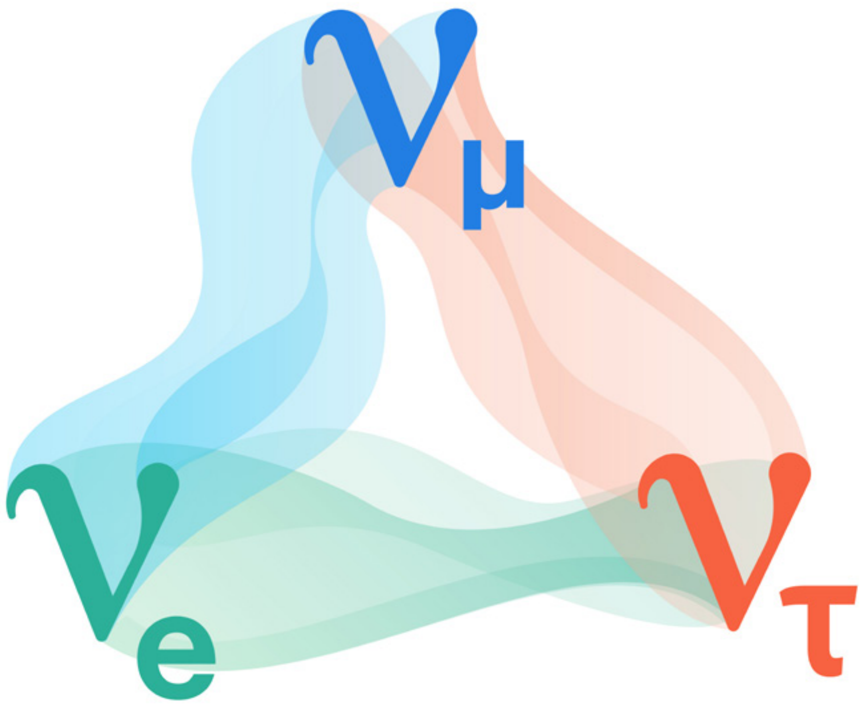
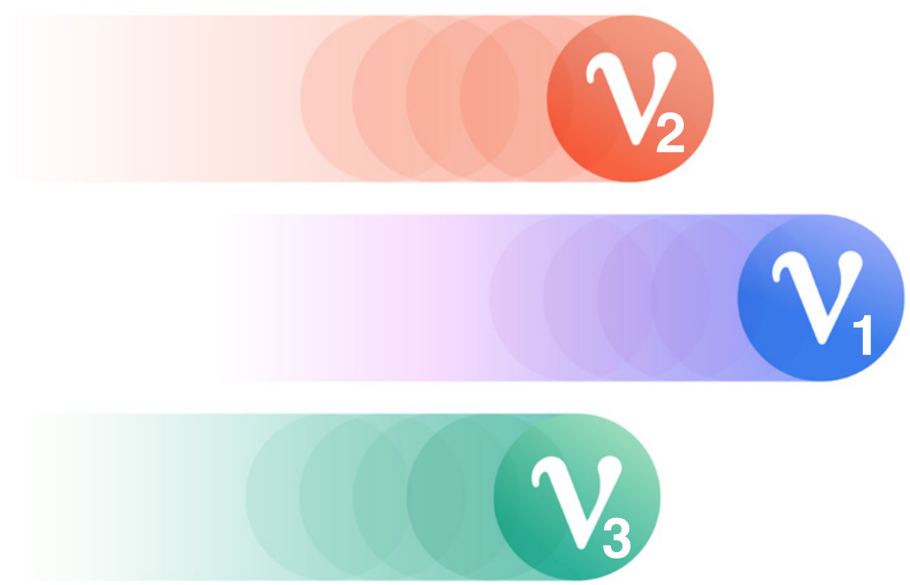
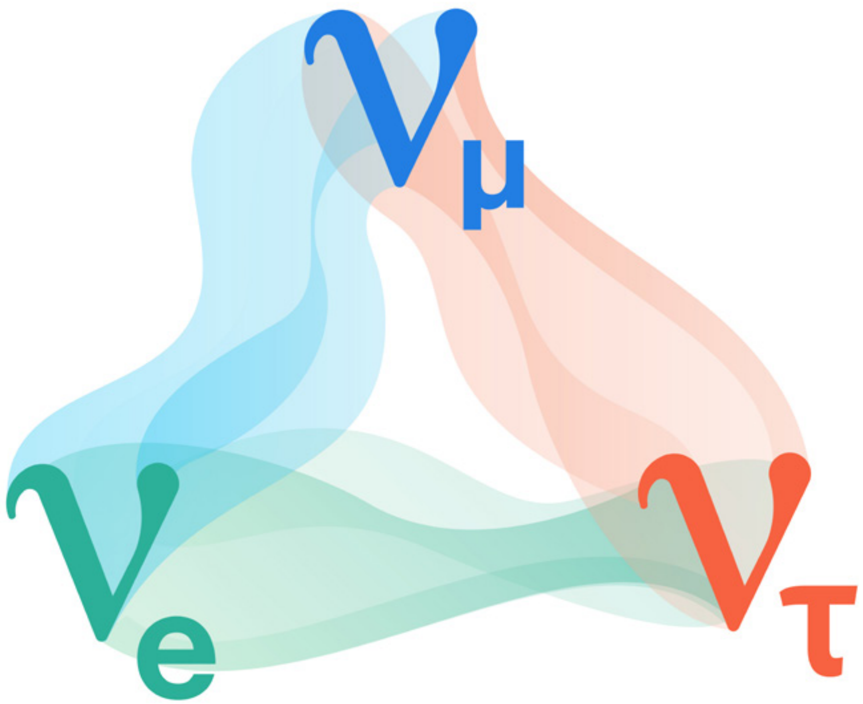
Theoretical Aspects of the Quantum Neutrino circa 2025+



