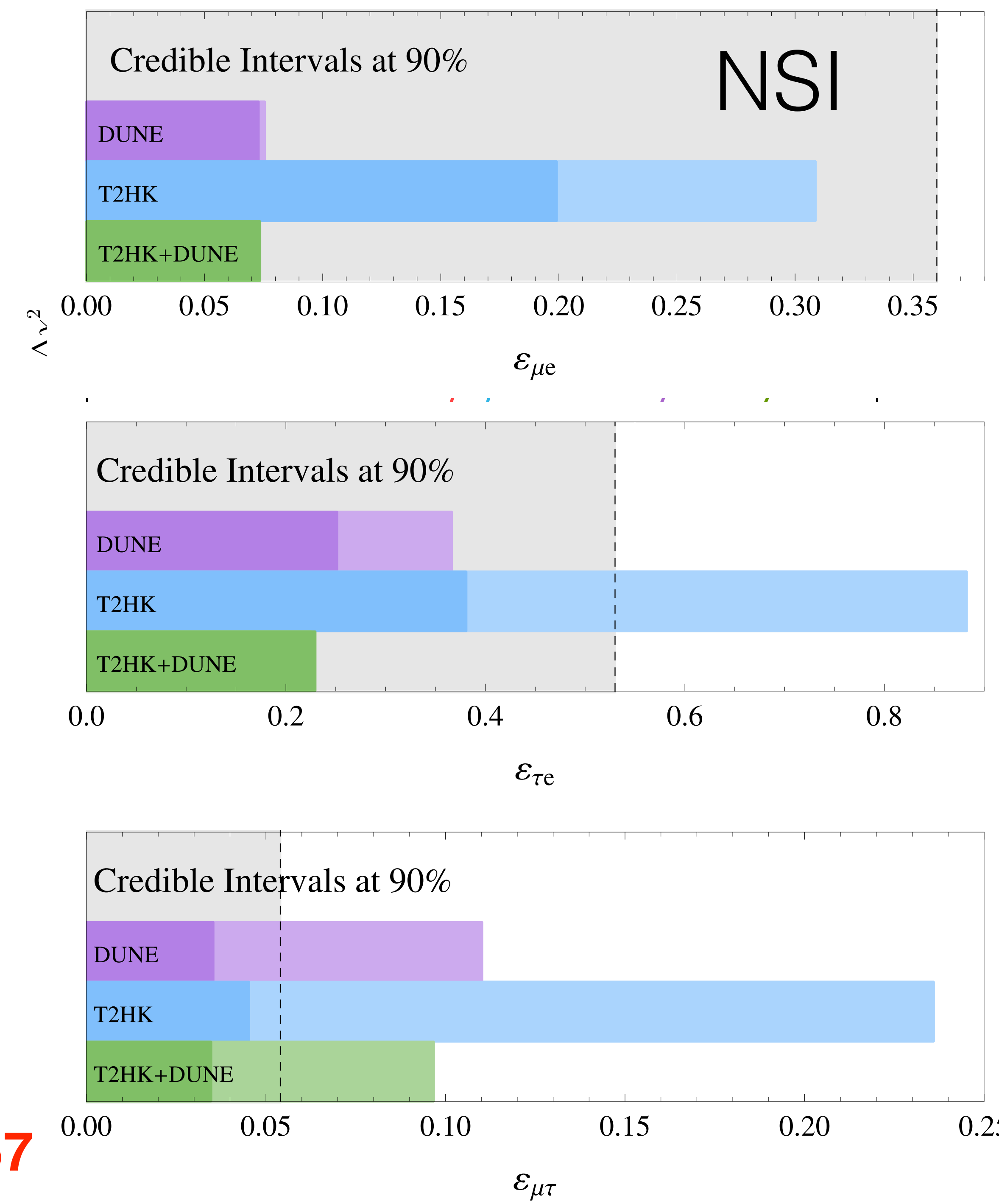
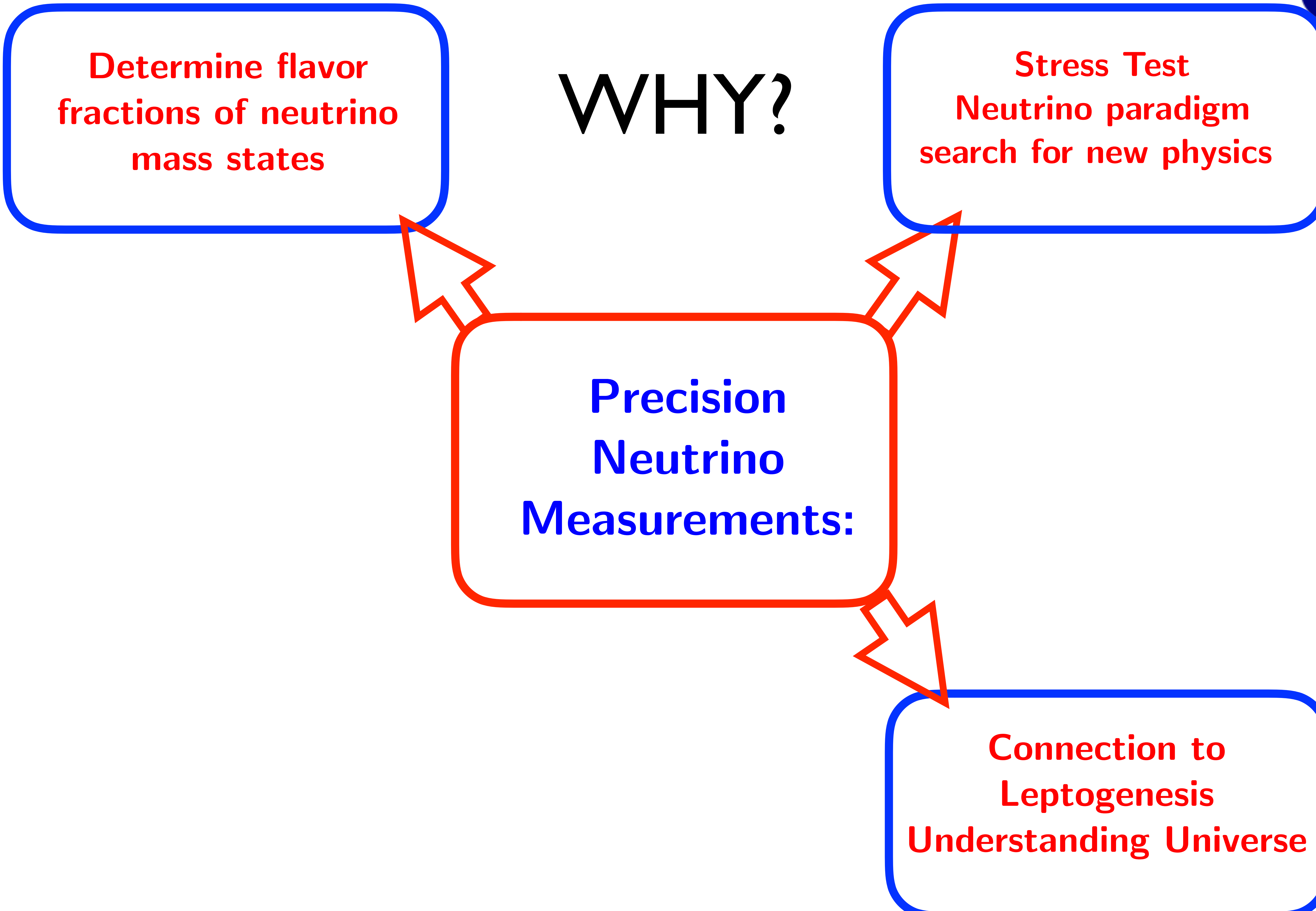


P.Coloma
arXiv:1511.06357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Determine flavor fractions of neutrino mass states
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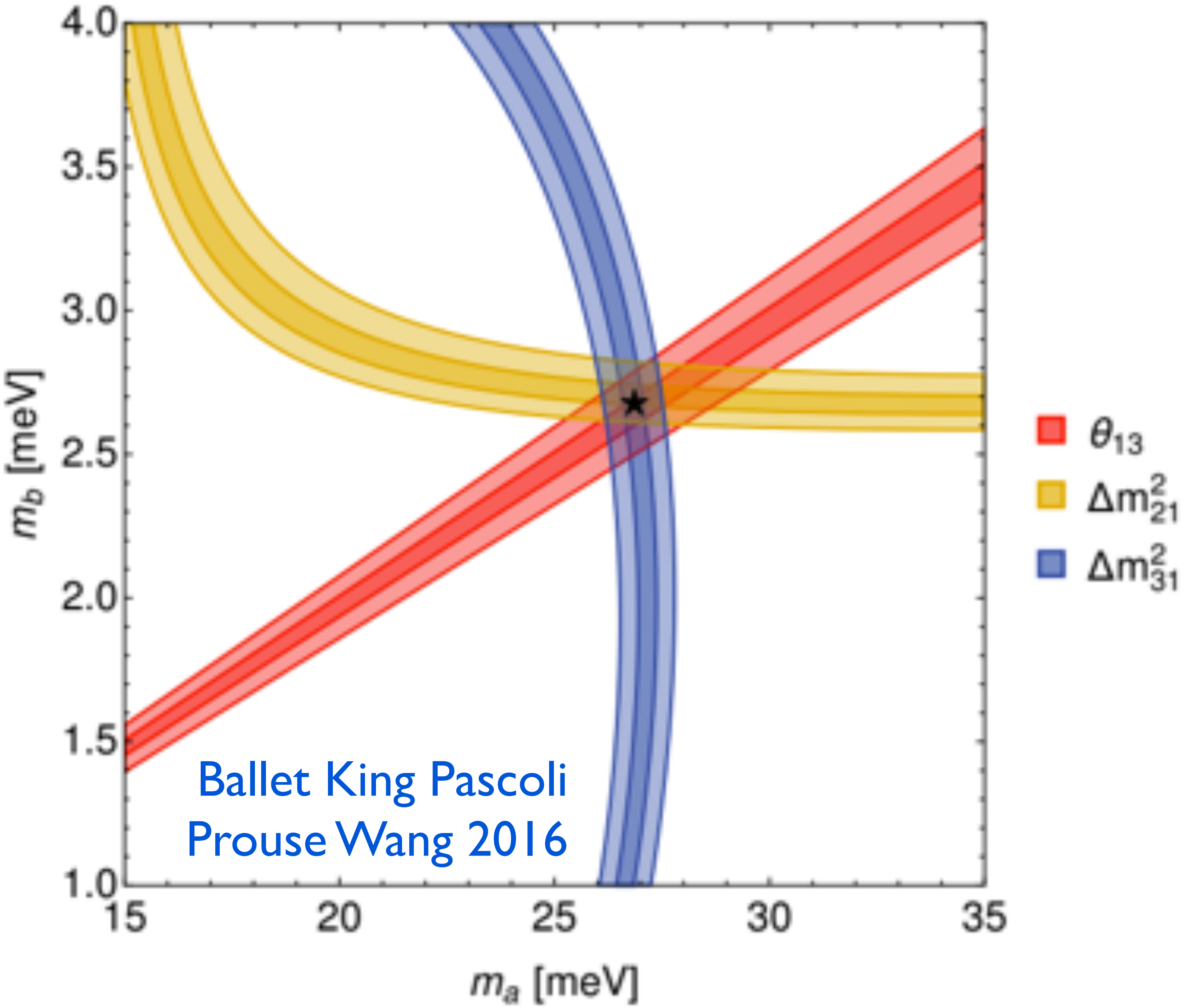
Precision Neutrino Measurements:
Connection to Leptogenesis Understanding Universe



Connection to
Leptogenesis
Understanding Universe

WHY?

Determine flavor fractions of neutrino mass states

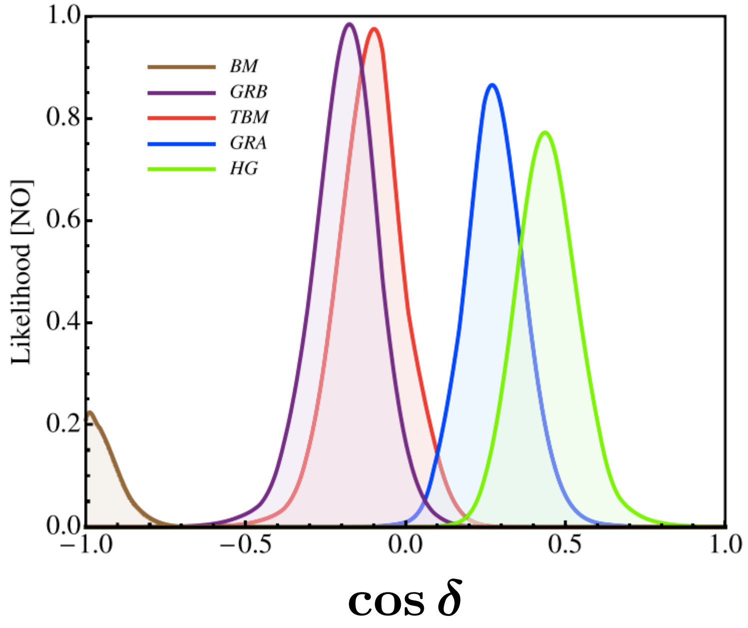
Stress Test Neutrino paradigm search for new physics

Precision Neutrino Measurements:

Test Theoretical Neutrino Models

Connection to Leptogenesis Understanding Universe

Predictions from flavor symmetry forms
with current measurement precision

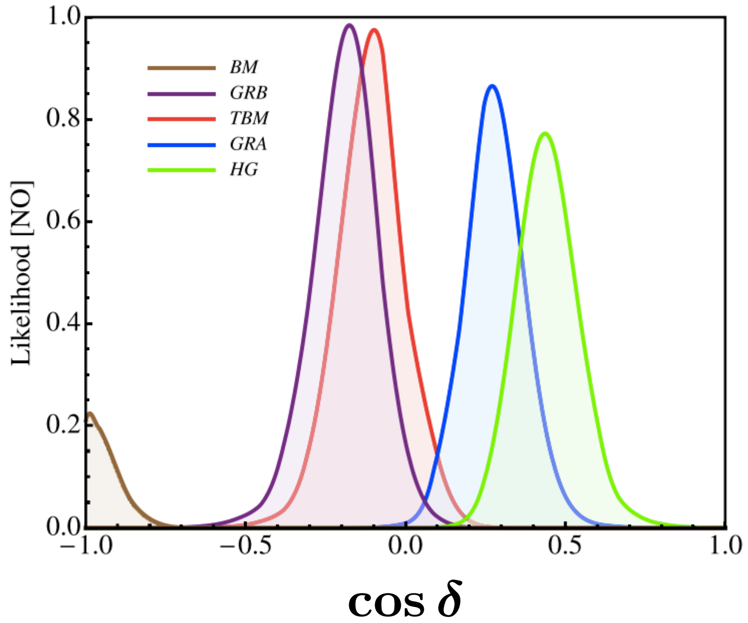


Test Theoretical Neutrino Models

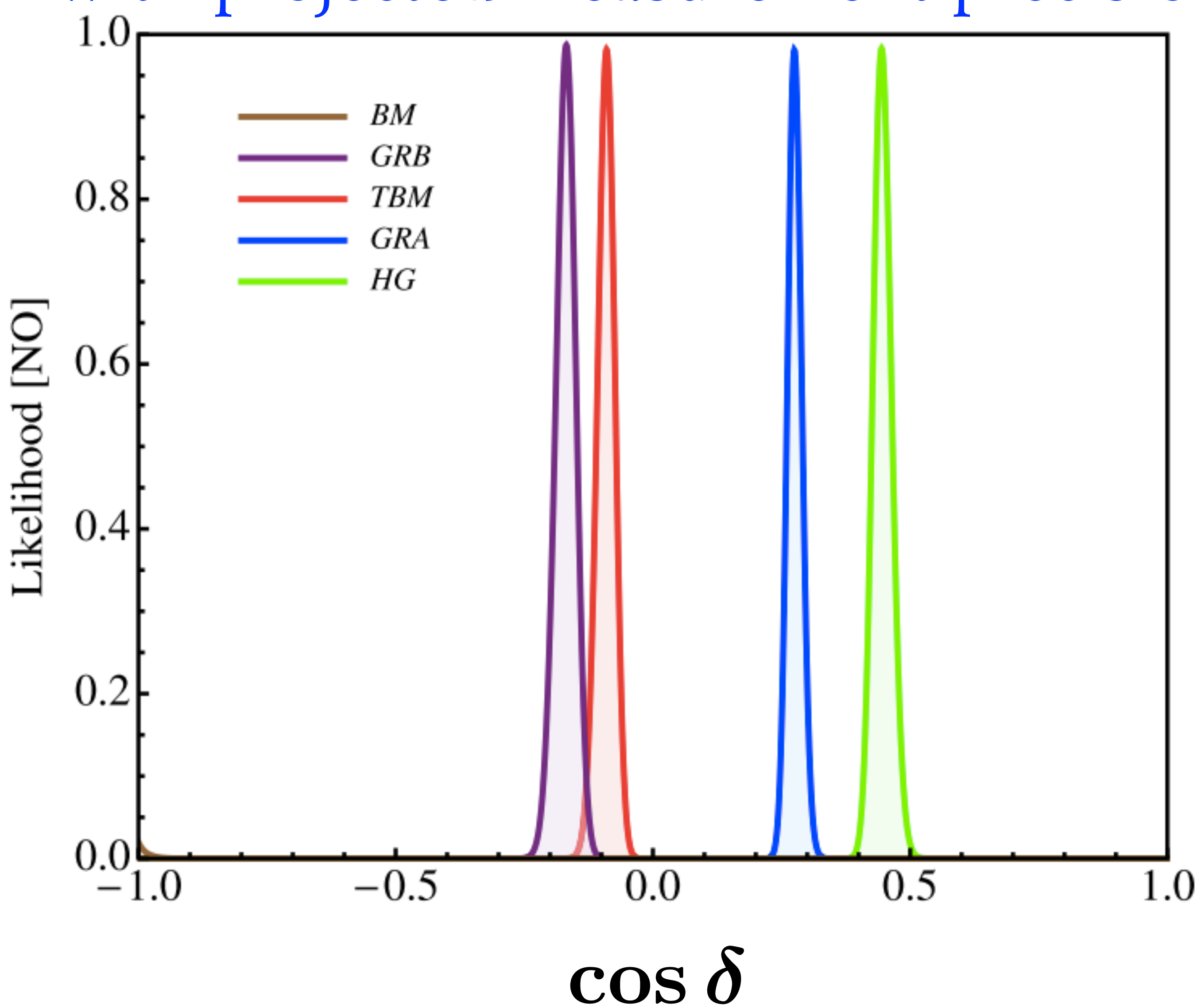
Girardi, Petcov, Titov, arXiv:1410.8056

Nucl. Phys. B, Vol. 894, 733-768 (2015)