Stephen Parke
Fermilab



Theoretical Aspects of the Quantum Neutrino circa 2025+



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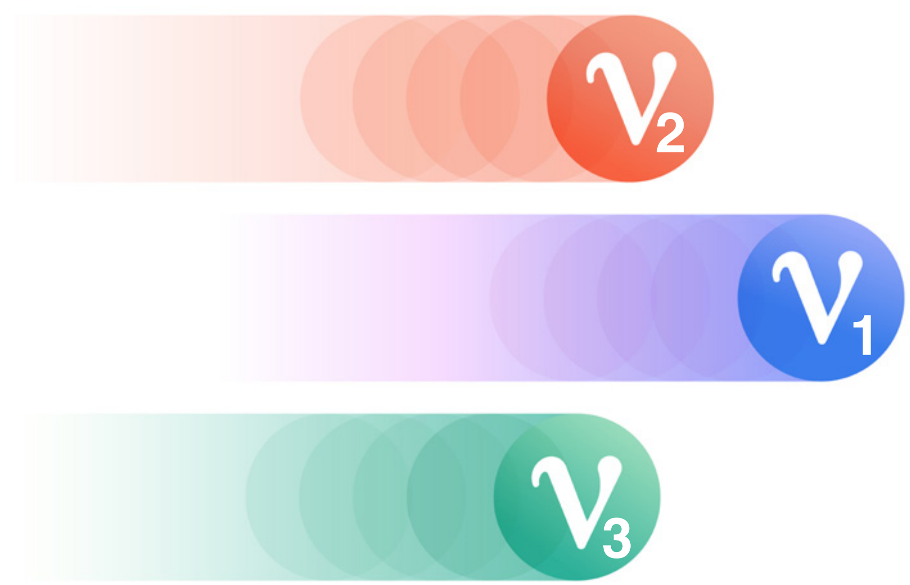
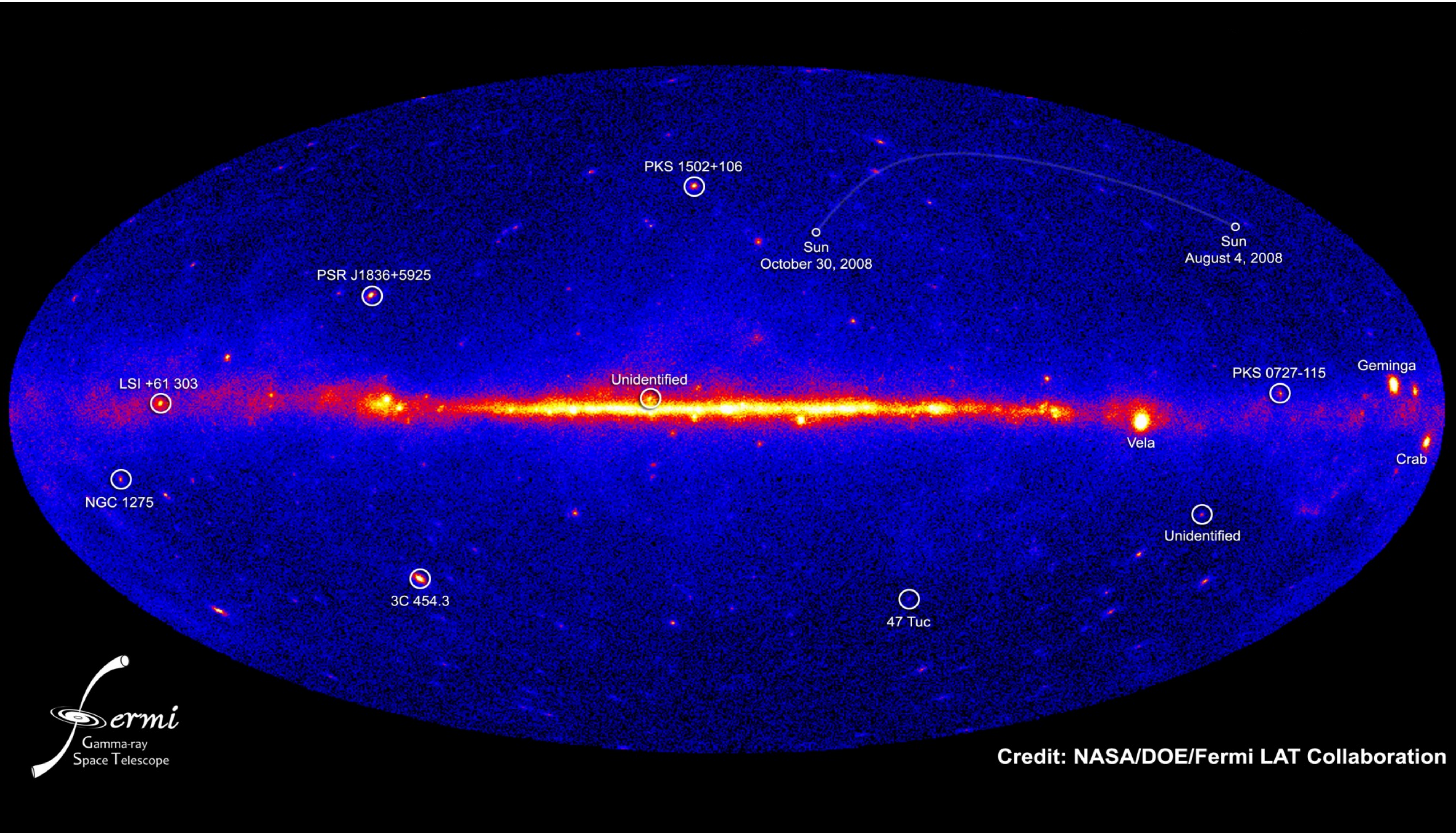
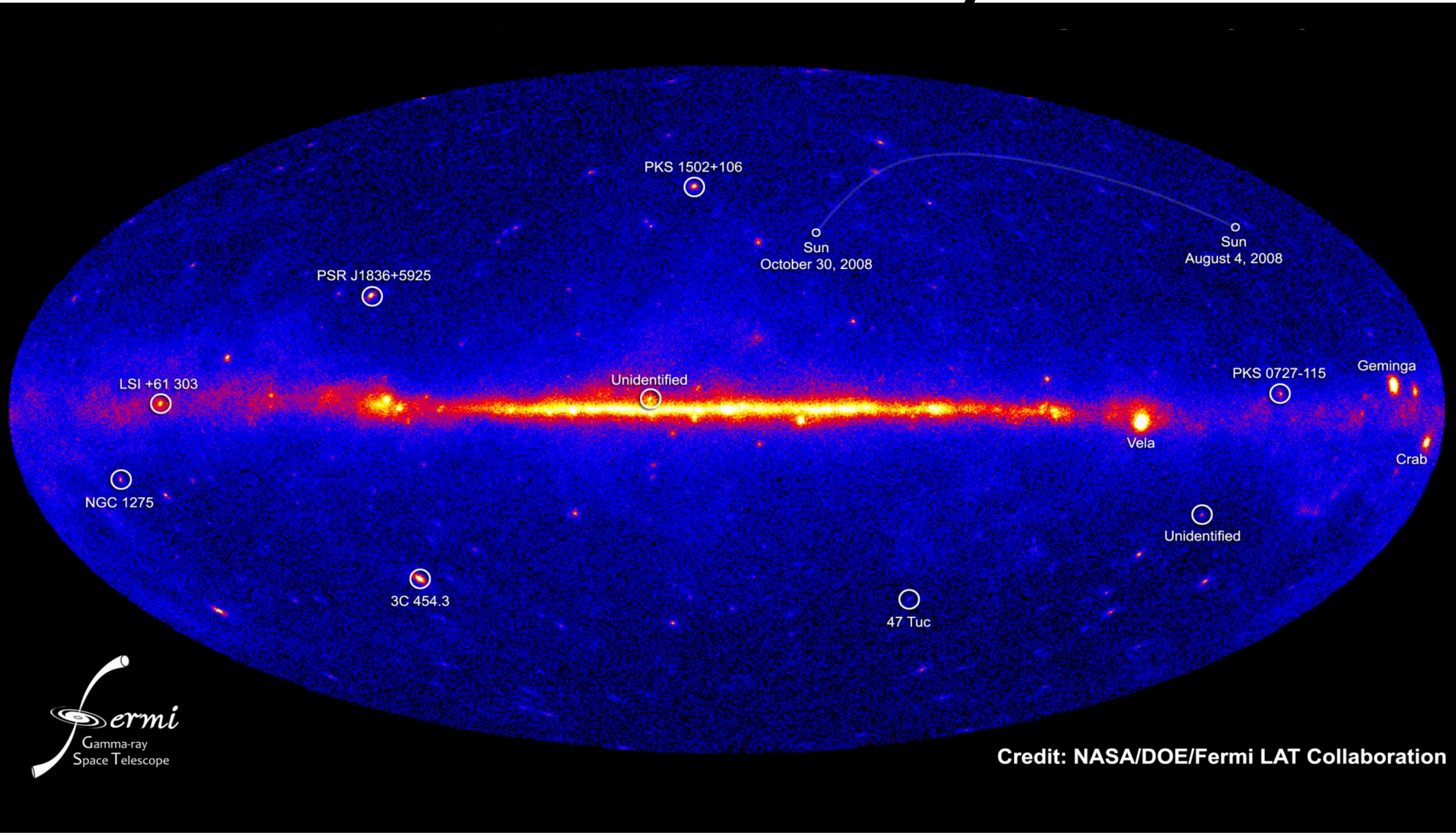



PKS 1502+106
Sun
October 30, 2008
Sun
August 4, 2008
PSR J1836+5925
Unidentified
LSI +61 303
PKS 0727-115
Geminga
Vela
Crab
NGC 1275
Unidentified
3C 454.3
47 Tuc
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

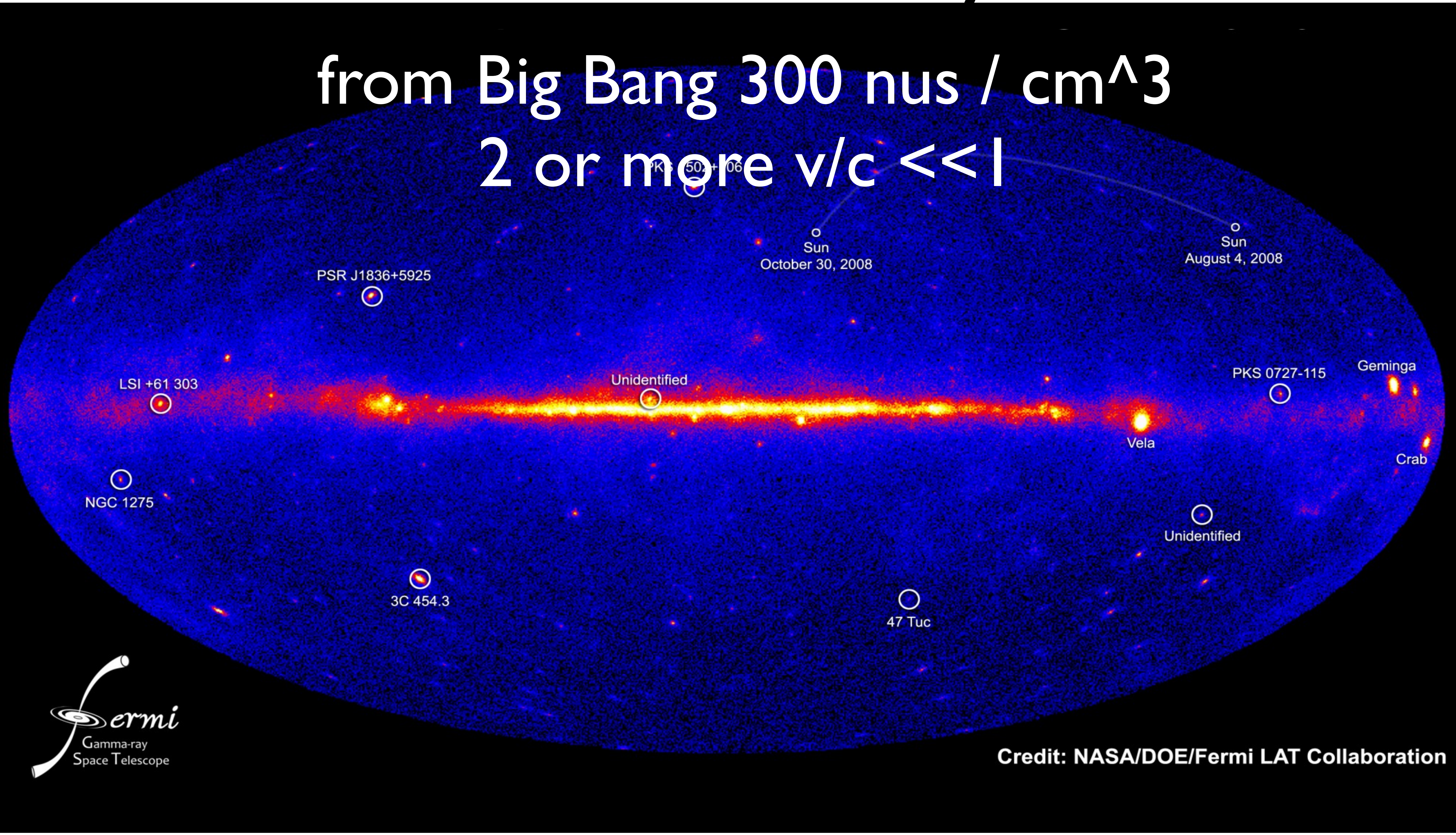
Neutrinos are Everywhere !