Predictions from flavor symmetry forms
with current measurement precision



Predictions of flavor symmetry forms with projected measurement precision



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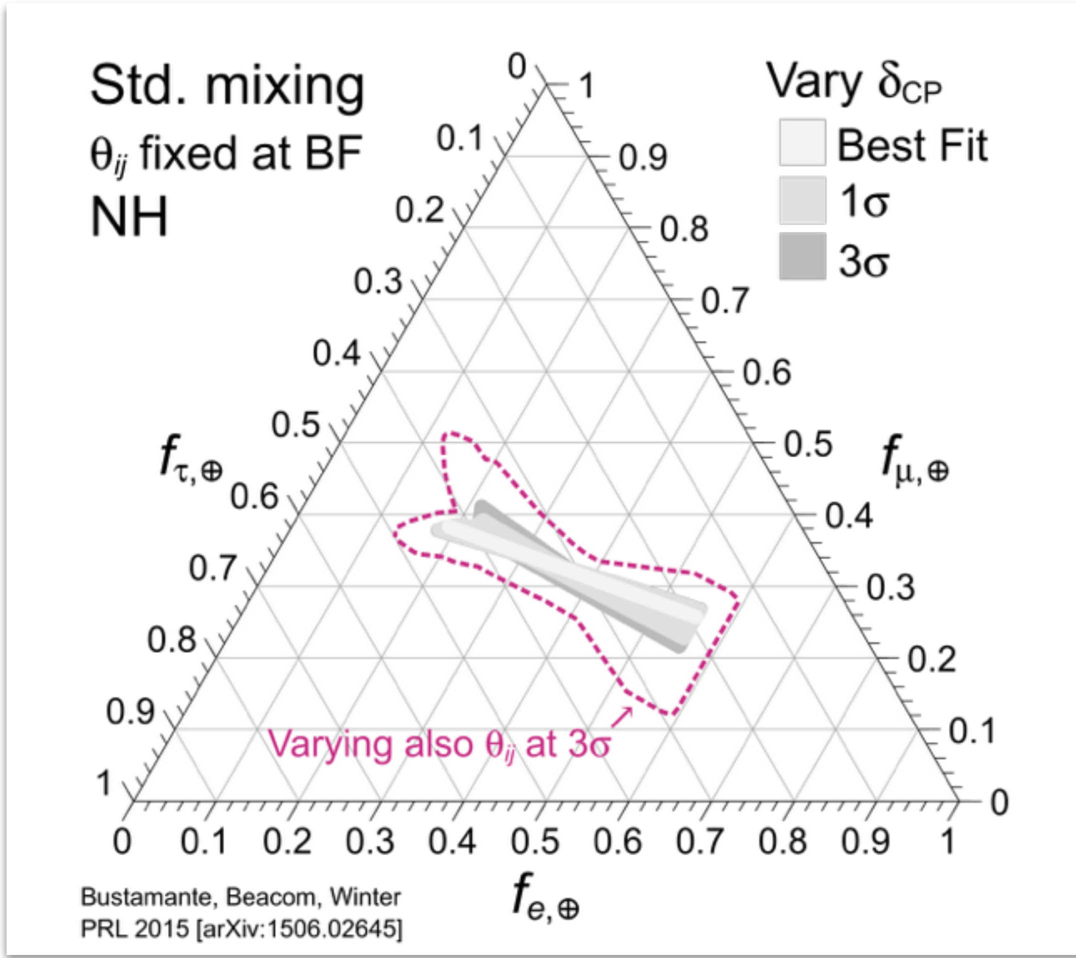
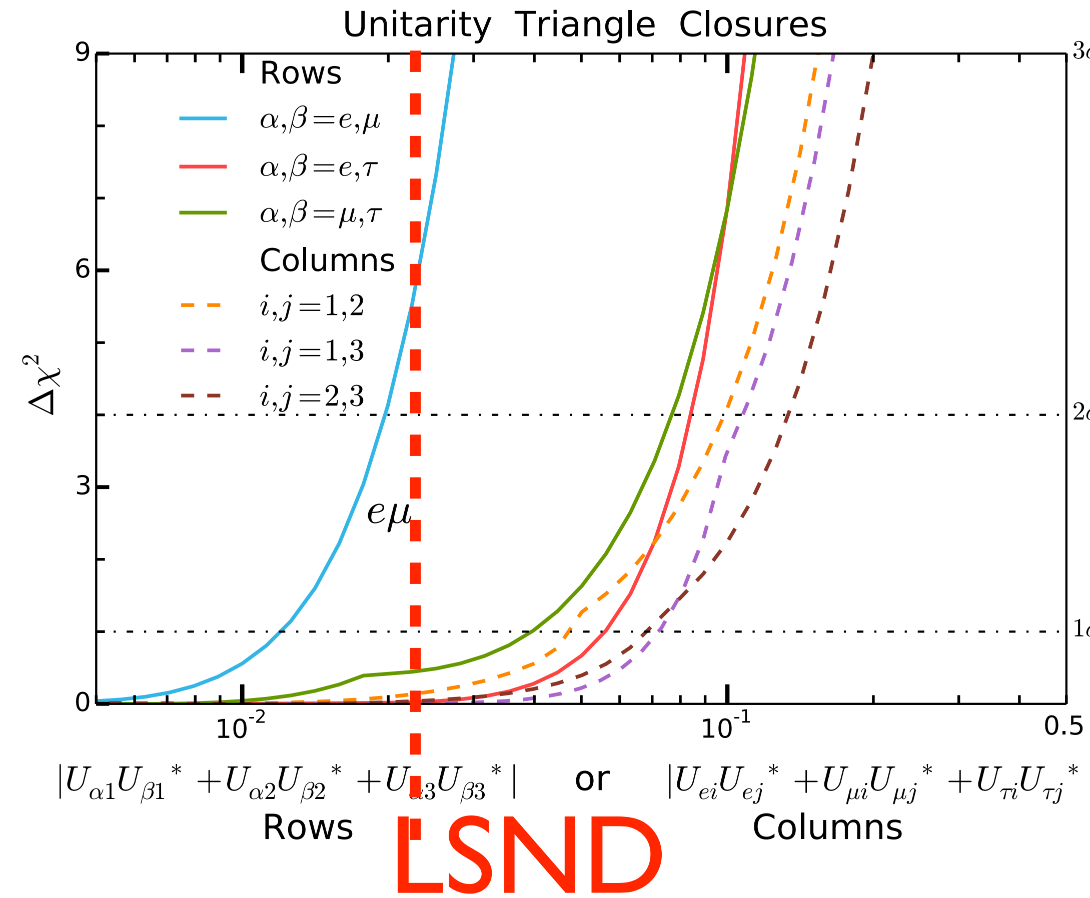
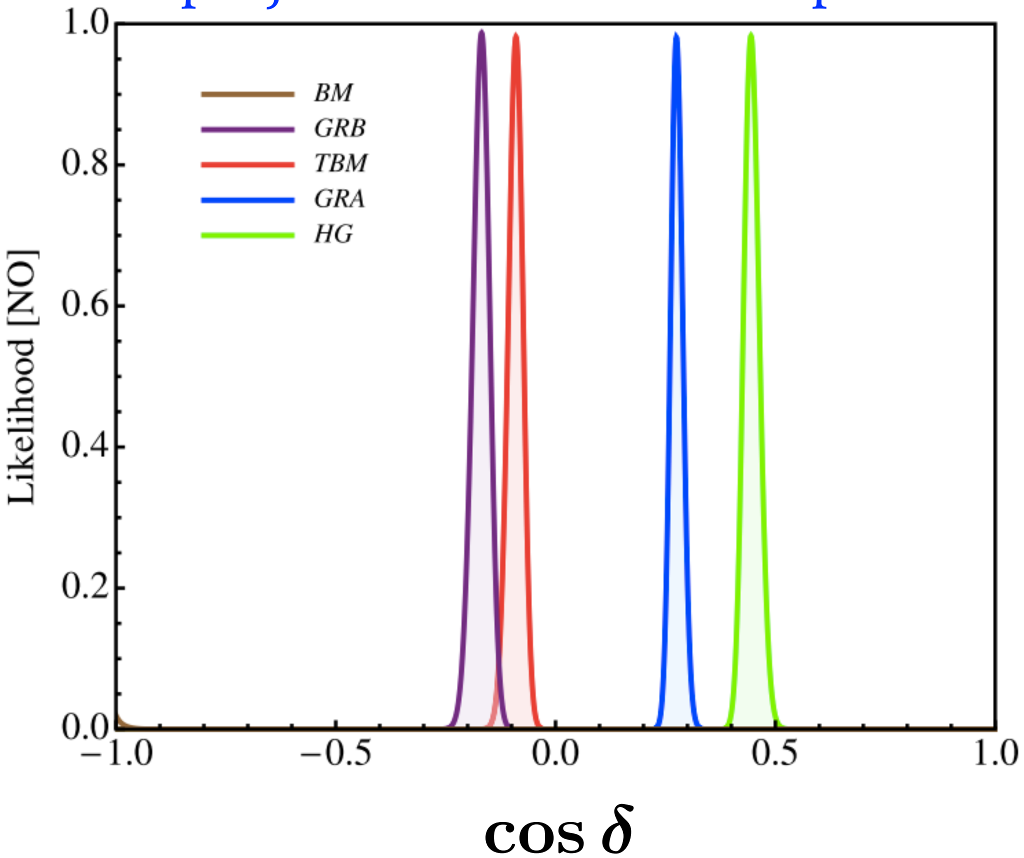
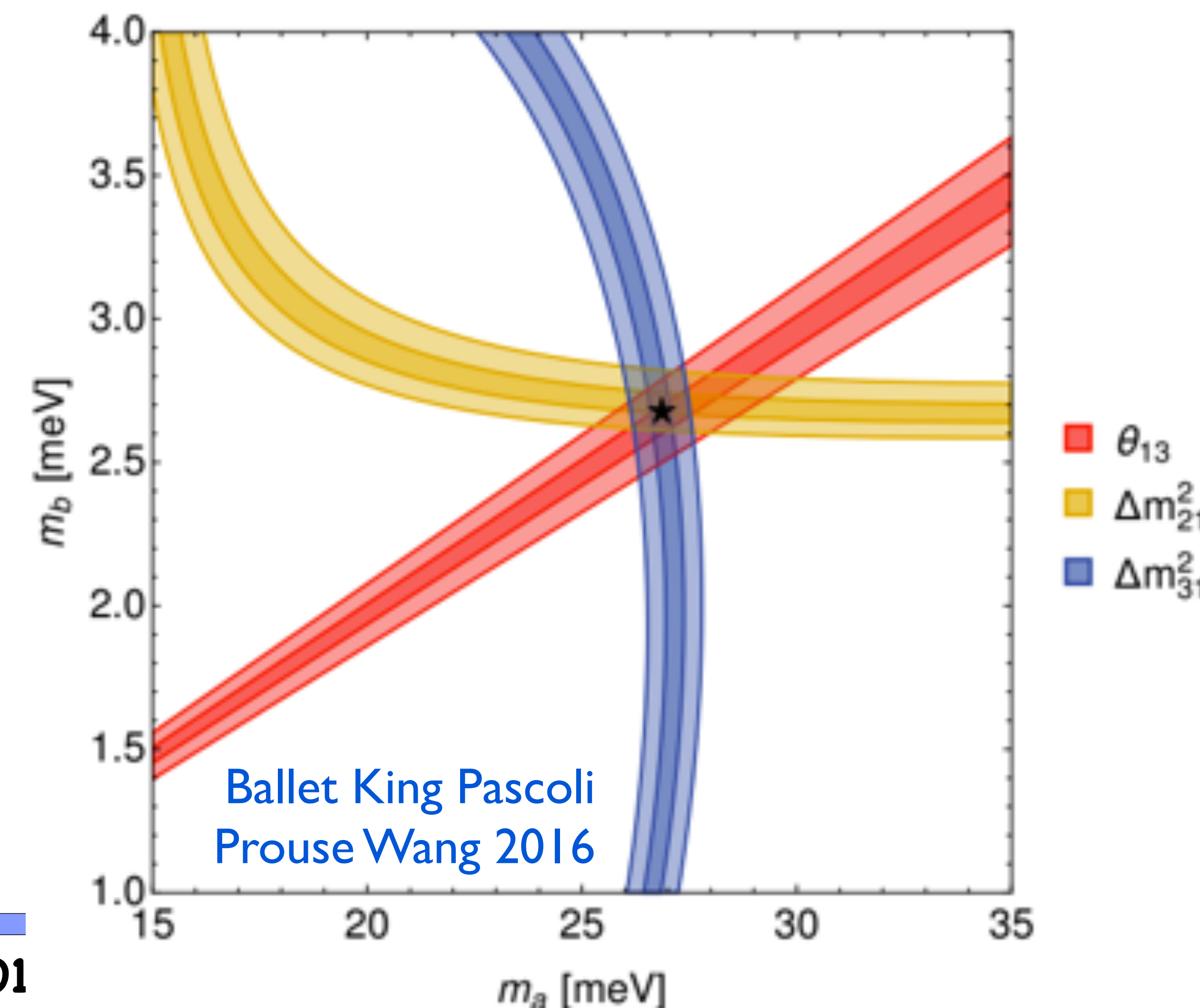




Predictions of flavor symmetry forms with projected measurement precision





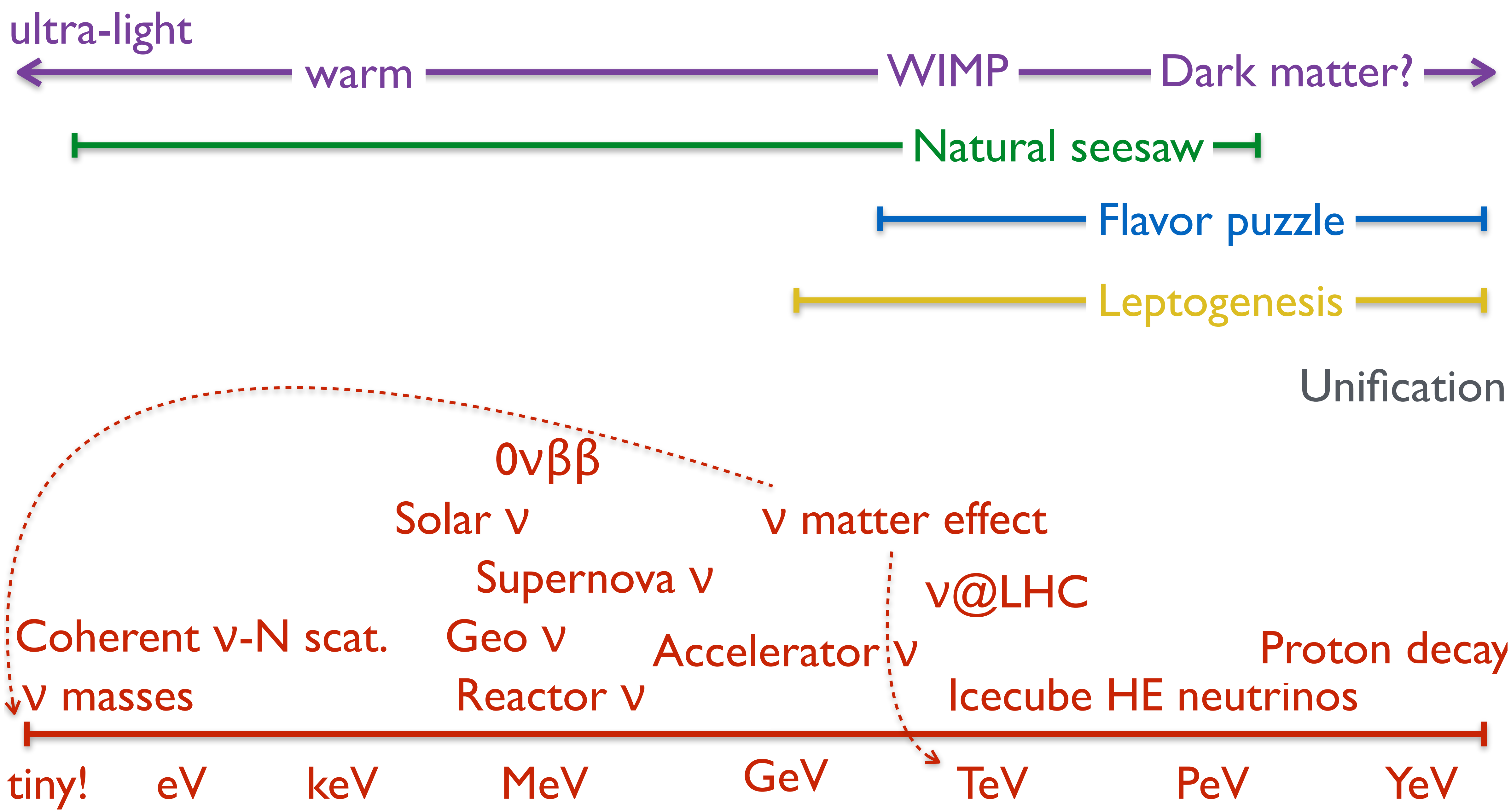
Recent highlights from neutrino theory

Pedro A. N. Machado
Fermilab *soon to be at LANL as junior staff member*

Aug/2017

pmachado@fnal.gov

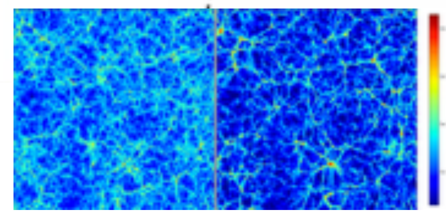
Neutrinos as a portal to new Physics



Many many many other fronts!

Neutrino cross sections
(NuSTEC effort)

Neutrinos in cosmology
Early universe - BBN
Abazajian, Barbieri, Cirelli, Chizov, Di Bari, Dodelson, Dolgov, Foot, Holanda, Iocco, Kirilova, Kusenko, Mangano, Lesgourges, Pastor, Smirnov, Steigman, Volkas



Secret neutrino interactions
Dasgupta Kopp 2013, Chu Dasgupta Kopp 2015, Lundkvist Archidiacono Hannestad Tram 2016, Ghalsasi McKeen Nelson 2016, Archidiacono Gariazzo Giunti Hannestad Hansen Laveder Tram 2016, Forastieri Lattanzi Mangano Mirizzi Natoli Saviano 2017

Supernova evolution: non-linear effects from collective oscillations

Friedland 2010, Cherry Carlson Friedland Fuller Vlaesnko 2012, Chakraborty Hansen Izaguirre Raffeelt 2016, Capozzi Basudeb Dasgupta 2016, Izaguirre Raffelt Tamborra 2016, Capozzi Dasgupta Lisi Marrone Mirizzi 2017

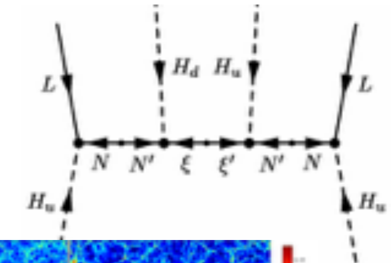
Chen Ratz Trautner 2015

Cosmic neutrino background: ideas to measure it?
Non-thermal component?

Type II, type III and radiative seesaw
Akhmedov, Bonnet, Babu, Barbieri, Barger, Berezhiani, Ellis, Gaillard, Glashow, Hirsch, Keung, Ma, Mohapatra, Ota, Pakvasa, Schechter, Senjanovic, Valle, Yanagida, Winter, Wolfenstein, Zee, and many others

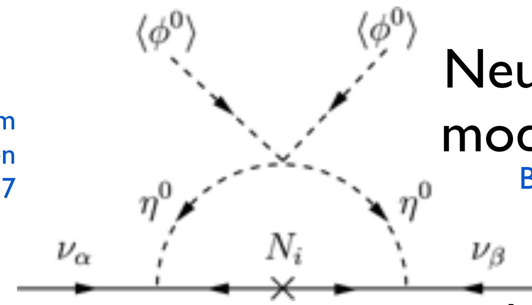
Flat extra dimensions: light sterile neutrinos
Antoniadis, Arkani-Hamed, Barbieri, Berryman, Davoudiasl, Dimopoulos, Dvali, de Gouvea, Langacker, Machado, Mohapatra, Nandi, Nunokawa, Perelstein, Peres, Perez-Lorenzana, Smirnov, Strumia, Tabrizi, Zukanovich-Funchal, …

Leptogenesis
Barenboim, Davidson, Di Bari, Dolgov, Fukugita, Kuzmin, Rubakov, Servant, Shaposhnikov, Yanagida, Zeldovich, …



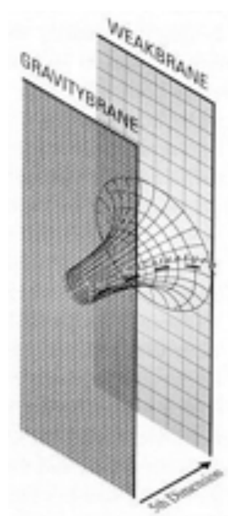
Sterile neutrino in long baseline oscillation experiments
Agarwalla, Bhattacharya, Chaterjee, Dasgupta, Dighe, Donini, Fuki, Klop, Lopez-Pavon, Meloni, Migliozzi, Palazzo, Ray, Tang, Terranova, Thalapillil, Wagner, Yasuda, Winter, …

Dark matter in neutrino detectors: light DM and light mediators
Ballett, Batell, Chen, Coloma, deNiverville, Dobrescu, Frugiuele, Harnik, McKeen, Pascoli, Pospelov, Ritz, Ross-Lonergan



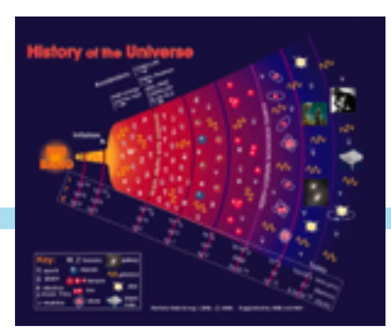
Neutrinos and the standard solar model: CNO cycle and metallicity
Bailey, Busoni, Christensen-Dalsgaard, Krief, Simone, Serenelli, Scott, Vincent, Vilante, Vissani, Vynioli, …

Neutrino magnetic moment
see e.g. Salam 1957, Barbieri Fiorentini 1988, Barbieri Mohapatra 1989, Babu Chang Keung Phillips 1992, Tarazona Diaz Morales Castillo 2015 Cañas Miranda Parada Tortola Valle 2015, Barranco Delepine Napsuciale Yebra 2017 Coloma Machado Martinez-Soler Shoemaker 2017



Discrete symmetries with non-zero θ_{13}
Feruglio Hagedorn Toroop 2011, Lam 2012, Lam 2013, Holthausen Lim Lindner2012, Neder King Stuart 2013, Hagedorn Meroni Vitale 2013 King Neder 2014, Ishimori King Okada Tanimoto 2014, Yao Ding 2015 , …

Effective operator approach to neutrino masses and collider/low scale pheno
de Gouvea Jenkins 2007, Boucenna Morisi Valle 2014, Nath Syed 2015, Geng Tsai Wang 2015, Chiang Huo 2015, Bhattacharya Wudka 2015, Geng Huang 2016, Quintero 2016, Mohapatra 2016, Kobach 2016



New physics in neutrinoless double beta decay, lepton number violation at the LHC, left-right models, RS models and neutrino masses, neutrinos as dark matter, and much more!

Fermilab

35

pmachado@fnal.gov

Towards a better understanding of Osc. Prob.

Towards a better understanding of Osc. Prob.

Globes,
while a very useful tool,
is not enough !

$\bar{\nu}_e \to \bar{\nu}_e$

- $P_{ee} \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$

$\Delta \equiv \Delta m^2 L/4E$

$+\ \mathcal{O}(0)$ $\quad \Delta m^2_{YY} \equiv \left(\frac{4E}{L}\right)\arcsin\left[\sqrt{(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}\right]$

OR

$+\ \mathcal{O}(10^{-4})$ $\quad \Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$

ν_e average !

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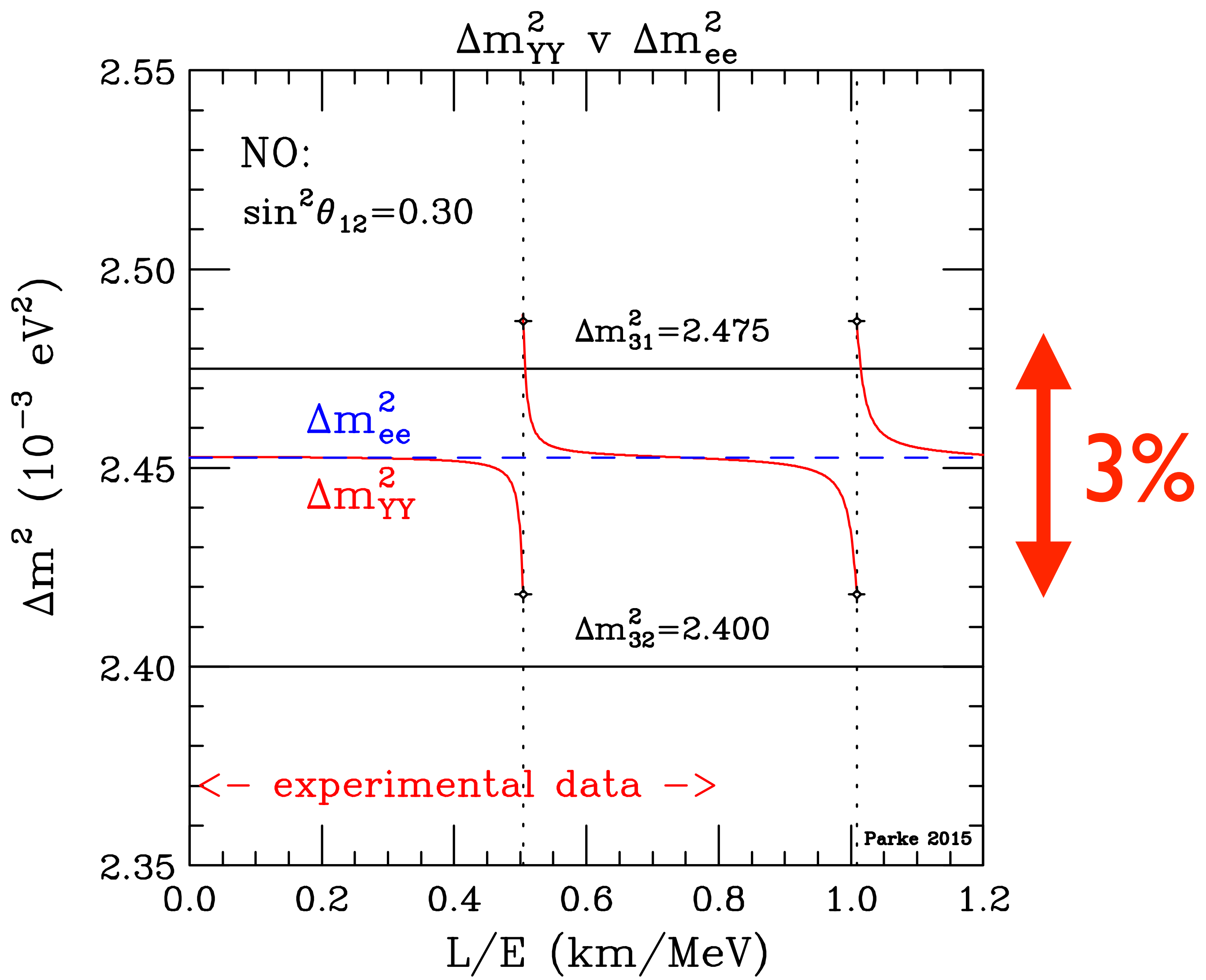

ν_e average !