Neutrinos are Everywhere !

from Big Bang 300 nus / cm^3

2 or more v/c <<1



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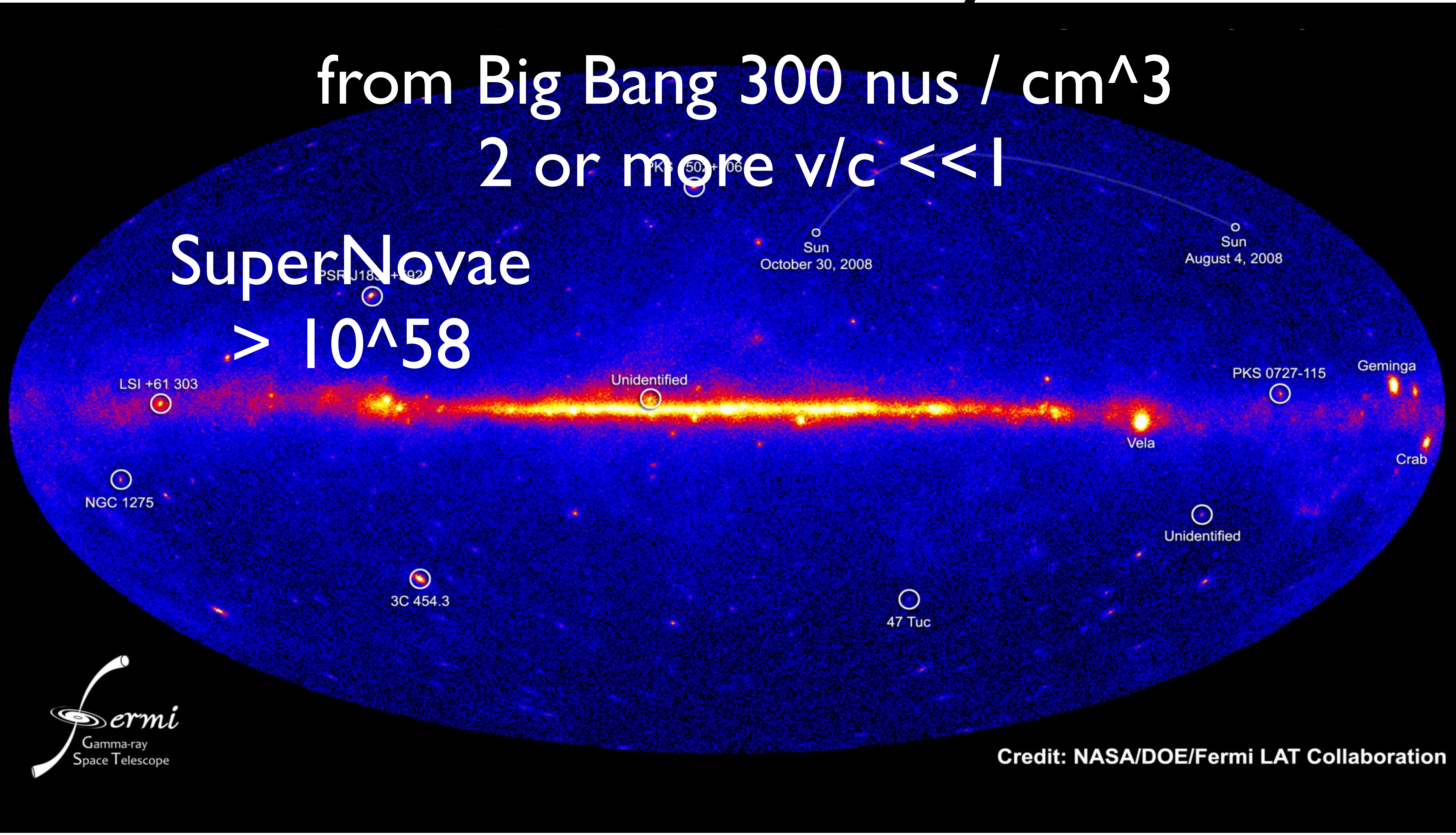

from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Neutrinos are Everywhere !