H. Nunokawa, S. J. Parke and R. Zukanovich Funchal, "Another possible way to determine the neutrino mass hierarchy," Phys. Rev. D **72**, 013009 (2005), hep-ph/0503283

SP arXiv:1601.07464

$\nu_\mu \rightarrow \nu_\mu$

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \approx 4\,|U_{\mu 3}|^2\,(\,1 - |U_{\mu 3}|^2\,)\ \sin^2 \Delta_{\mu\mu}$$

Amplitude of Oscillation:

ν_μ average !

$$c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}$$

$$= \quad 4\, c_{13}^2 s_{23}^2\,(\,1 - c_{13}^2 s_{23}^2\,)$$

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for every $(s_{23}^2)_1$ point,

$$(s_{23}^2)_2 \;=\; 1/c_{13}^2 - (s_{23}^2)_1 \approx\; (1 + s_{13}^2) - (s_{23}^2)_1$$

has approx. same χ^2

and $(s_{23}^2)_1 + (s_{23}^2)_2 \;\approx\; (1 + s_{13}^2)$

Symmetry about $s_{23}^2 \approx \frac{1}{2}(1 + s_{13}^2) \approx 0.51$

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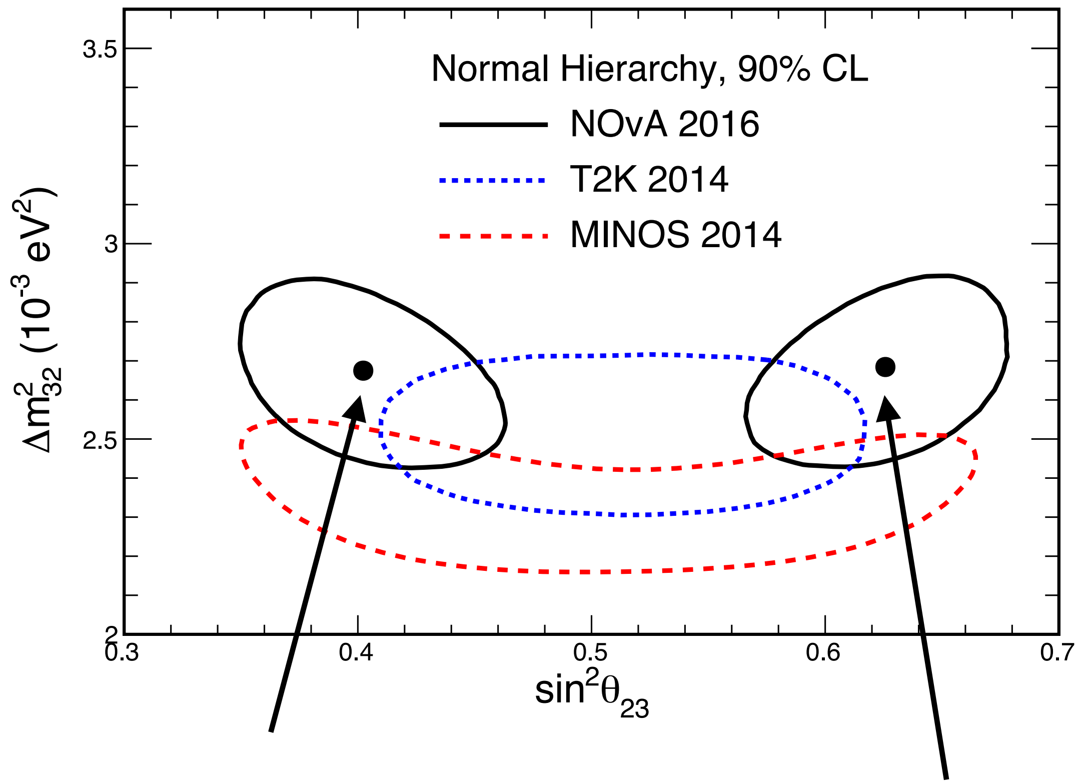

$(s_{23}^2)_1$ $(s_{23}^2)_2$

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Neutrino Oscillation Amplitudes

$$P(\nu_\alpha \rightarrow \nu_\beta) \quad = \quad |\mathcal{A}_{\alpha\beta}|^2$$

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Neutrino Oscillation Amplitudes

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Two Flavors:

$$\mathcal{A}_{\alpha\alpha} = 1 + (2i)\; s_\theta^2\; e^{+i\Delta}\; \sin\Delta$$

and $\mathcal{A}_{\alpha\beta} = (2i)\; s_\theta c_\theta\; e^{-i\Delta}\; \sin\Delta$

$$\Delta \equiv \Delta m^2 L/4E$$

Neutrino Oscillation Amplitudes

in vacuum:

"the billion \$ process"

$$P(\nu_\mu \to \nu_e) \quad = \quad |\mathcal{A}_{\mu e}|^2$$

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$$+\ (c_{23}c_{13}s_{12}c_{12})\ e^{i\delta}\ \sin\Delta_{21}\ ]$$

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maintain the symmetry: $m_1^2 \leftrightarrow m_2^2$ with $\theta_{12} \rightarrow \theta_{12} \pm \pi/2$

Denton, Minakata, SP arXiv:1604.08167

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$$\Delta P_{CP} = 8\,(s_{23}s_{13}c_{13})\,(c_{23}c_{13}s_{12}c_{12})\,\sin\delta\,\sin\Delta_{21}\,\sin\Delta_{31}\,\sin\Delta_{32}$$

Neutrino Oscillation Amplitudes in vacuum:

"the billion \$ process"

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$$\Delta_{32} \approx \Delta_{31}$$

$$\mathcal{A}_{\mu e} \approx (2i)\,[\,(s_{23}s_{13}c_{13})\,\sin\Delta_{31} + (c_{23}c_{13}s_{12}c_{12})\,e^{i(\delta+\Delta_{31})}\sin\Delta_{21}\,]$$

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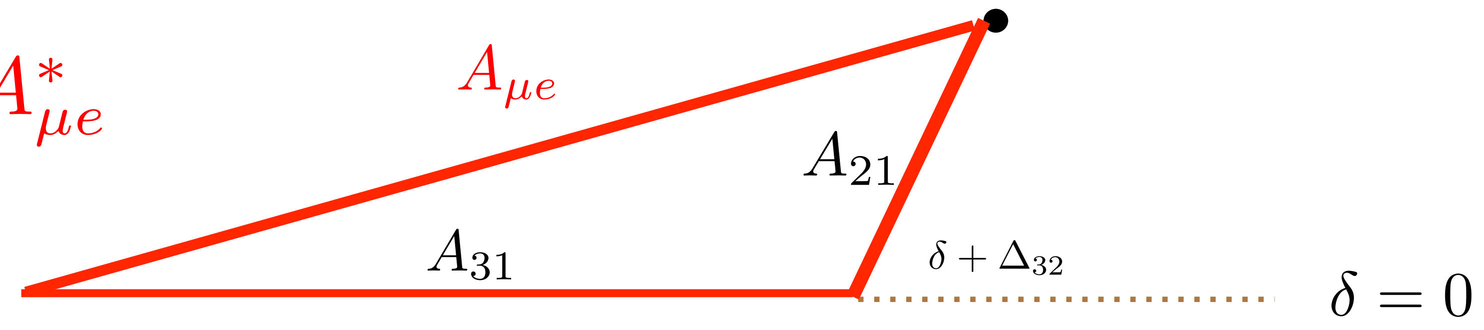

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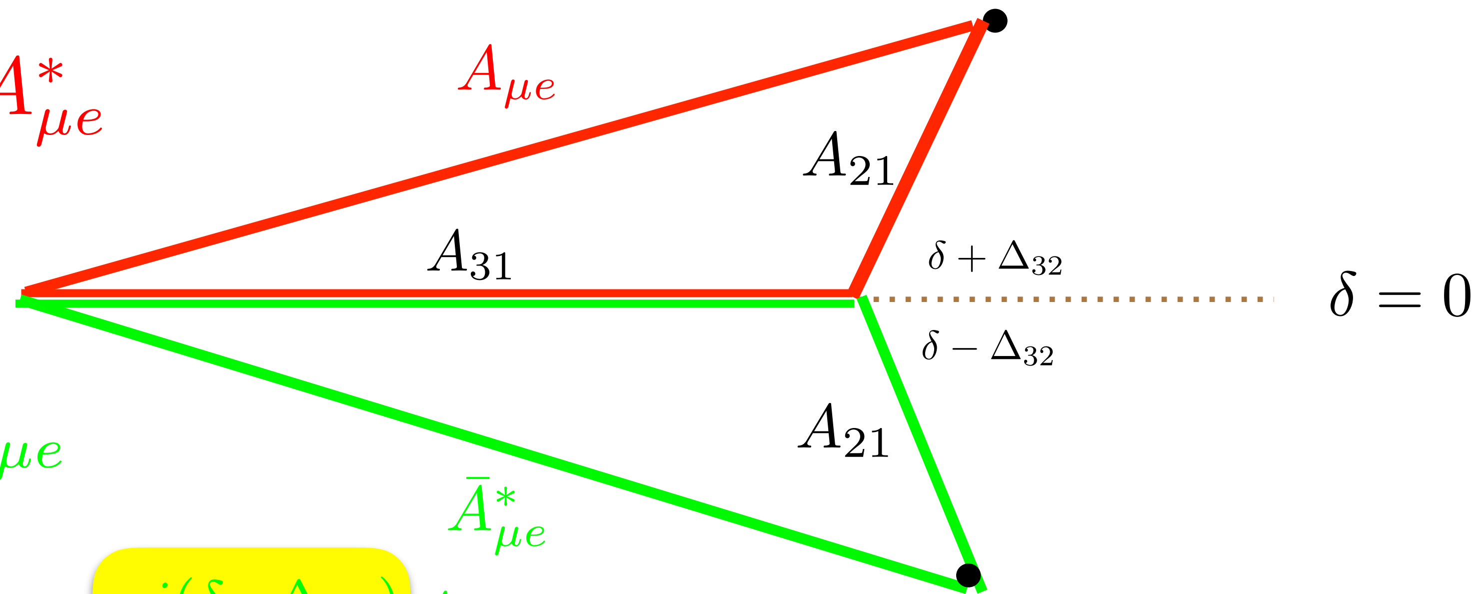

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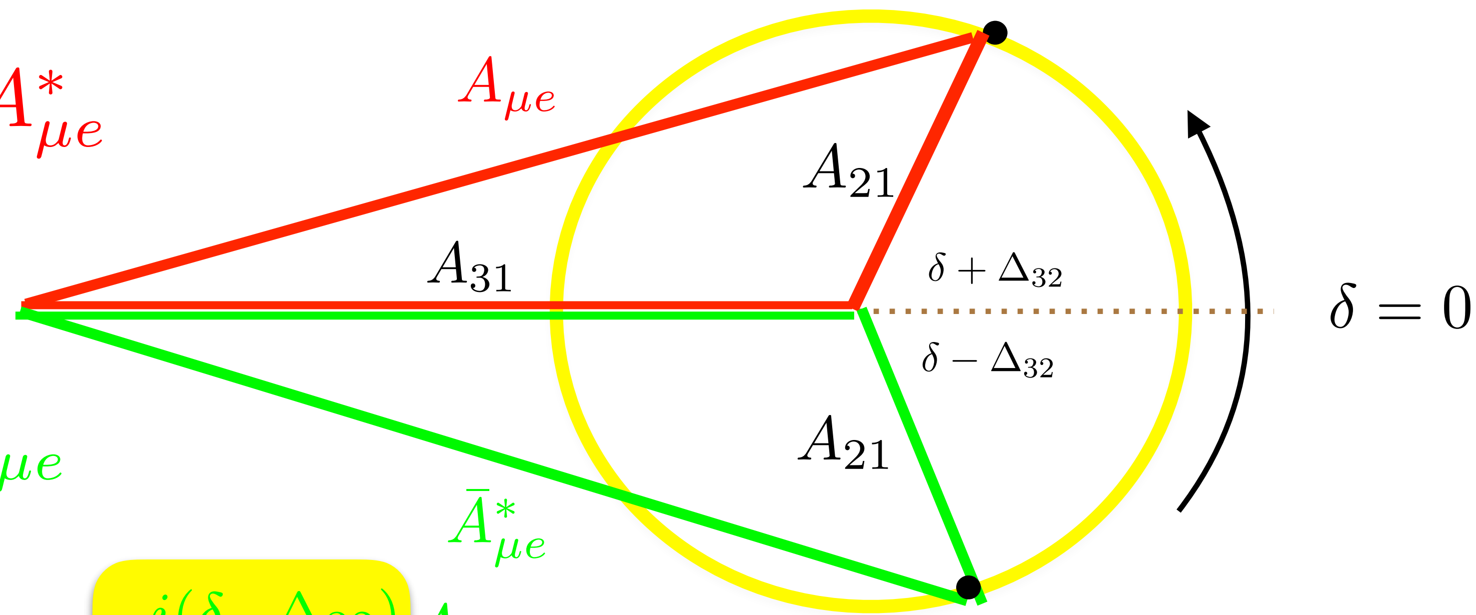

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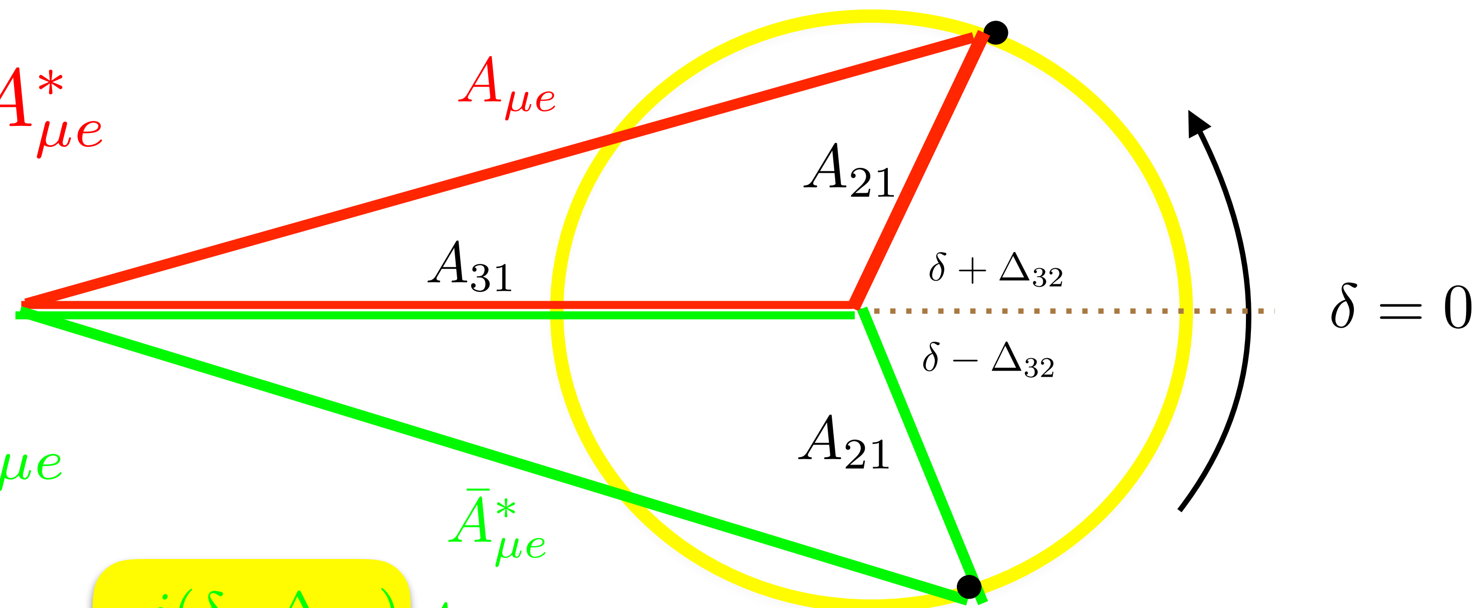

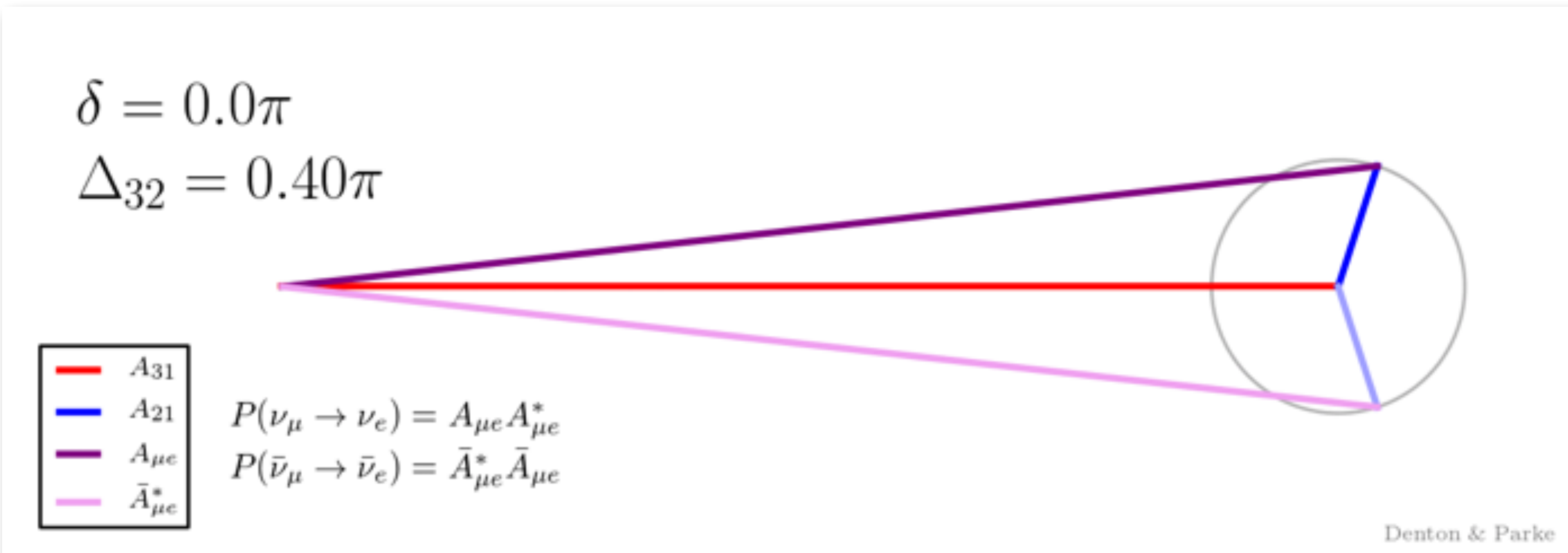

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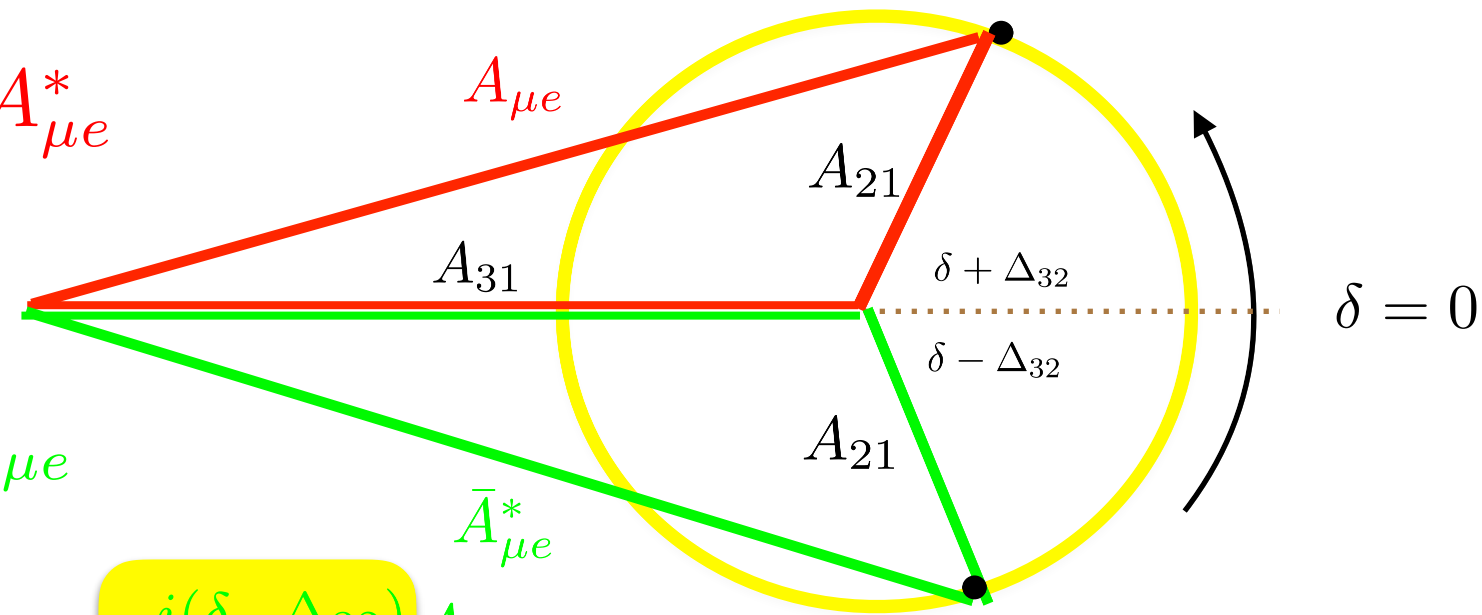

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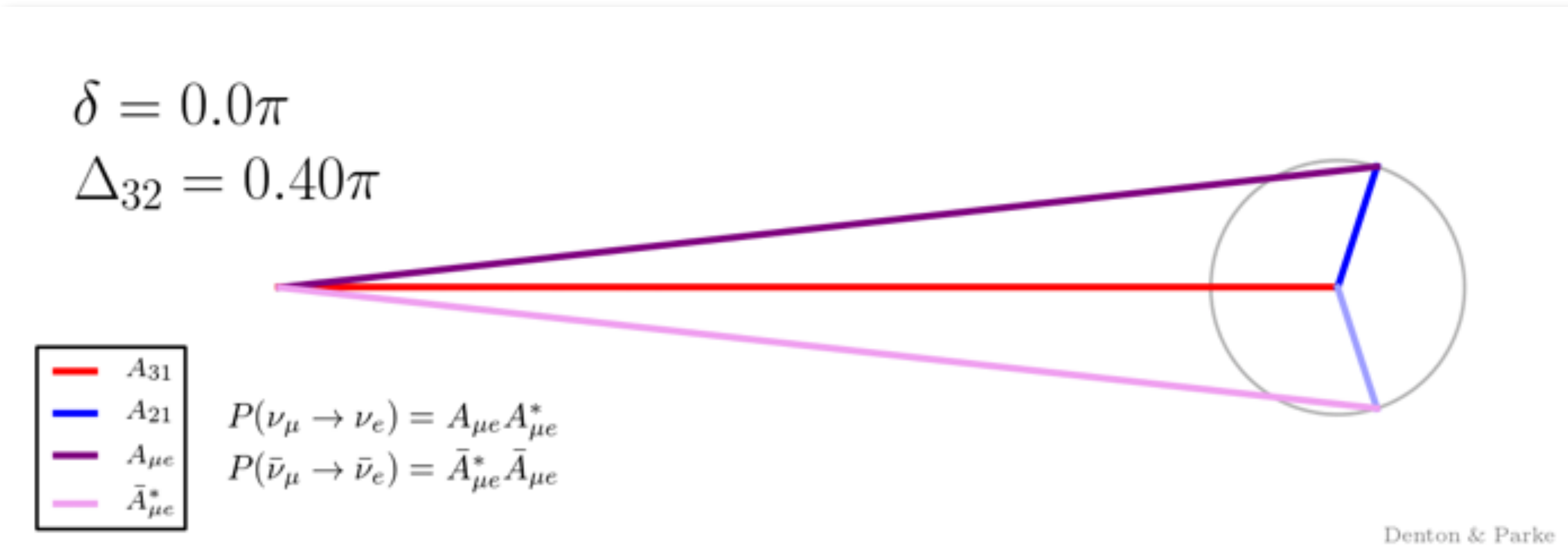

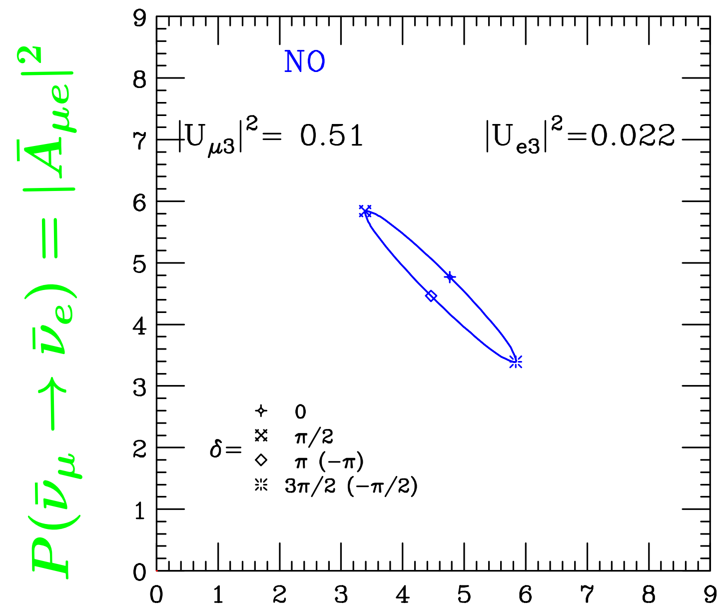

$$P(\nu_\mu \rightarrow \nu_e) = |\bar{A}_{\mu e}|^2$$

Matter Effects:

2 flavor mixing in matter

$$ax^2 + bx + c = 0$$

simple, intuitive, useful

2 flavor mixing in matter

$$ax^2 + bx + c = 0$$

simple, intuitive, useful

3 flavor mixing in matter

$$ax^3 + bx^2 + cx + d = 0$$

complicated, counter intuitive, ...