from Big Bang 300 nus / cm^3

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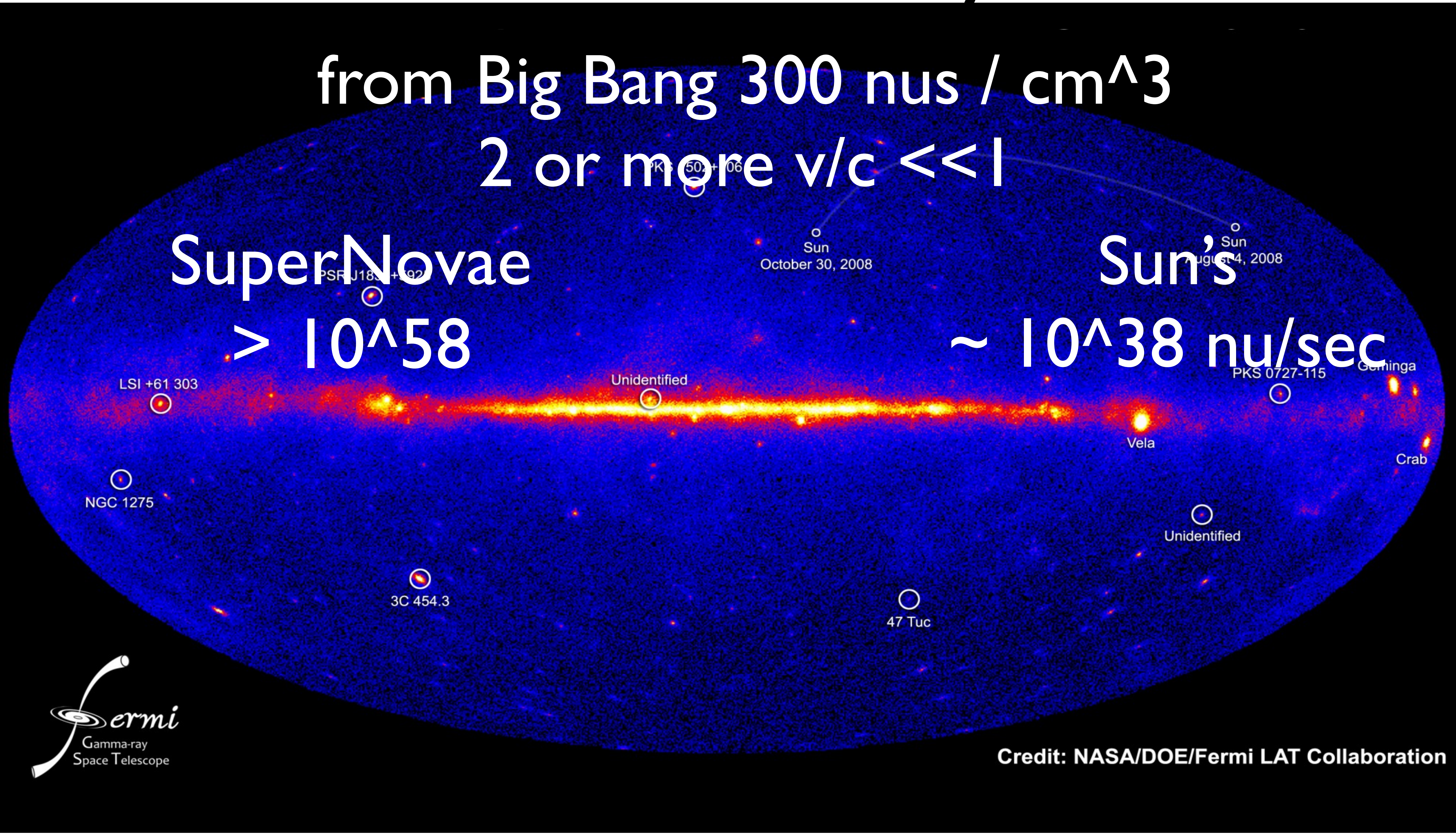
SuperNovae