Matter Effects:

$$A_{31} + e^{i(\Delta_{32} \pm \delta)} A_{21}$$

$$A_{31} = 2 s_{23} s_{13} c_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$$

$$A_{21} = 2 c_{13} c_{23} s_{12} c_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

$$a = G_F N_e / \sqrt{2} = (4000 \ km)^{-1},$$

Matter Effects:

$$A_{31} + e^{i(\Delta_{32} \pm \delta)} A_{21}$$

$$A_{31} = 2 s_{23} s_{13} c_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$$

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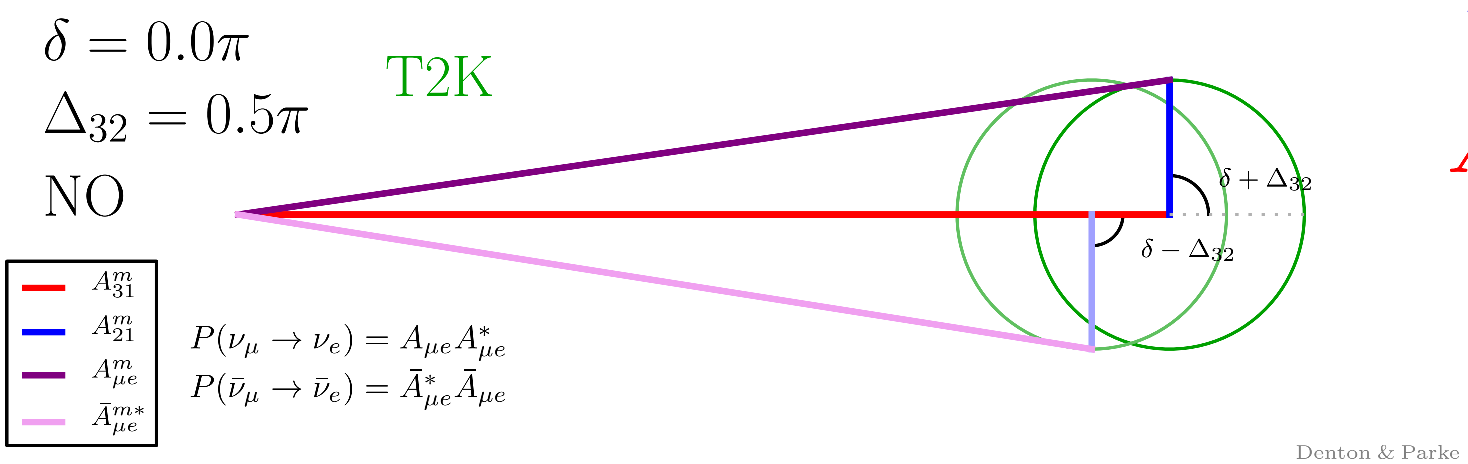

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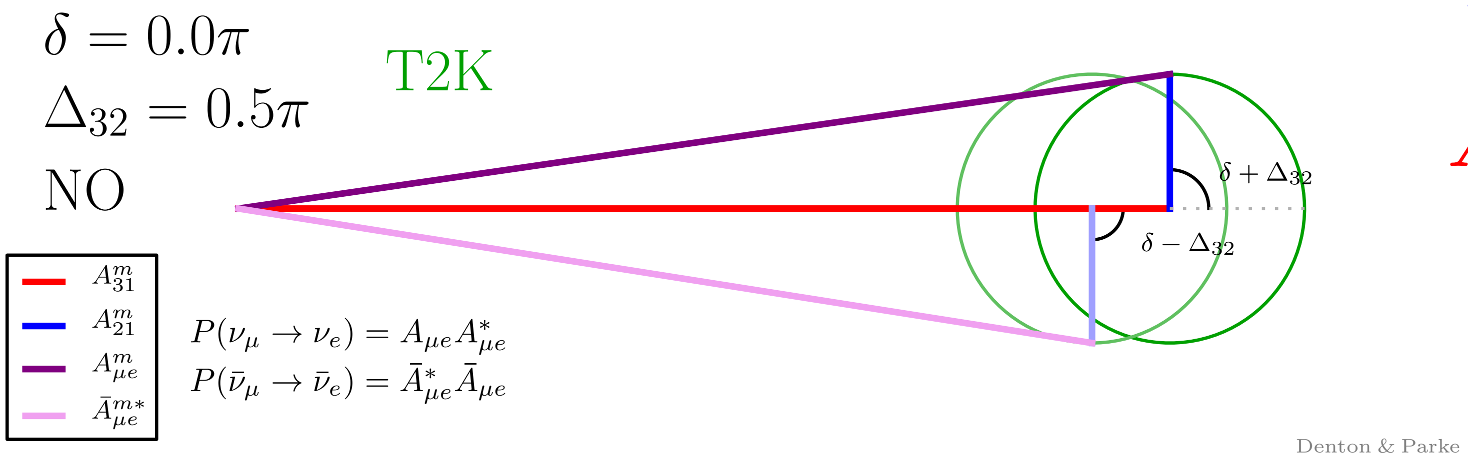

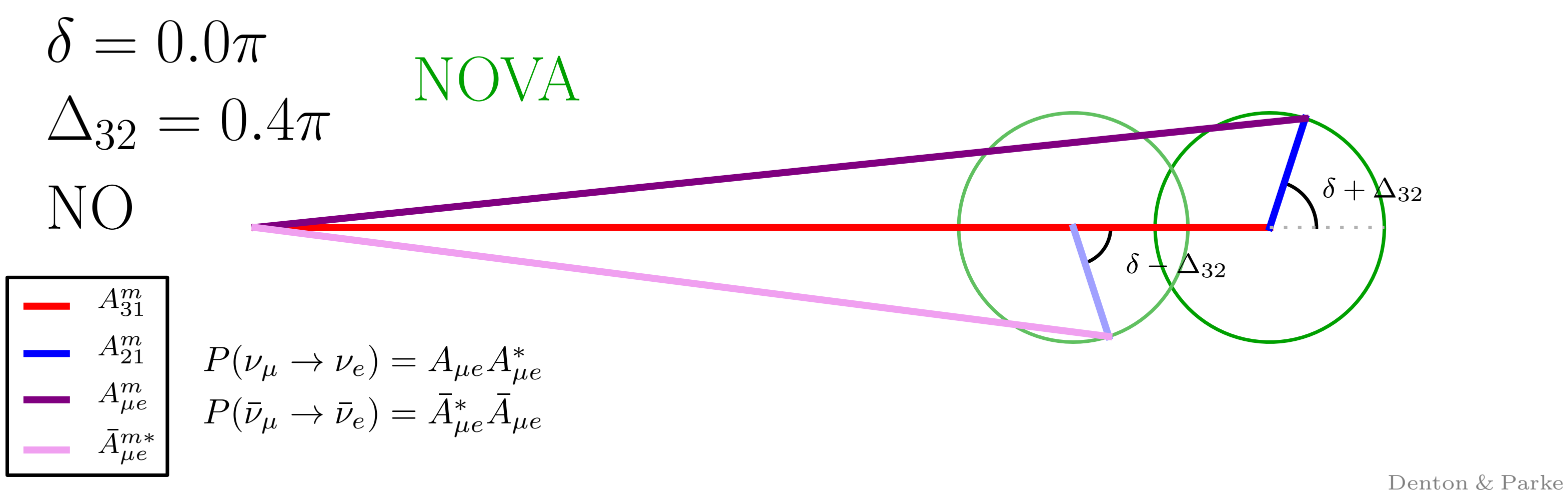

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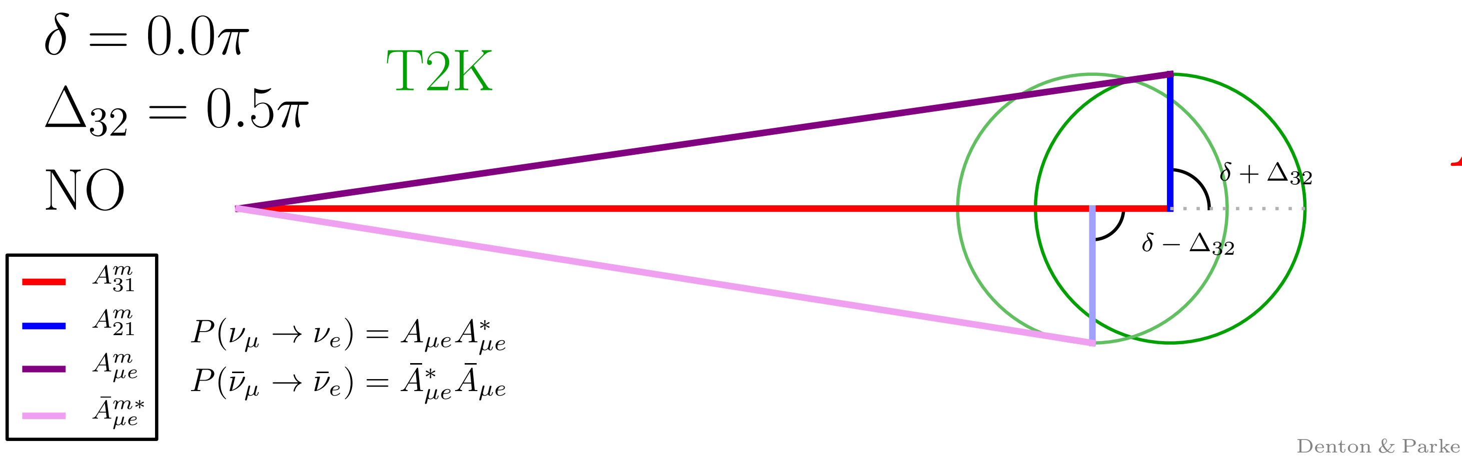

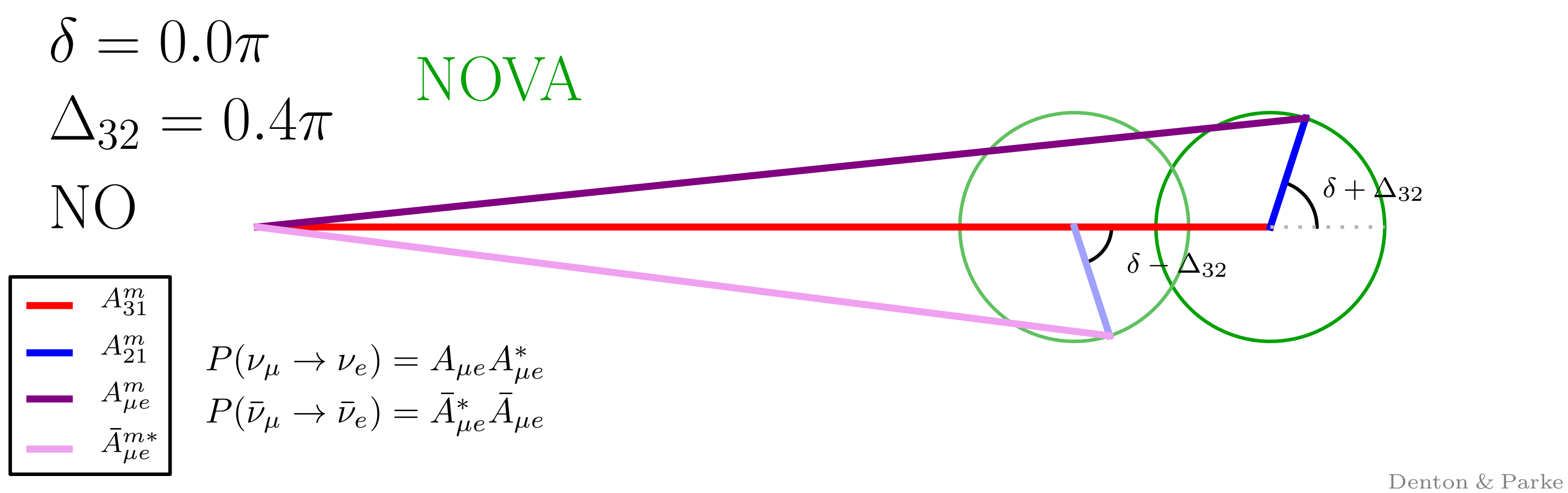

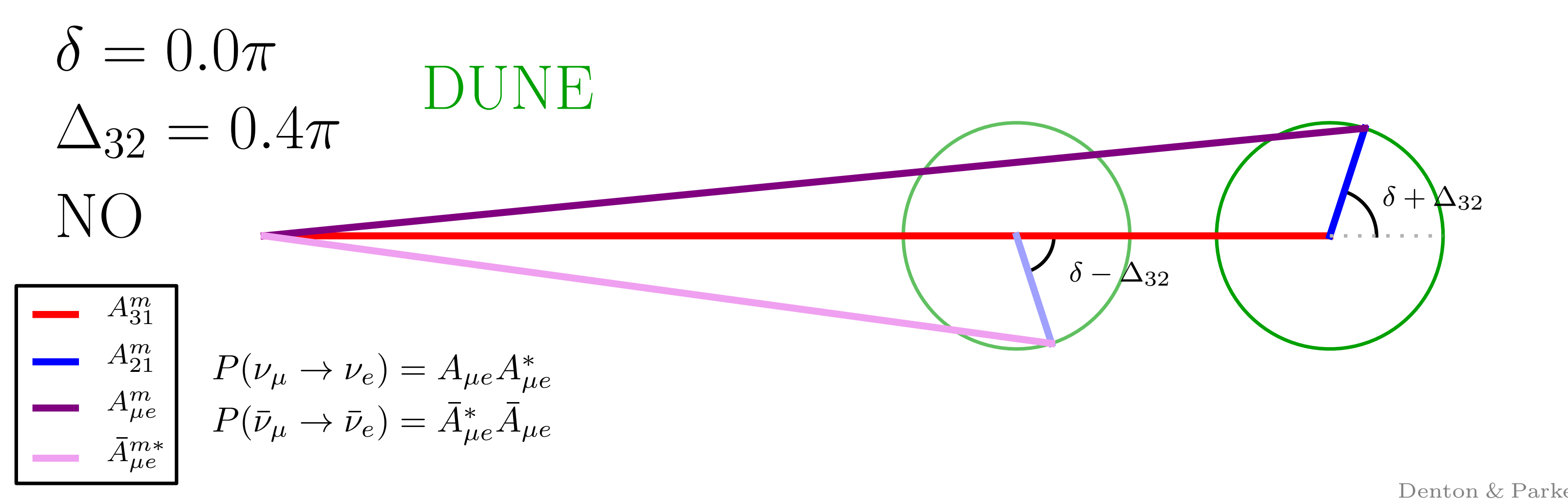

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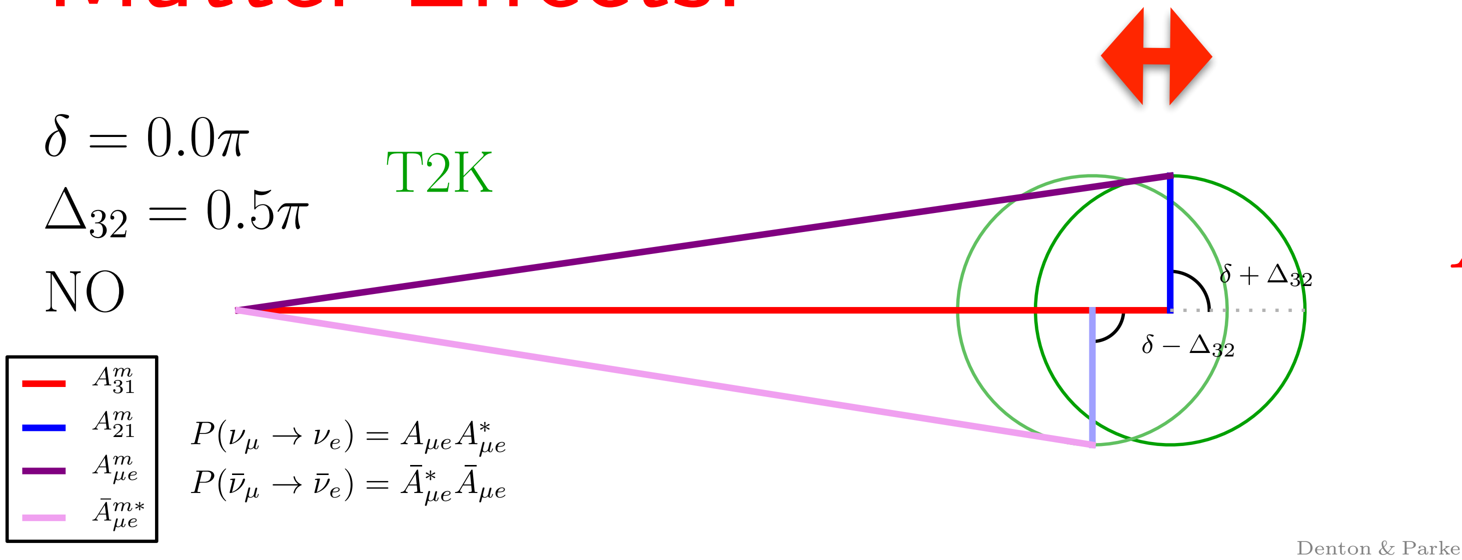
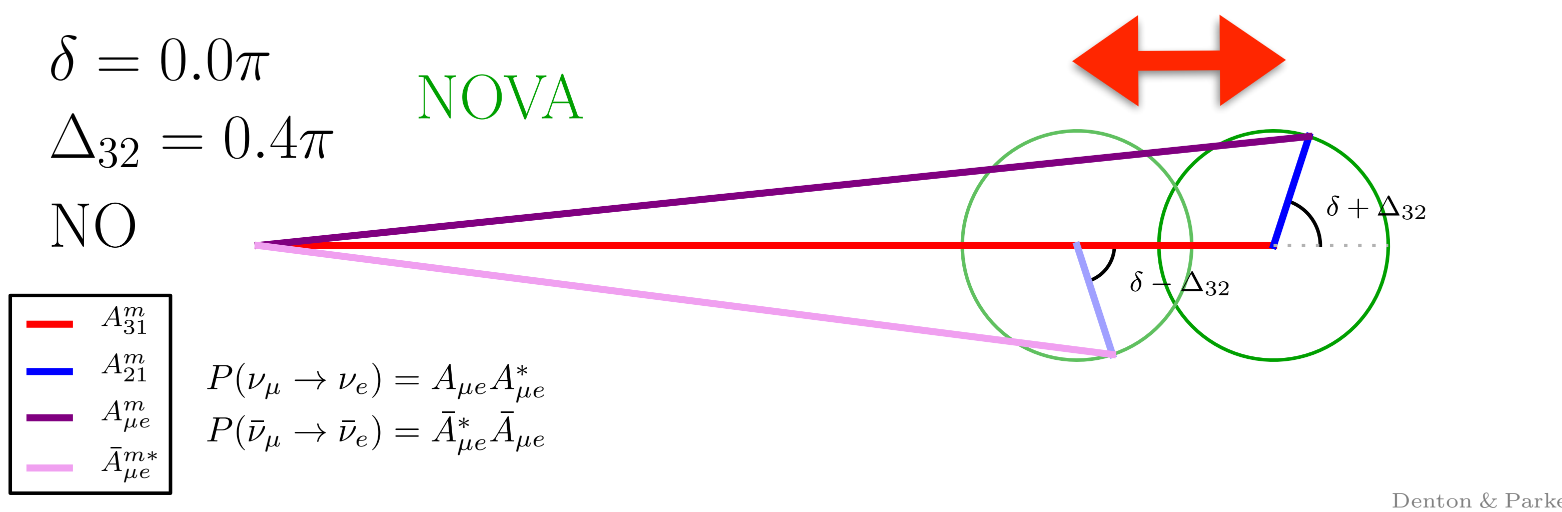
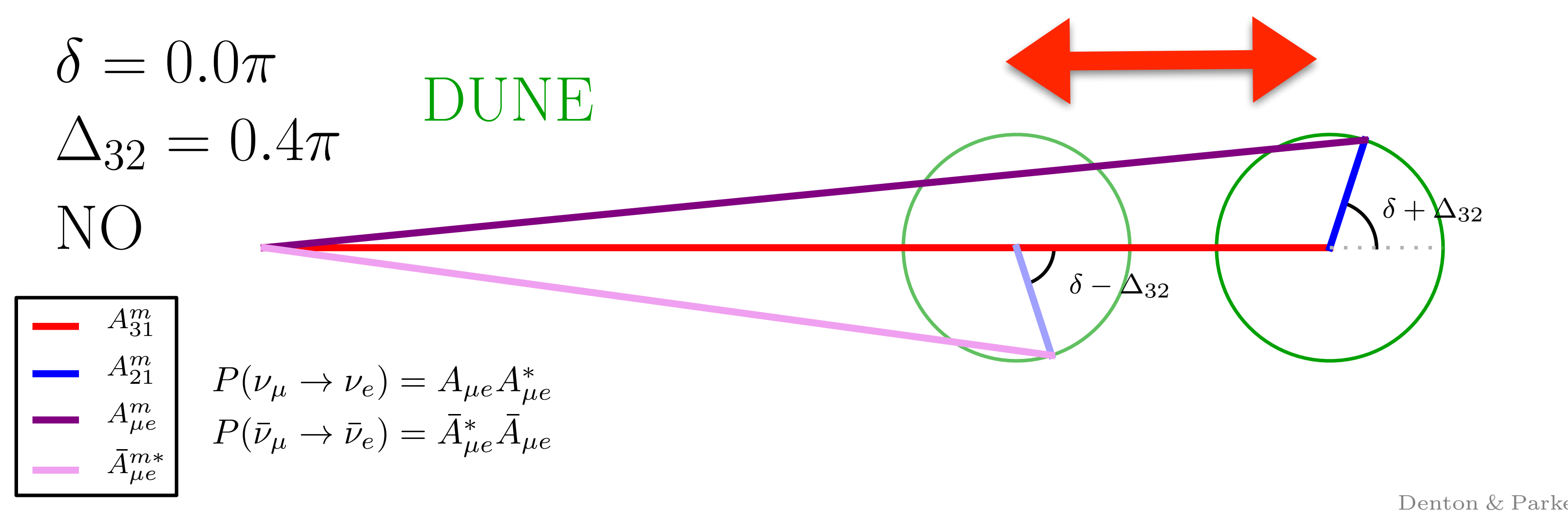




$$\propto \rho L \ \sin^2 \theta_{23}$$



Correlations between $\nu_\mu \to \nu_e \quad \bar{\nu}_\mu \to \bar{\nu}_e$

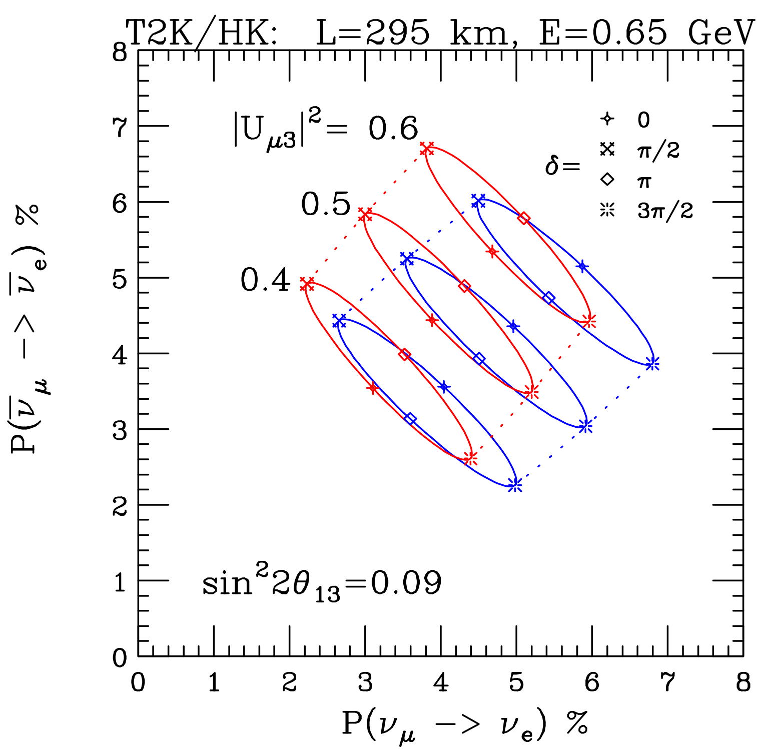
Normal Ordering — Inverted Ordering

$\nu_\mu \to \nu_\mu$ gives:

$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = 0.96 \; - \; 1.00$$

$|U_{\mu3}|^2 \leftrightarrow (1 - |U_{\mu3}|^2)$ degeneracy !