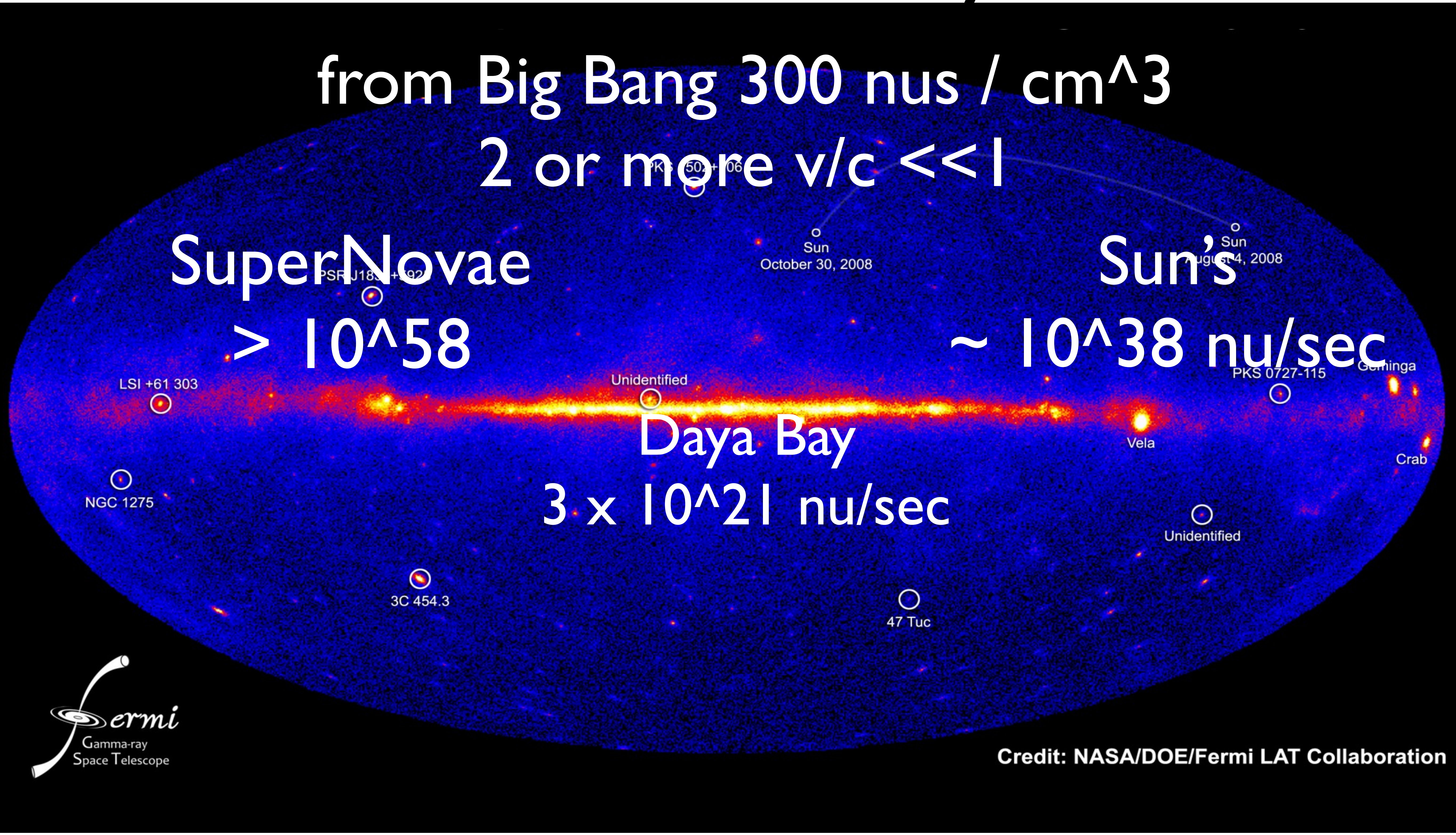
> 10^58

Sun's

~ 10^38 nu/sec



Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

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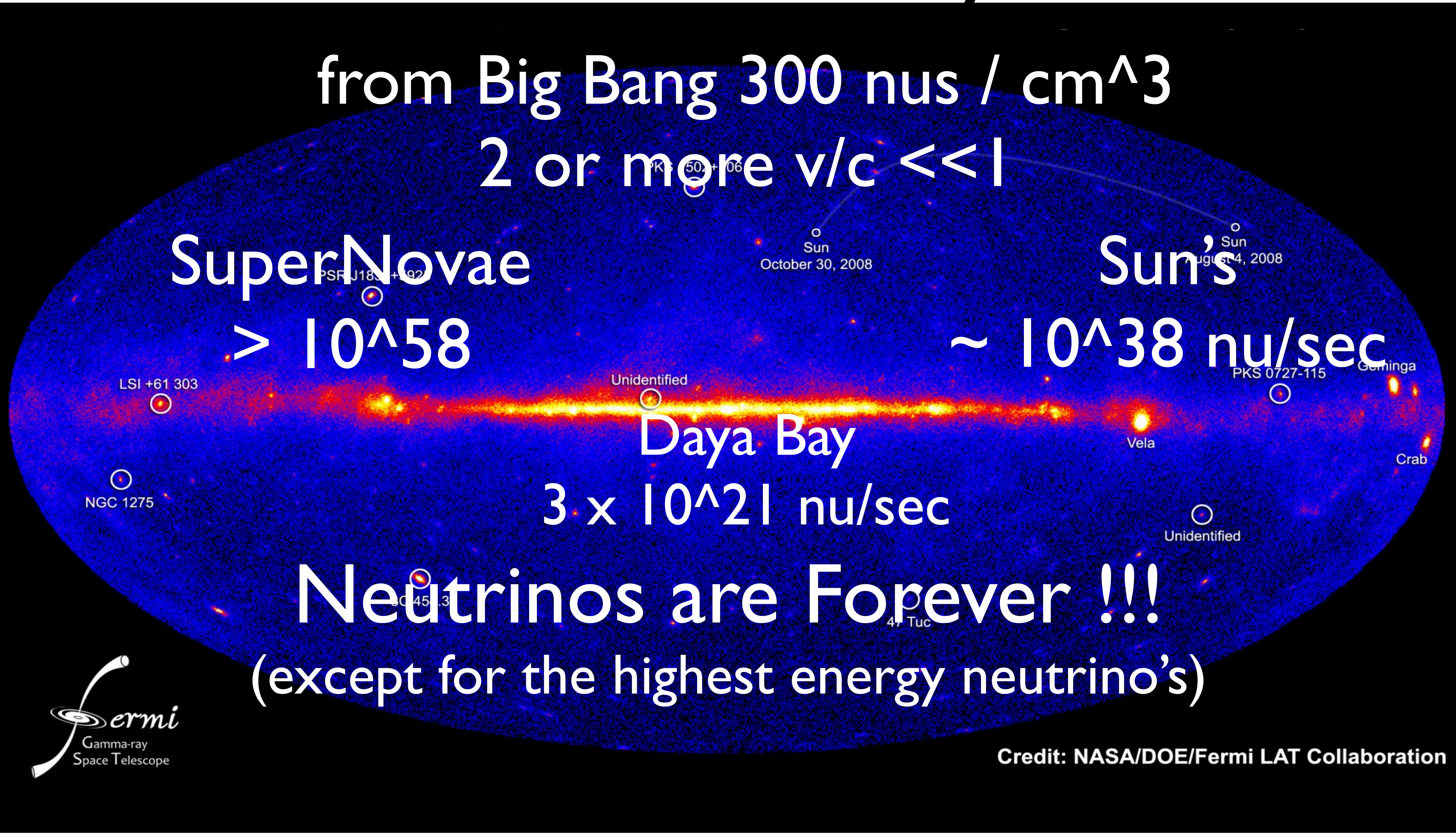
~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

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SuperNovae
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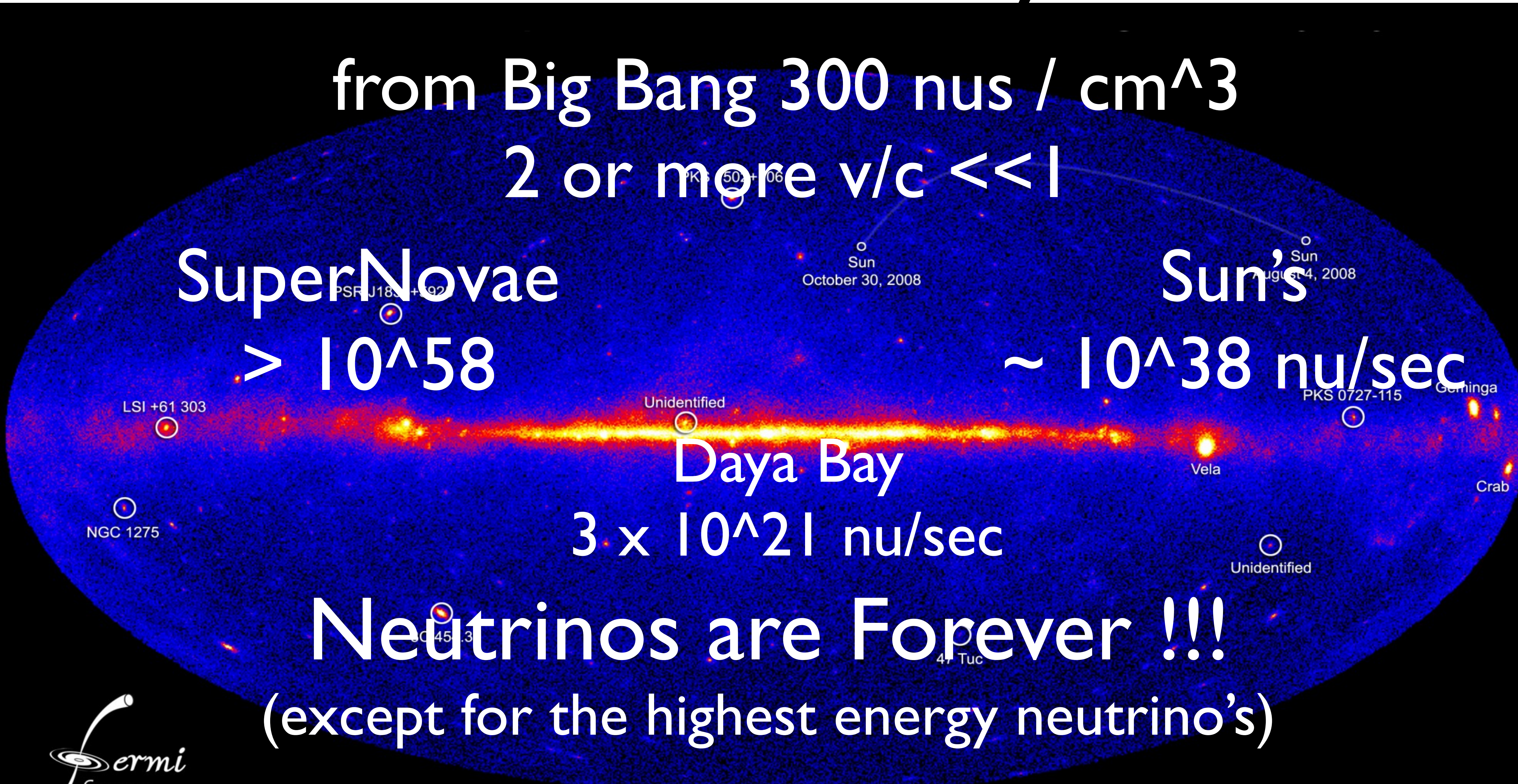
~ 10^38 nu/sec