T2K/HK



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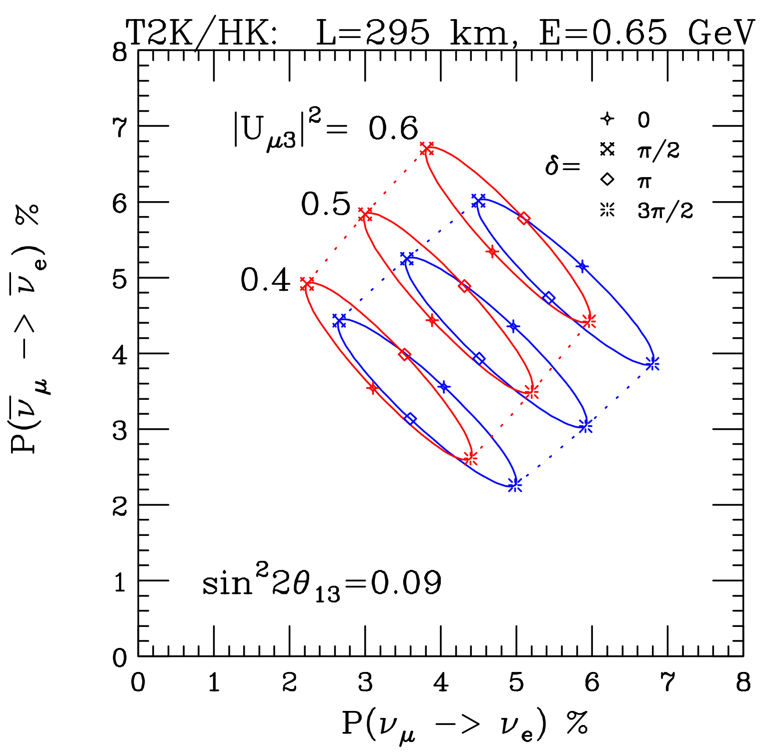
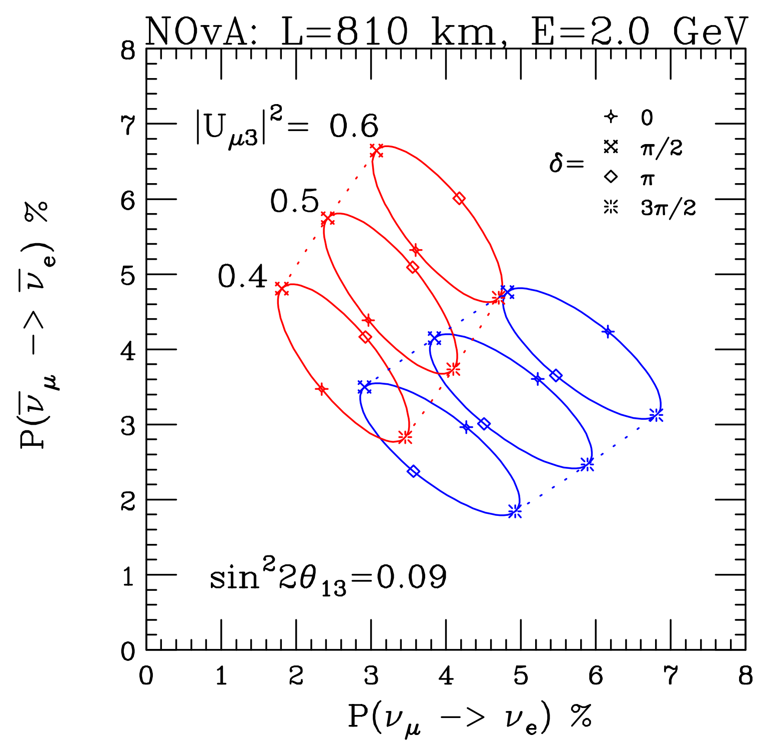


NOvA



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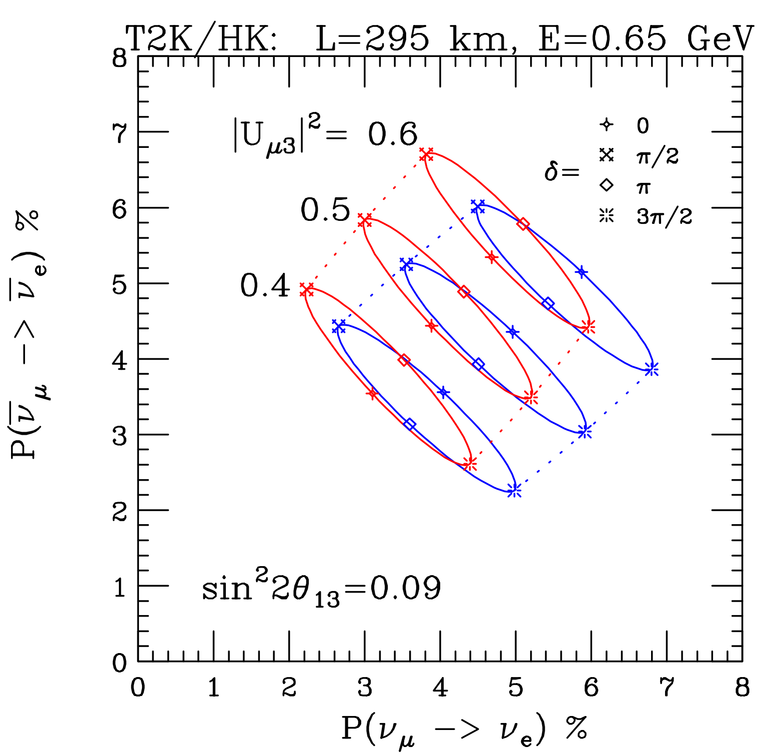
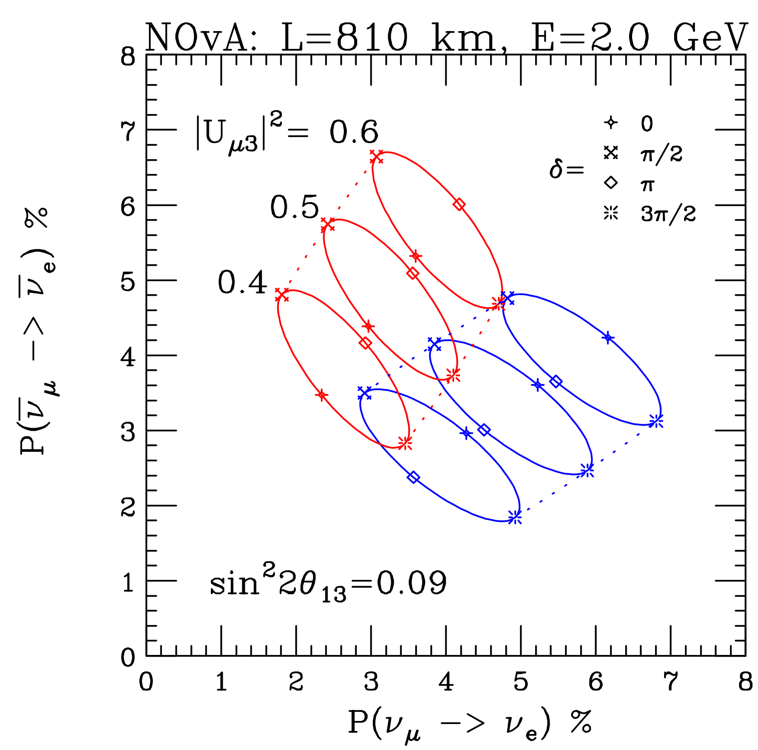
$|U_{\mu 3}|^2 \leftrightarrow (1-|U_{\mu 3}|^2)$ **degeneracy !**

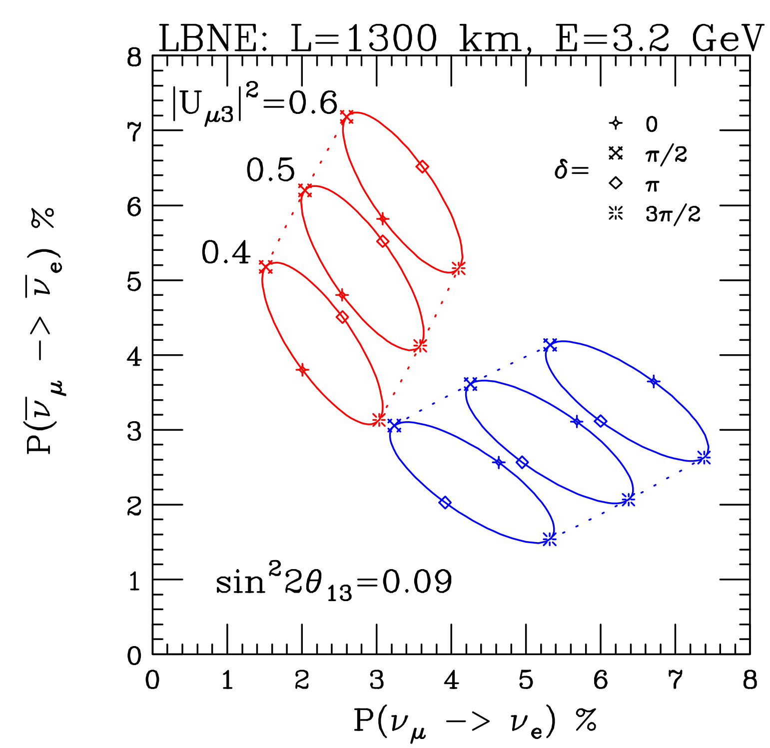
T2K/HK



NOvA



DUNE Same L/E as NOνA



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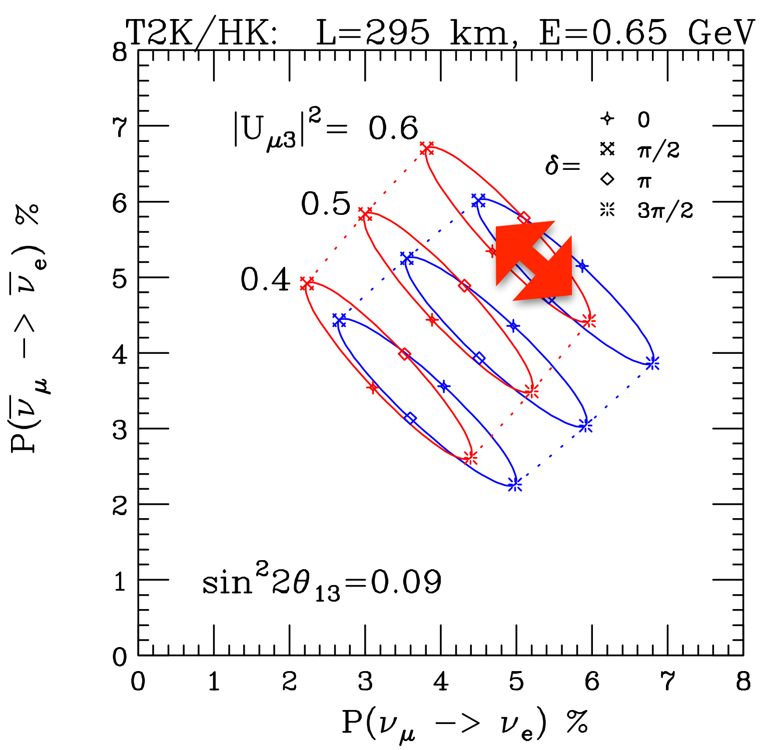
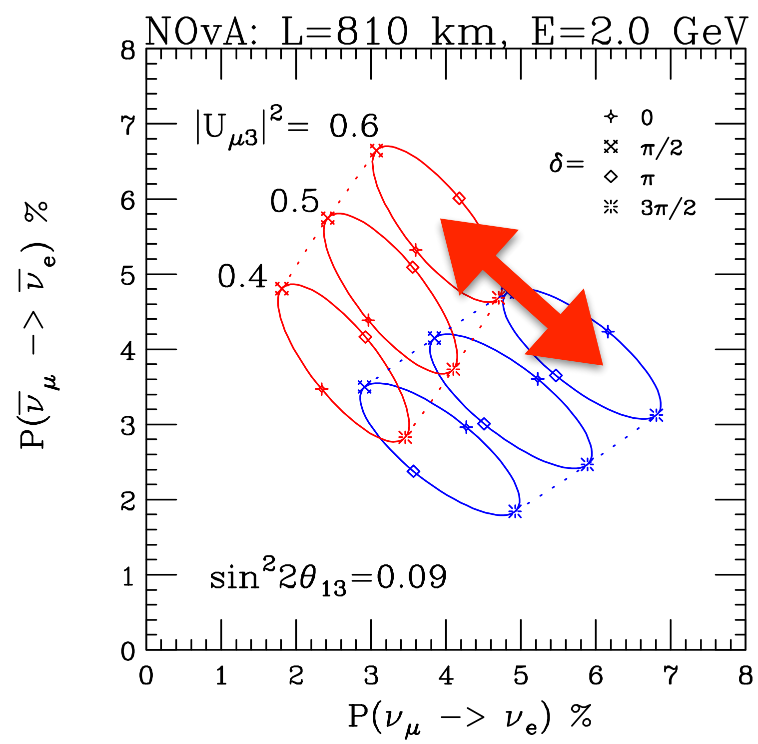
T2K/HK



NOvA



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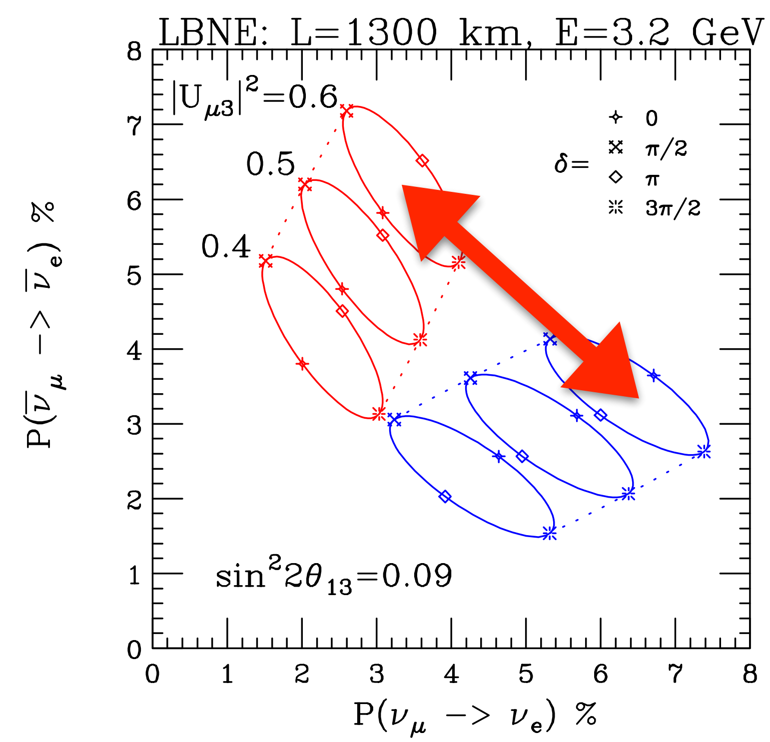

$\propto \rho L \; \sin^2\theta_{23}$

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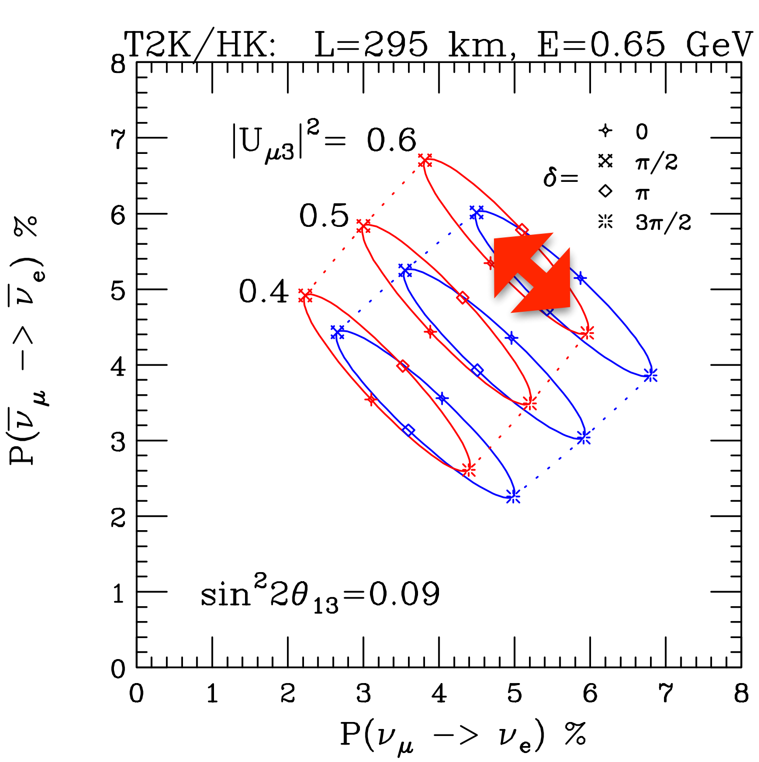
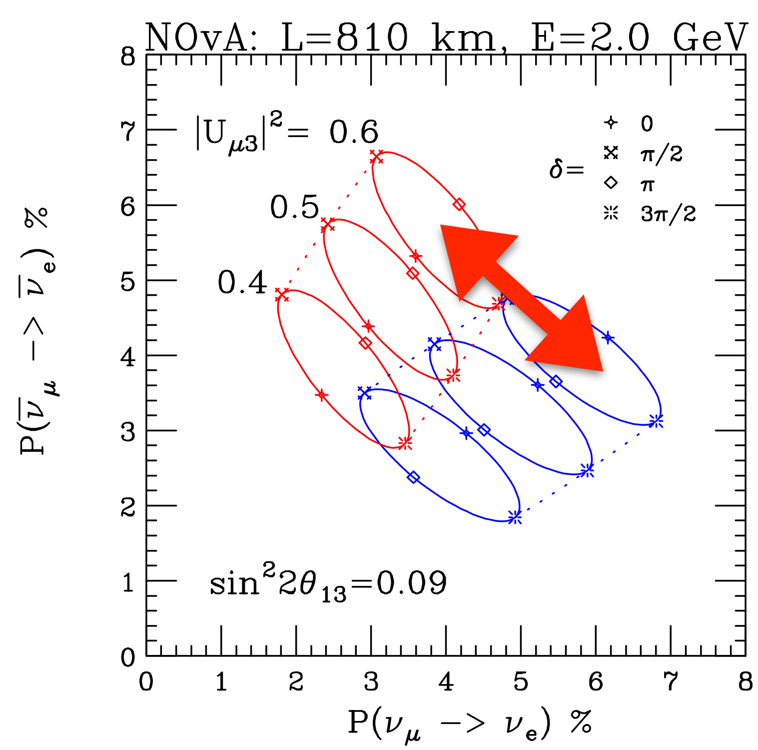