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

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SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

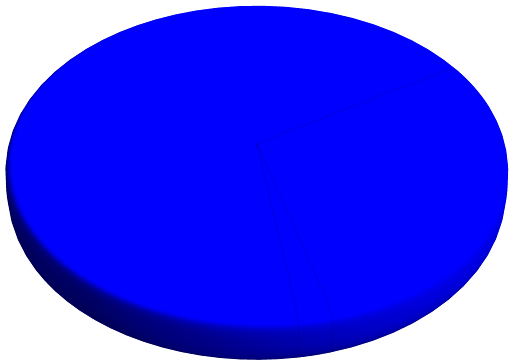
Neutrinos are Forever !!!

(except for the highest energy neutrino's)

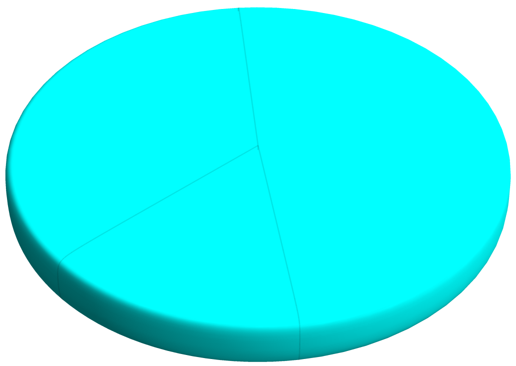
therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Flavor or Interaction States:

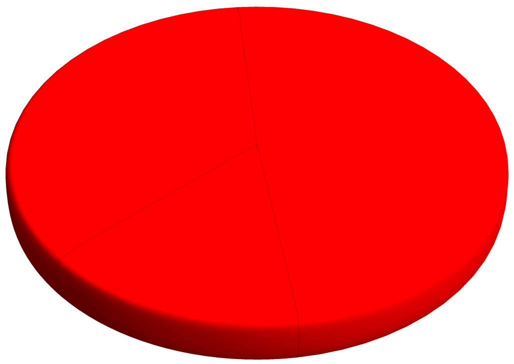
$W^+ \rightarrow e^+\nu_e$ $W^+ \rightarrow \mu^+\nu_\mu$ $W^+ \rightarrow \tau^+\nu_\tau$



ν_e



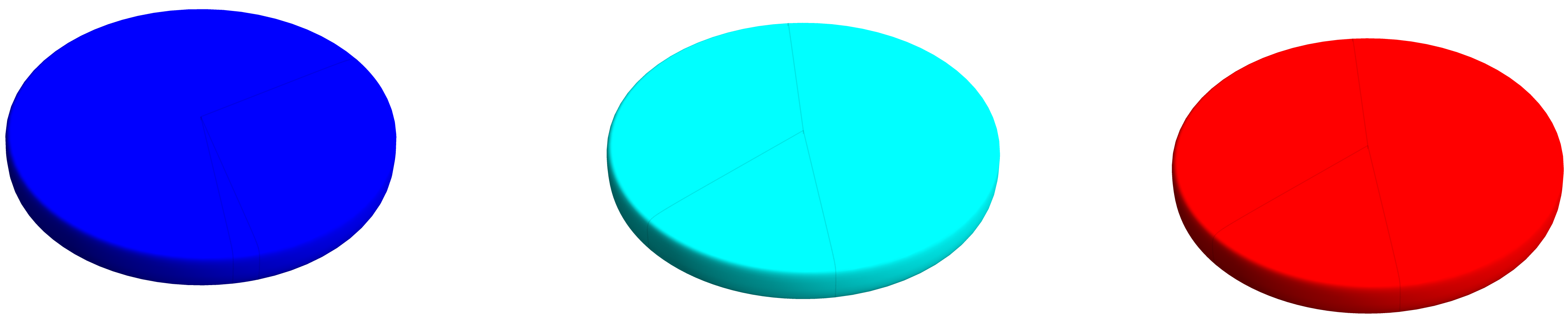
ν_μ



ν_τ

Neutrino Flavor or Interaction States:

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



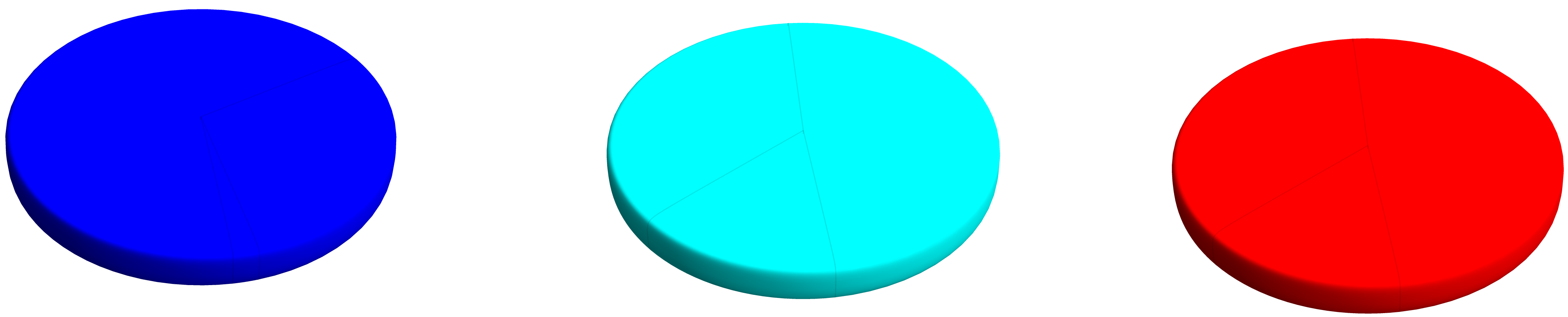
ν_e $\qquad$ ν_μ $\qquad$ ν_τ

provided $L/E \ll \mathbf{0.5}$ km/MeV $=$ $\mathbf{500}$ 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