NOvA



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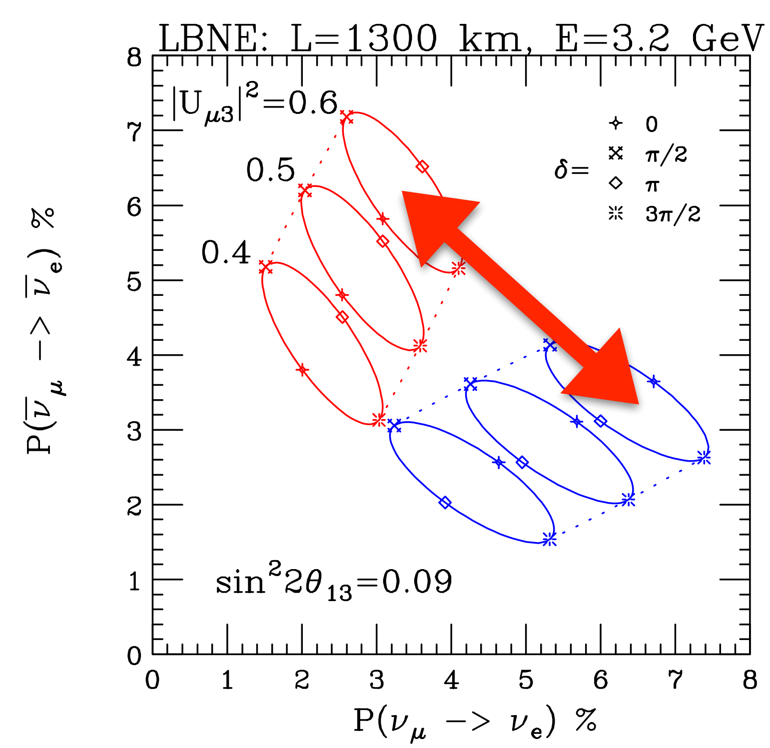
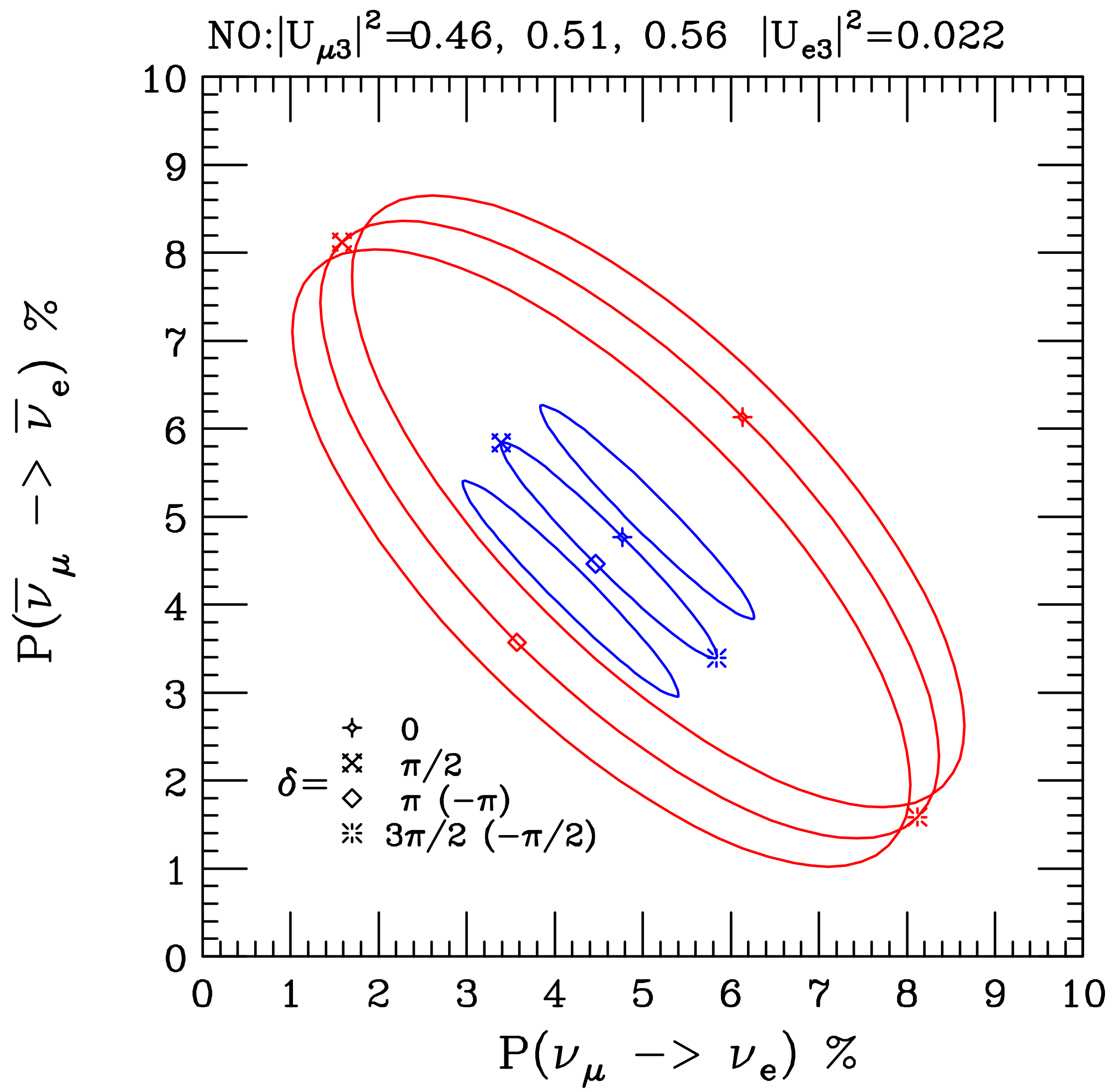


$\propto \rho L \;\; \sin^2\theta_{23}$

$$\sin\delta_{NO} - \sin\delta_{IO} = \tan\theta_{23} \times \begin{cases} 0.48 & \text{T2K} \\ 1.62 & \text{NO}\nu\text{A} \\ 2.60 & \text{DUNE} \end{cases}$$

O. Mena & SP hep-ph/0408070

2nd Osc Max: (vacuum)



$$A \equiv \frac{\overline{P} - P}{\overline{P} + P}$$

$$A_1 \approx 0.30 \sin\delta$$

$$A_2 \approx 0.75 \sin\delta$$

$$\frac{A_2}{A_1} \approx 2.5 \qquad \frac{\sqrt{N_2}}{\sqrt{N_1}} \approx \frac{1}{3}$$

Approximately same uncertainty on δ
until systematic uncertainitities dominate at 1st OM !

ESSnuSB, T2HKK

New Perturbation Theory for Osc. Probabilities

Denton, Minakata, SP arXiv:1604.08167

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$$\mathcal{A}_{\mu e} = (2i)\,[\,(s_{23}s_{13}c_{13})\,[\,c_{12}^2 e^{-i\Delta_{32}} \sin\Delta_{31} + s_{12}^2 e^{-i\Delta_{31}} \sin\Delta_{32}\,]$$
$$+\,(c_{23}c_{13}s_{12}c_{12})\, e^{i\delta}\, \sin\Delta_{21}\,]$$

mixing angles in matter $\theta_{13} \to \phi$ and $\theta_{12} \to \psi$ mass eigenvalues in matter $m_i^2 \to \lambda_i$

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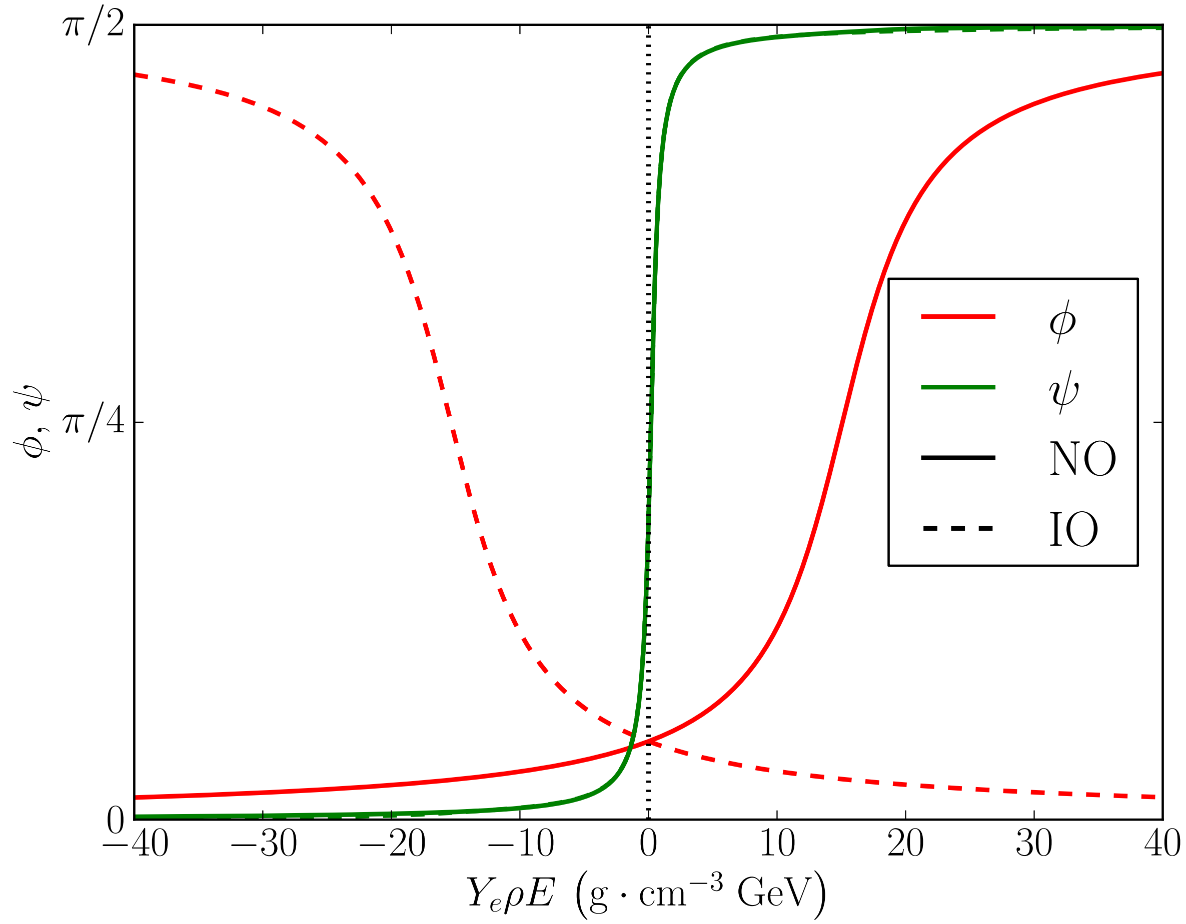

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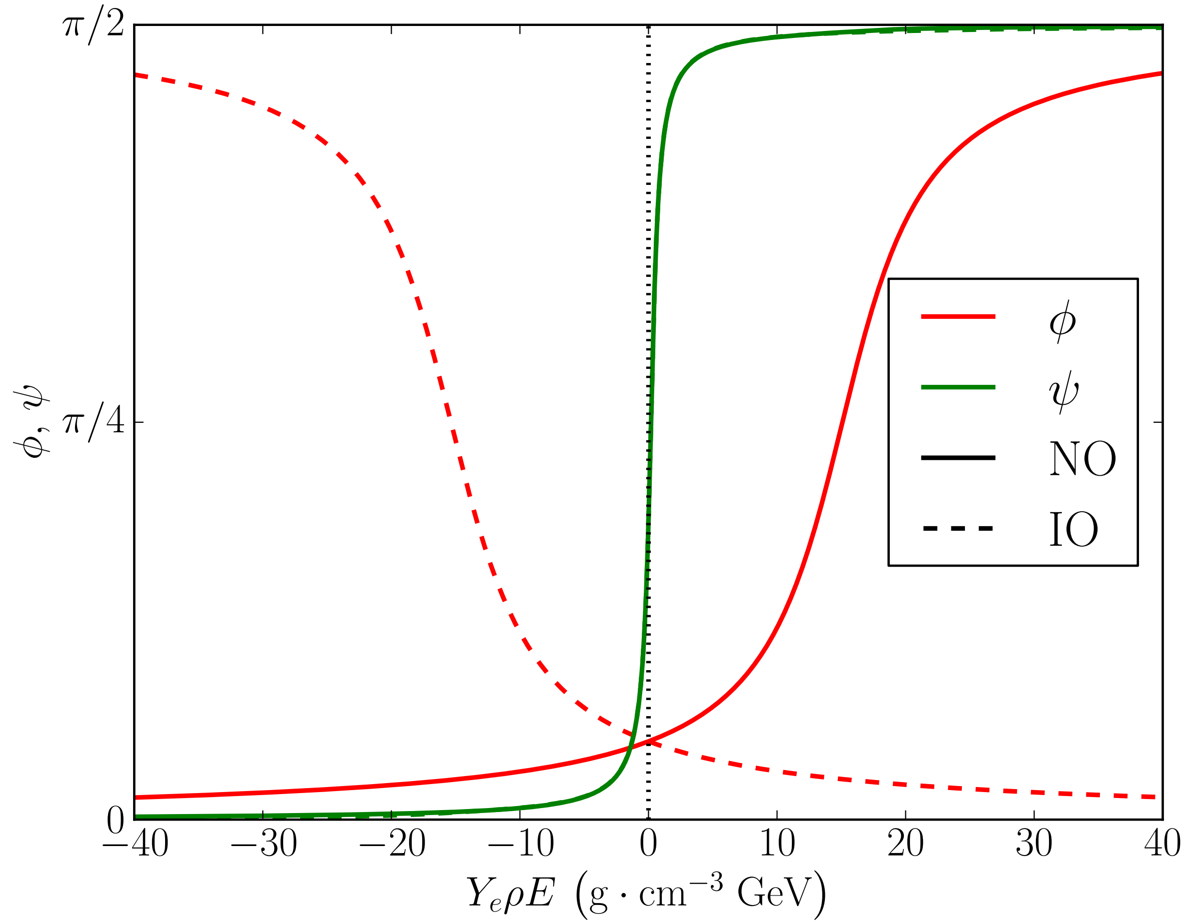

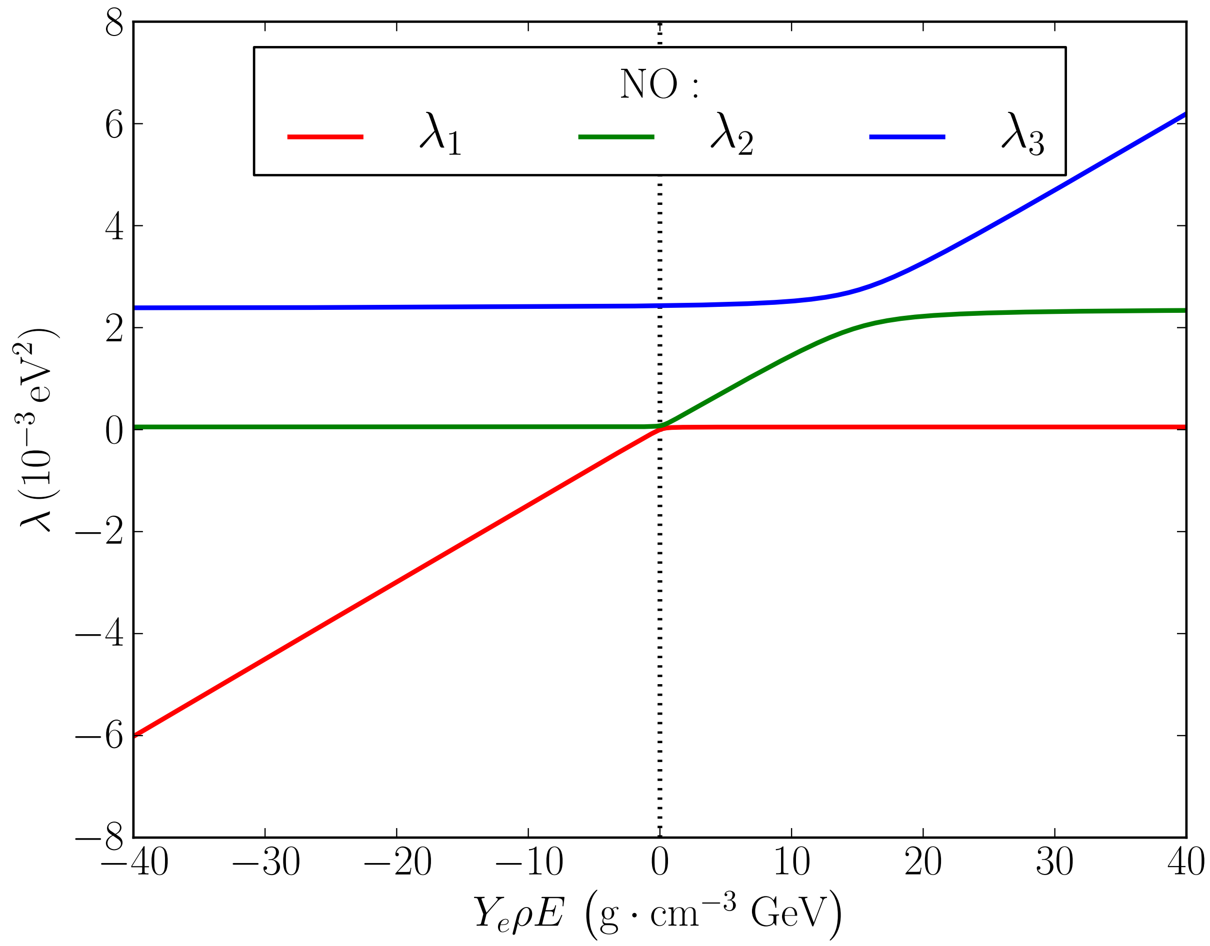

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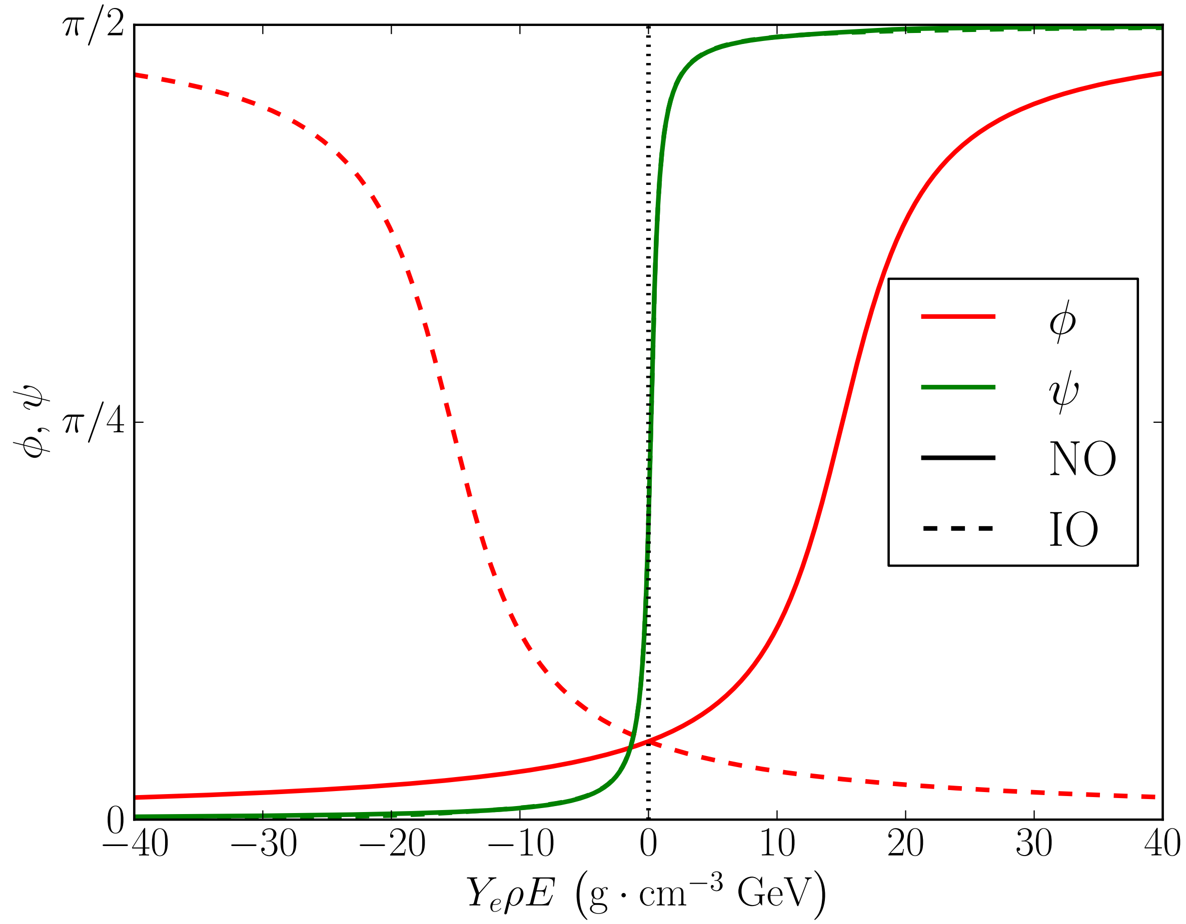
mixing angles in matter $\theta_{13} \rightarrow \phi$ and $\theta_{12} \rightarrow \psi$



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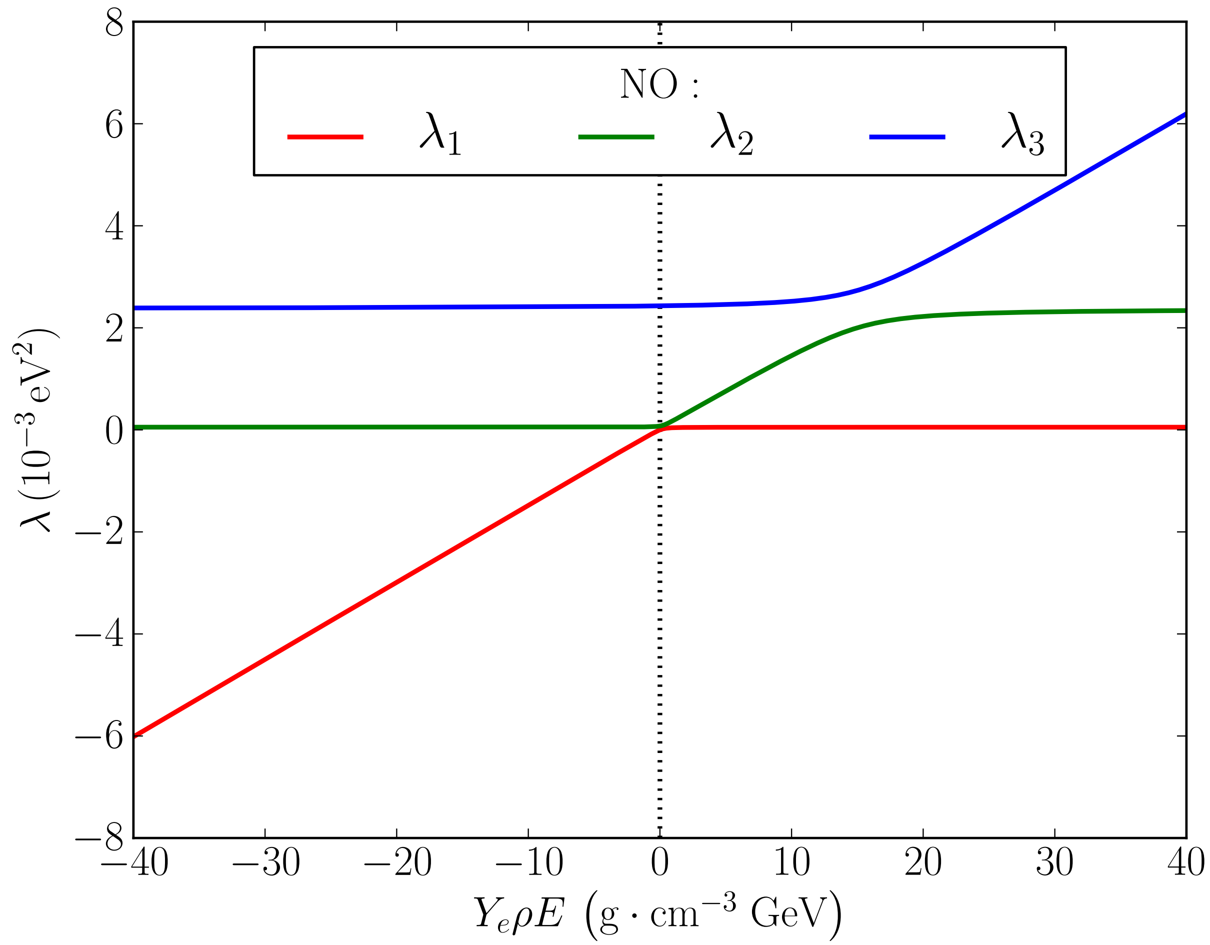
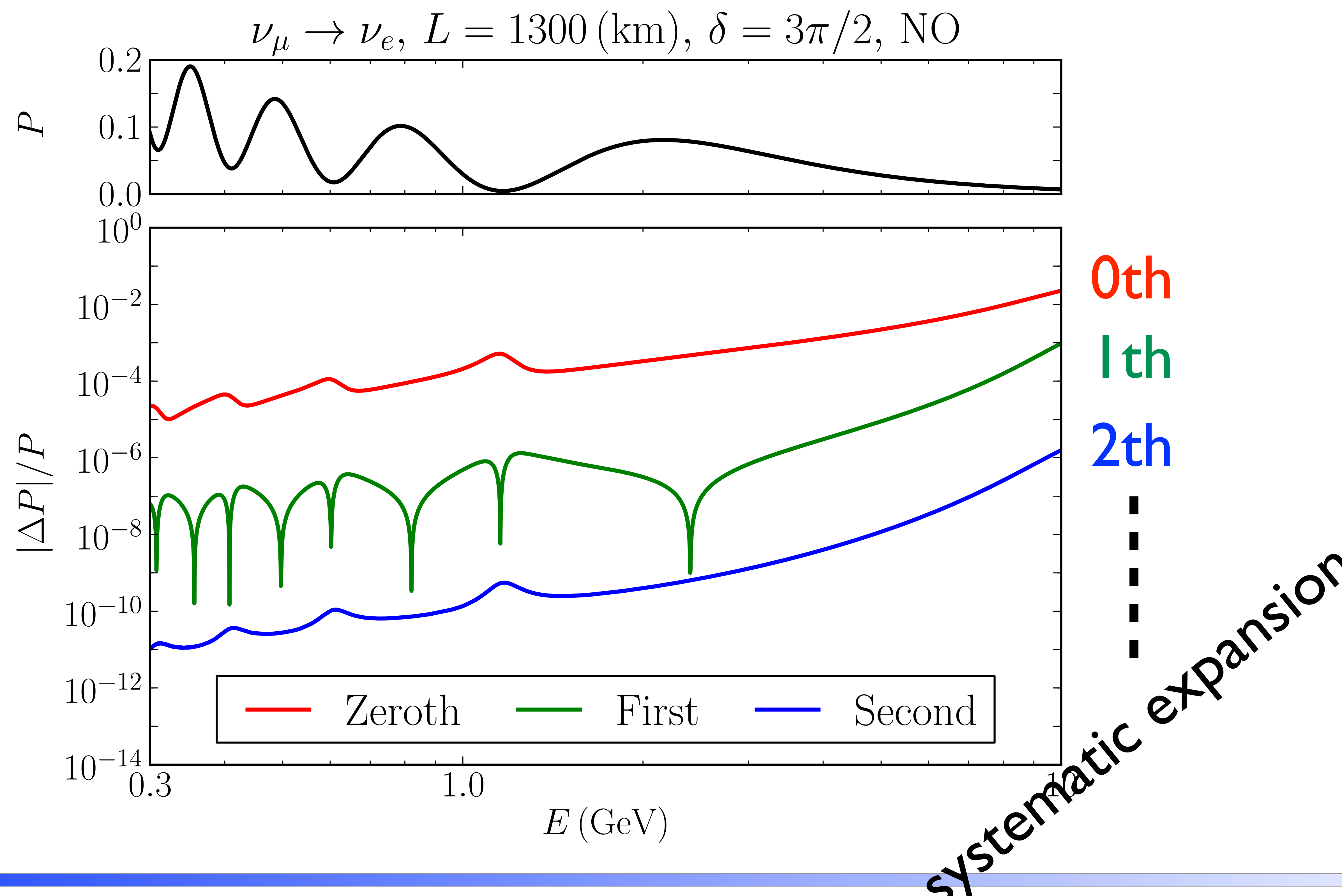
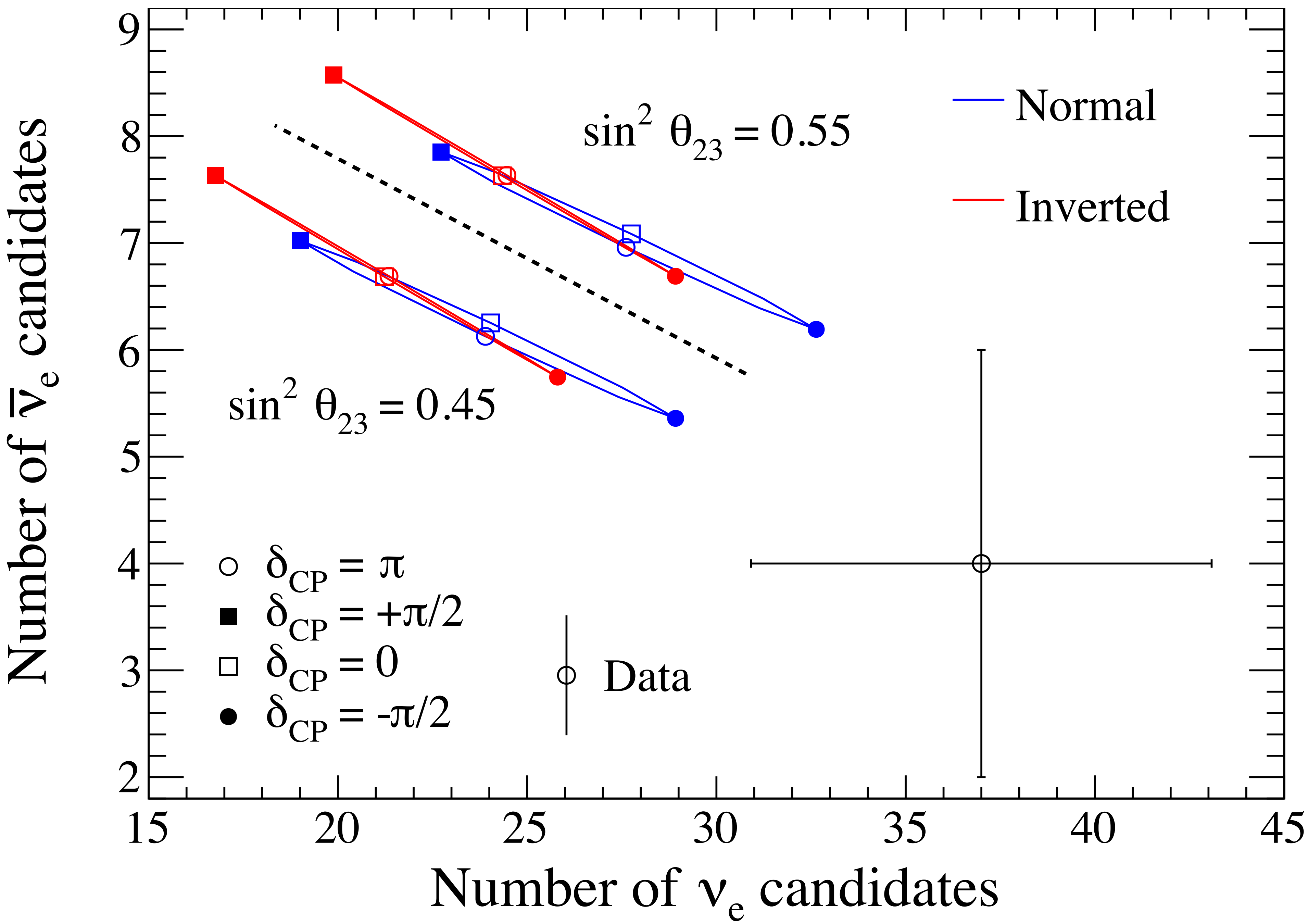


Intuitive and Analytically simple !

New Perturbation Theory for Osc. Probabilities

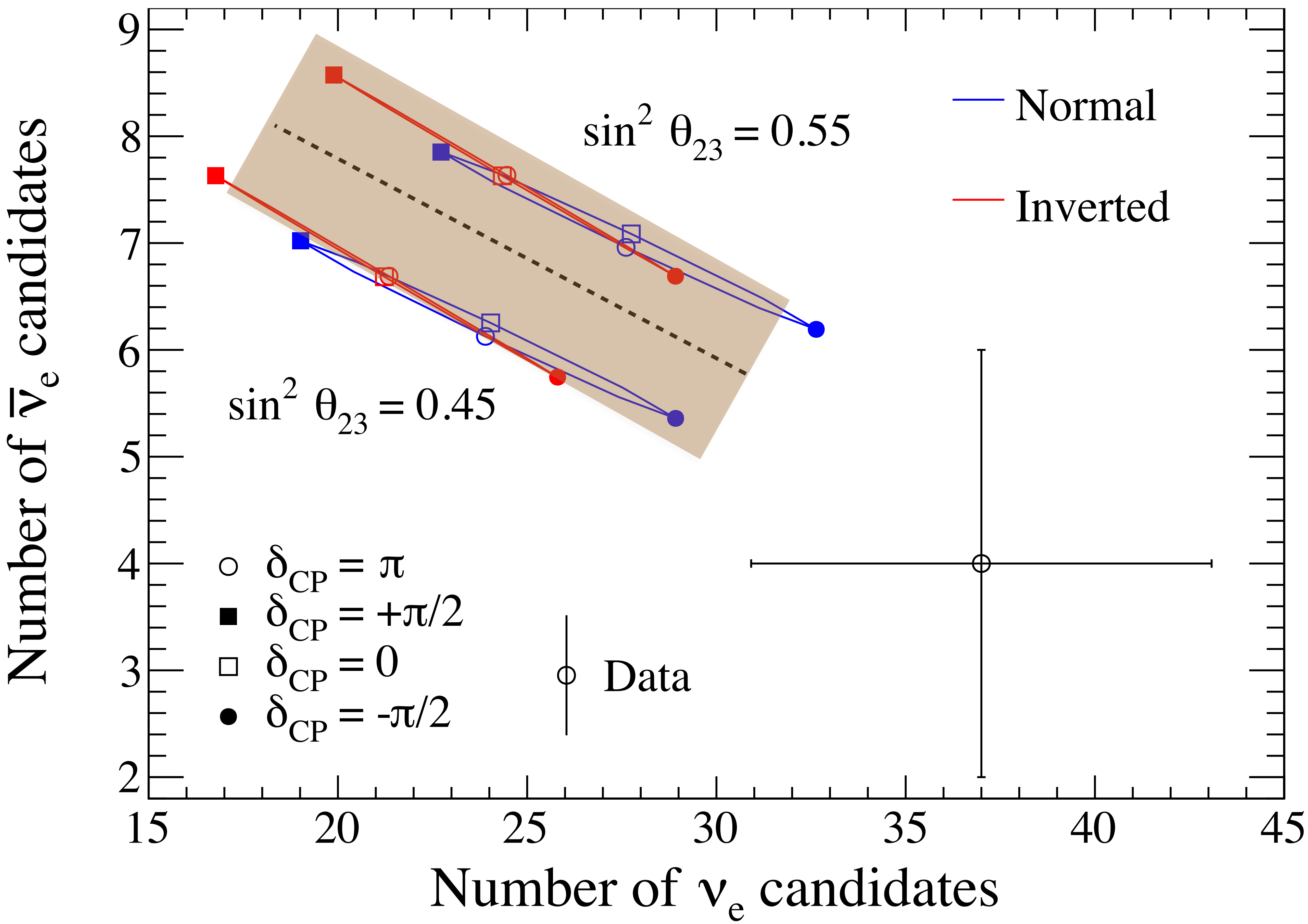


T2K



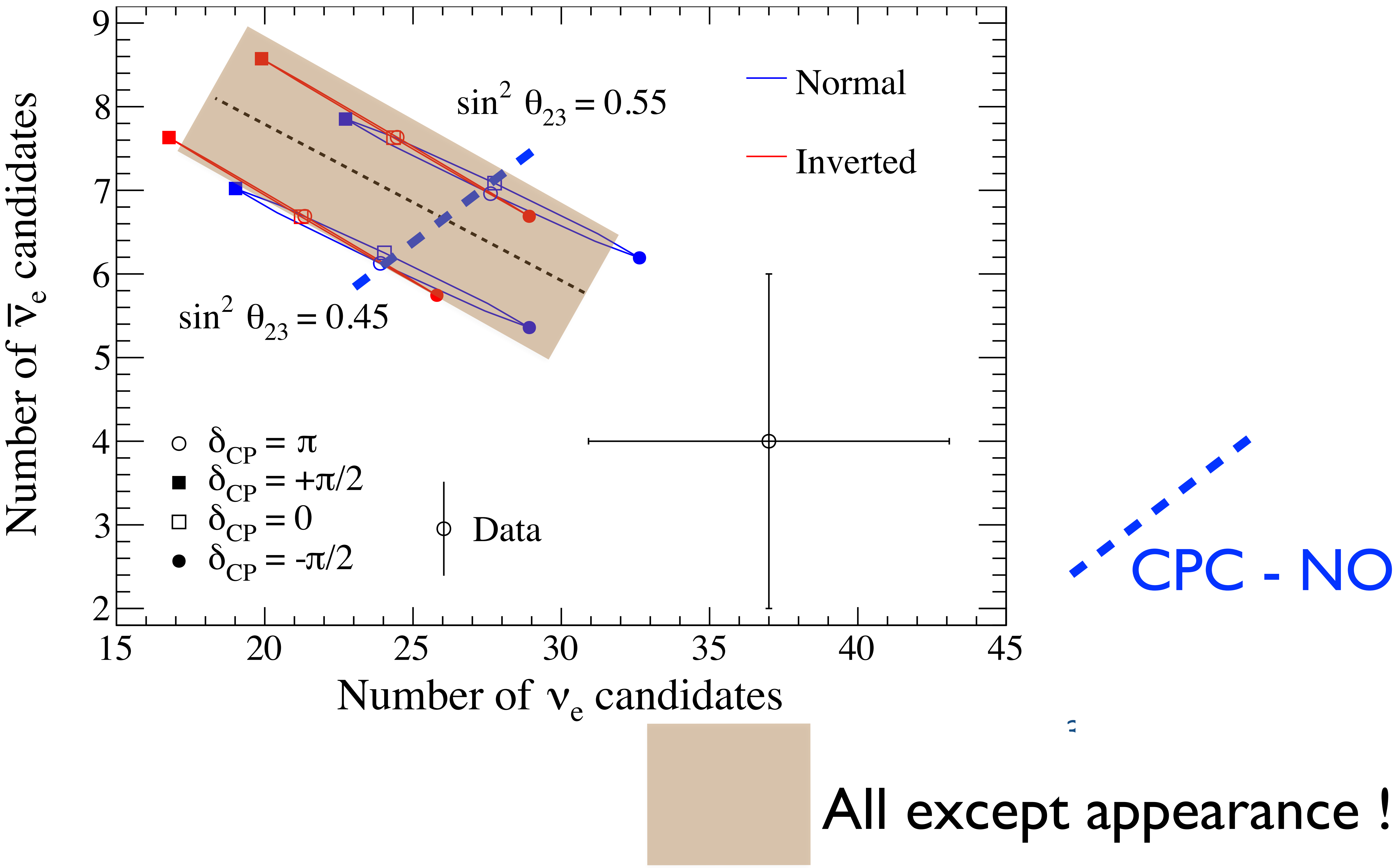
Normal
Inverted
$\sin^2\theta_{23} = 0.55$
$\sin^2\theta_{23} = 0.45$
$\delta_{CP} = \pi$
$\delta_{CP} = +\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = -\pi/2$
Data
Number of $\bar{\nu}_e$ candidates
Number of ν_e candidates
15 20 25 30 35 40 45
2 3 4 5 6 7 8 9

T2K



All except appearance !

T2K



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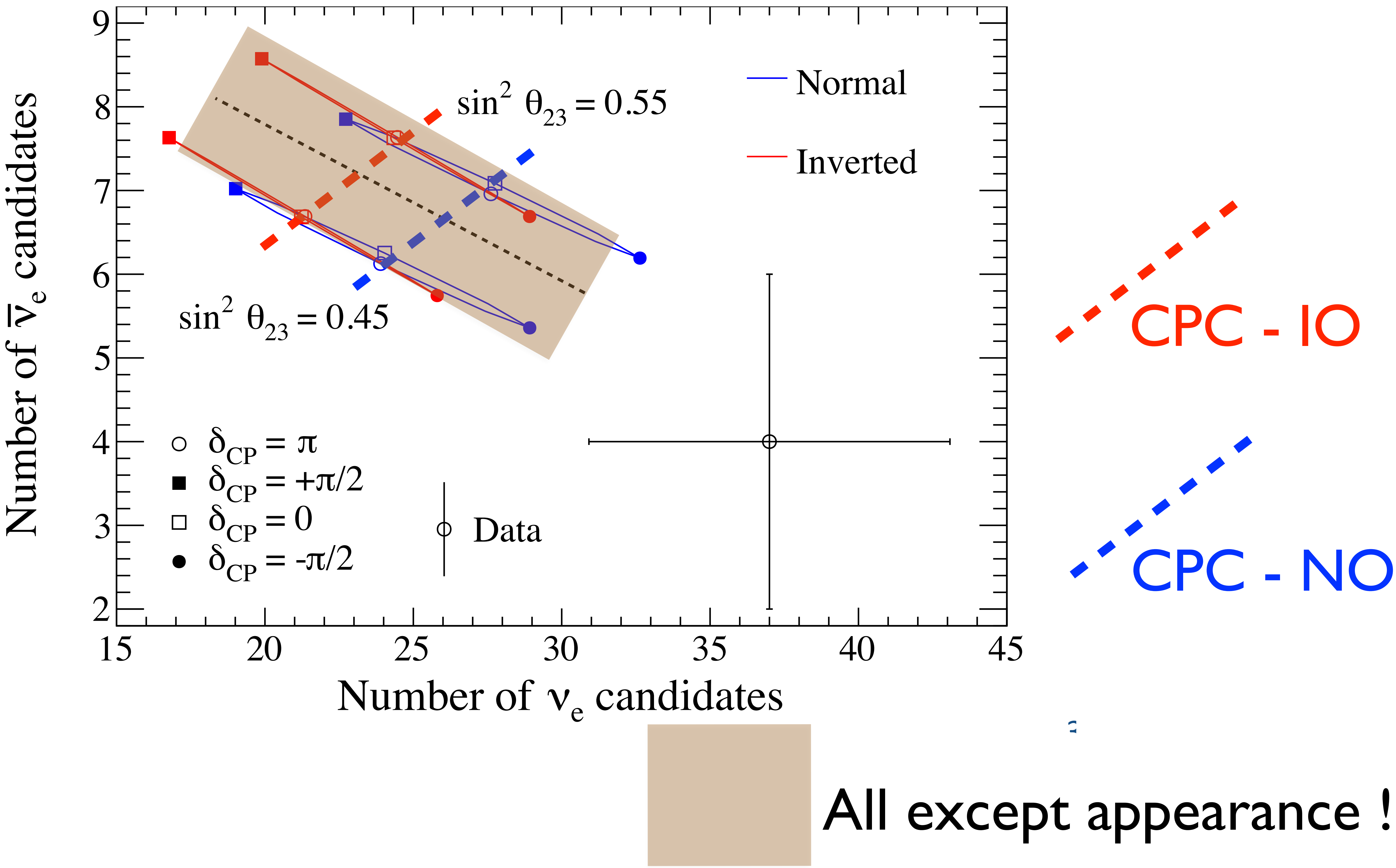
$\delta_{CP} = -\pi/2$
Data
Number of $\bar{\nu}_e$ candidates
Number of ν_e candidates
CPC - NO
All except appearance !

T2K



Number of $\bar{\nu}_e$ candidates
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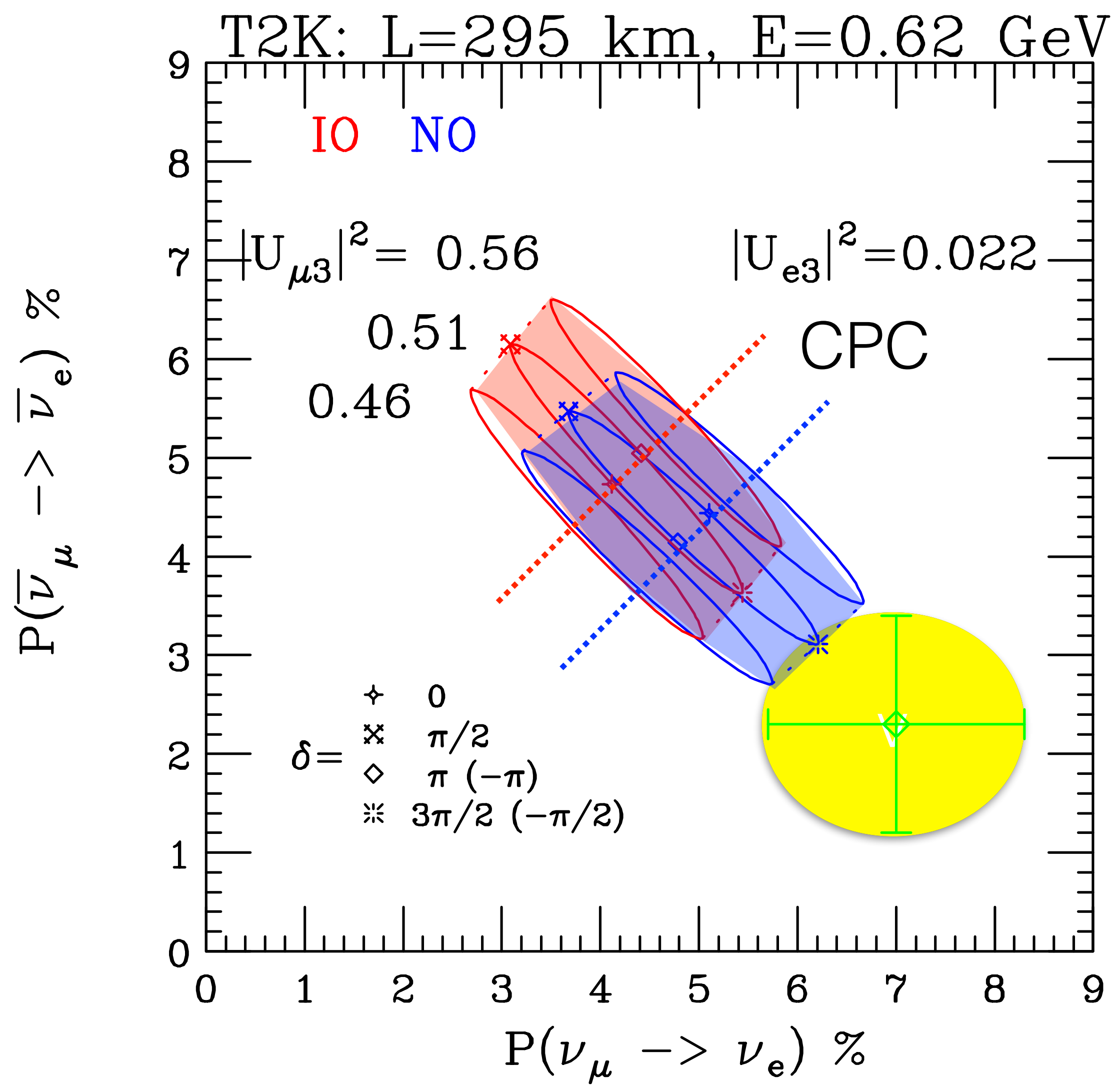
Normal
Inverted
$\delta_{CP} = \pi$
$\delta_{CP} = +\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = -\pi/2$
Data
CPC - IO
CPC - NO
All except appearance !

T2K & NOvA

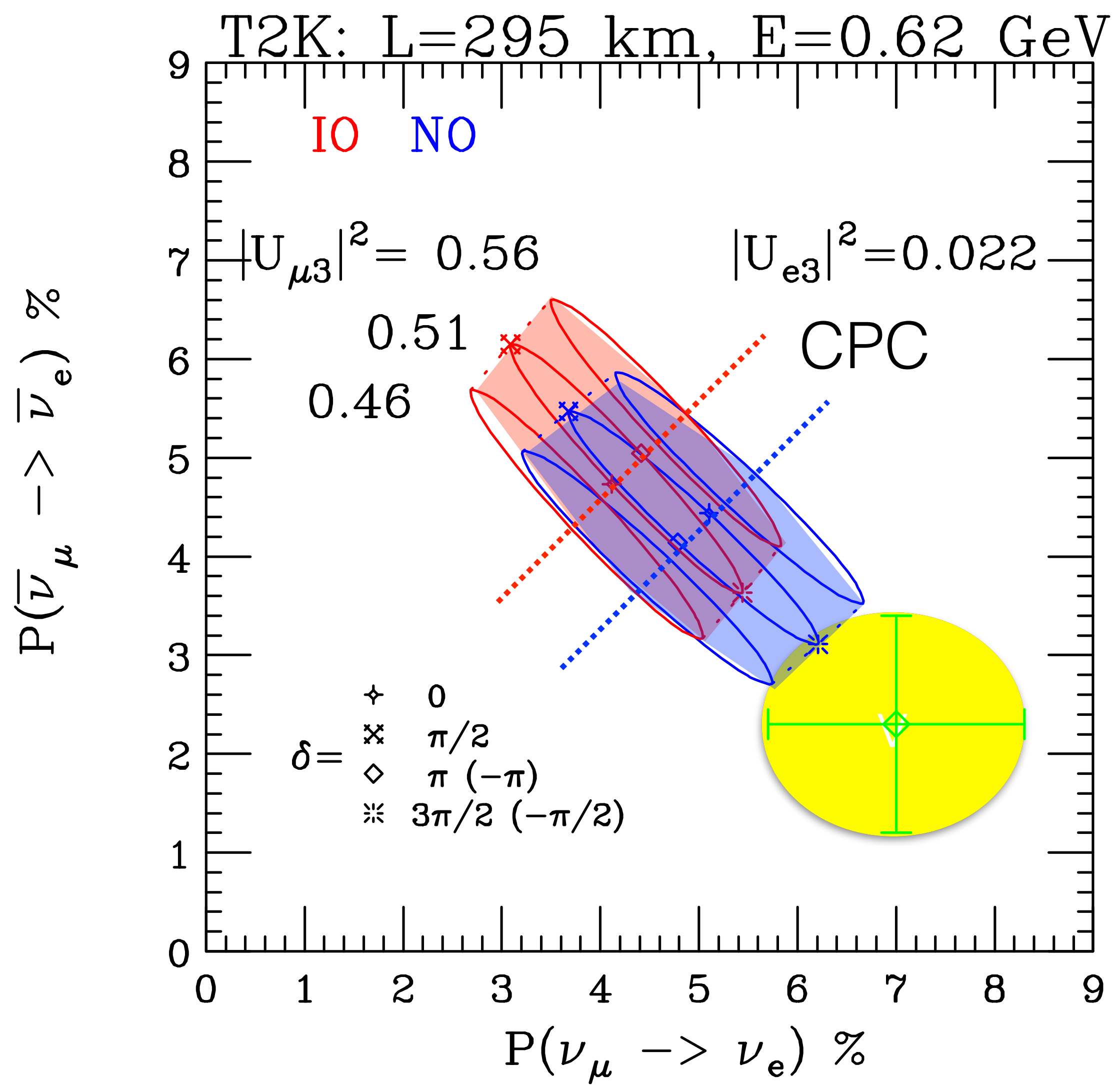
Number of Events proportional to Oscillation Probability

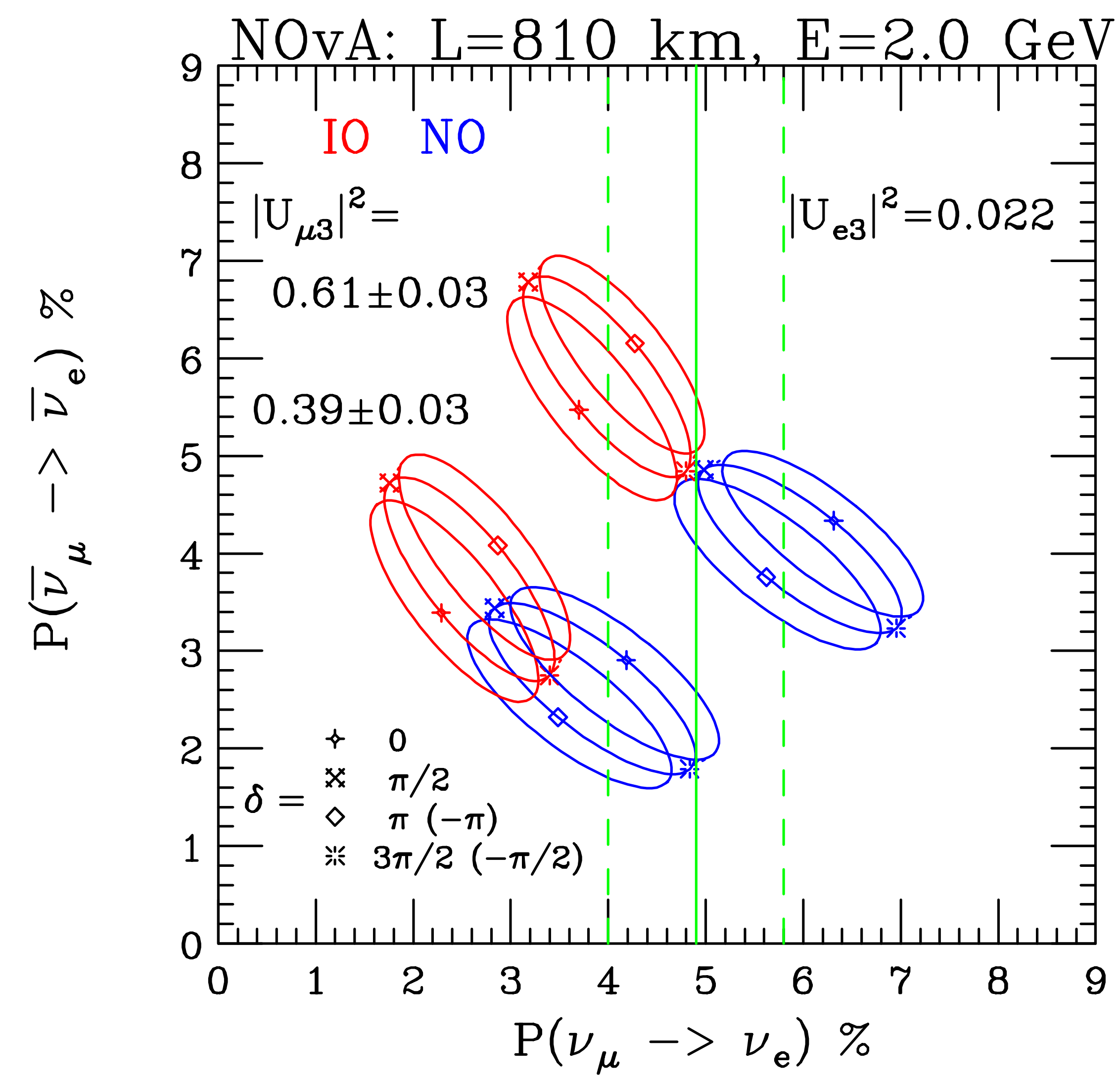


1 sigma: NO IO Appearance data

T2K & NOvA

Number of Events proportional to Oscillation Probability





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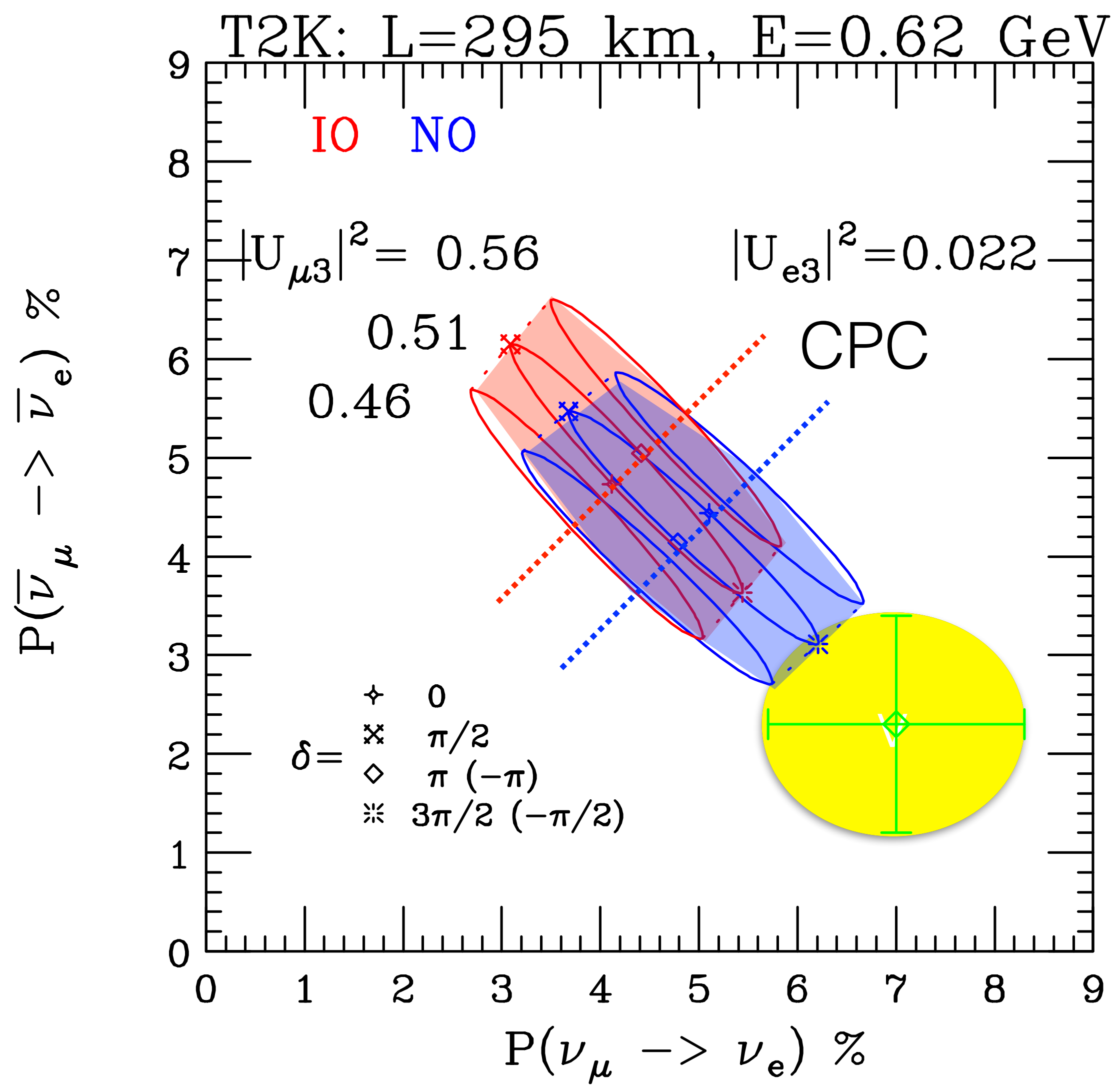

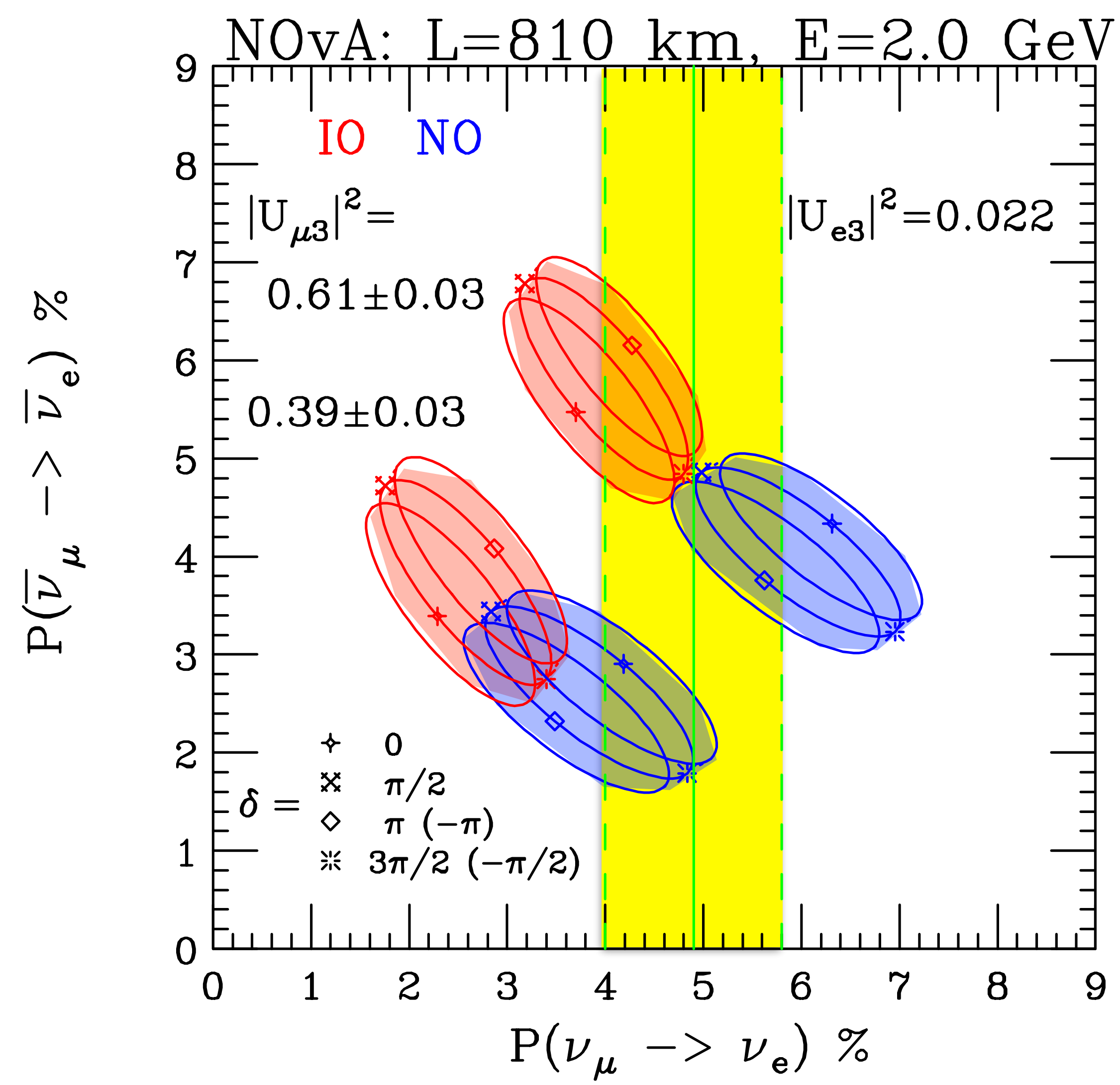

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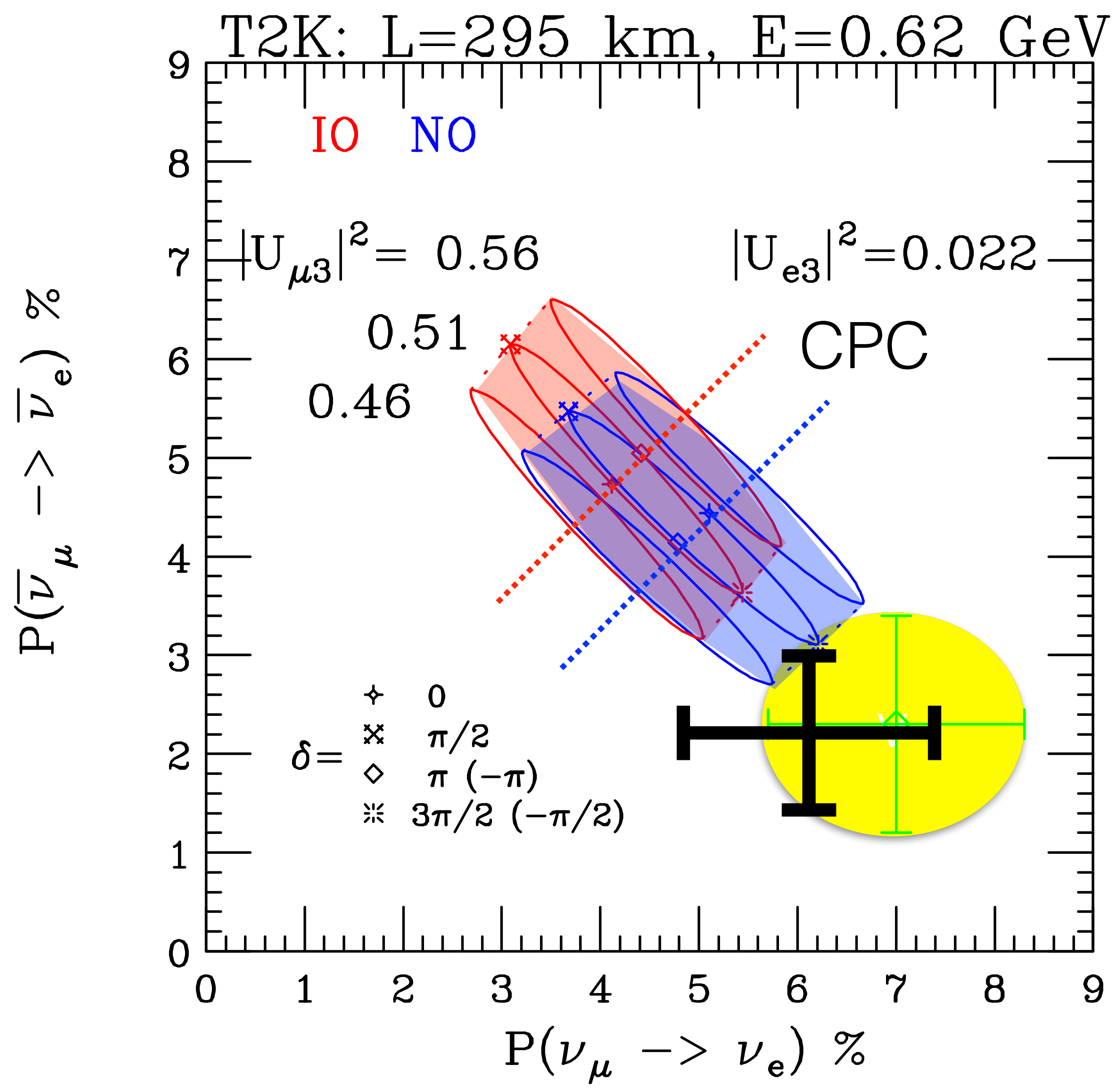

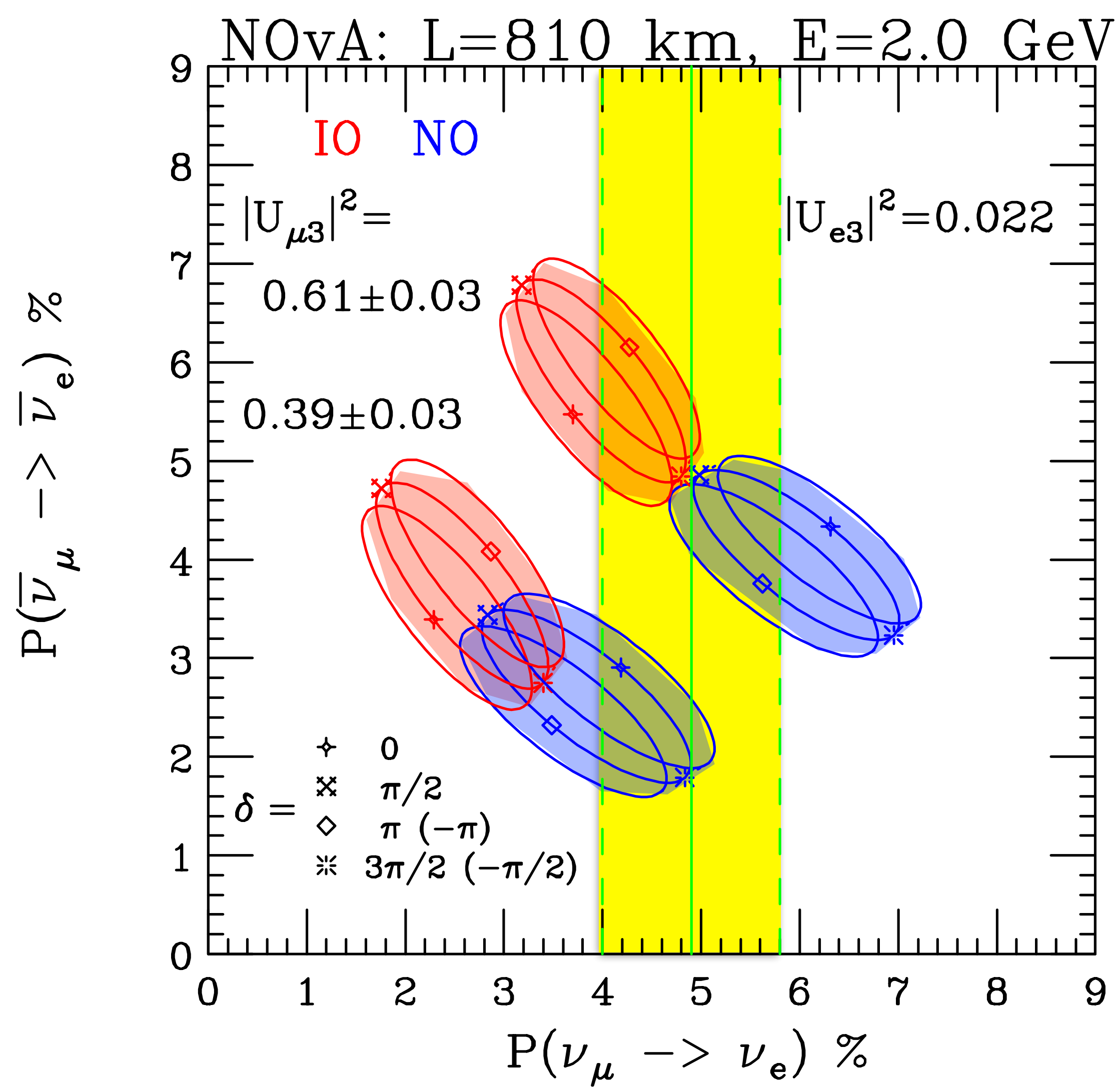

1 sigma: NO IO Appearance data

Summary:

- from Nu1998 to now, tremendous progress on Neutrino SM: more at Nu2018

- LSND Sterile Nu's neither confirmed or ruled out at acceptable CL: - ultra short baseline reactor exp.

- Great Theoretical progress on understand many aspects of Quantum Neutrino Physics: - Oscillations, Decoherence, Osc. Probabilities in Matter, Leptogenesis, ...

- Still searching for convincing model of Neutrino masses and mixings, with testable and confirmed predictions !