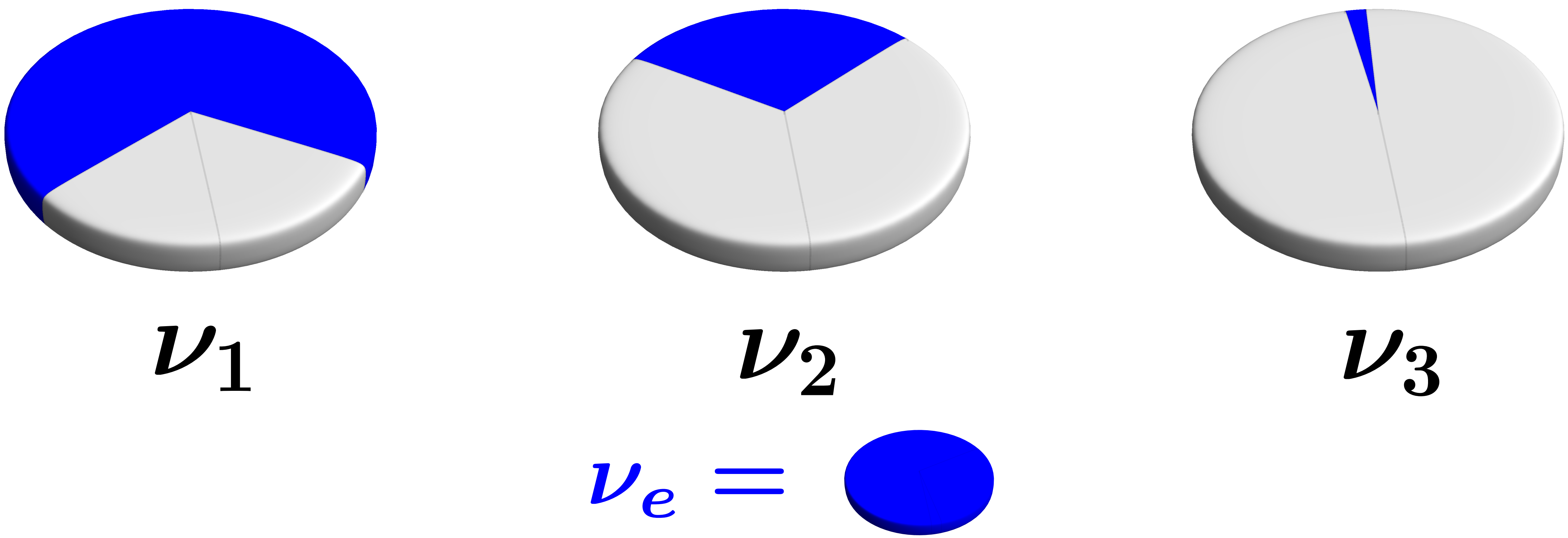
provided $L/E \ll \mathbf{0.5}$ km/MeV $= \mathbf{500}$ km/GeV !!!

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

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

Neutrino Mass EigenStates or Propagation States:

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



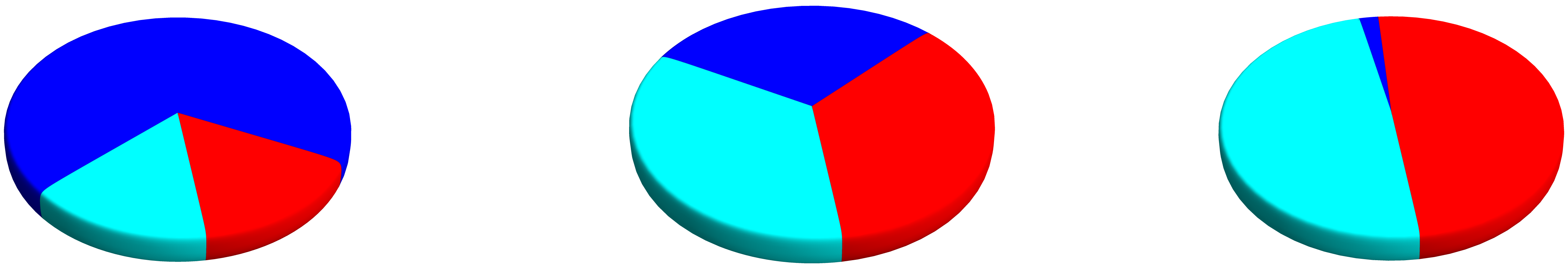
Neutrino Mass EigenStates or Propagation States:

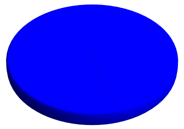
$$\text{Propagator } \nu_j \rightarrow \nu_k \;= \boldsymbol{\delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}}$$

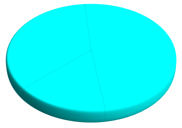
$\boldsymbol{\nu_1}$ most ν_e

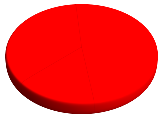
$\boldsymbol{\nu_2}$

$\boldsymbol{\nu_3}$ least ν_e



$\boldsymbol{\nu_e =}$ 

$\boldsymbol{\nu_\mu =}$ 

$\boldsymbol{\nu_\tau =}$ 

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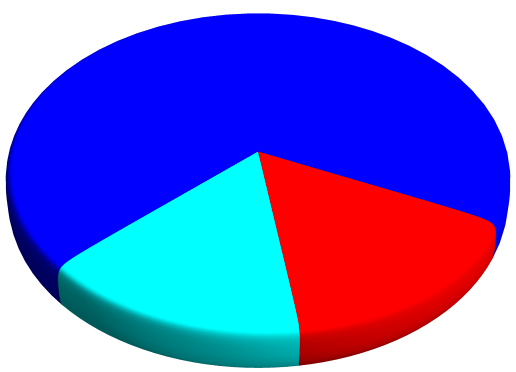
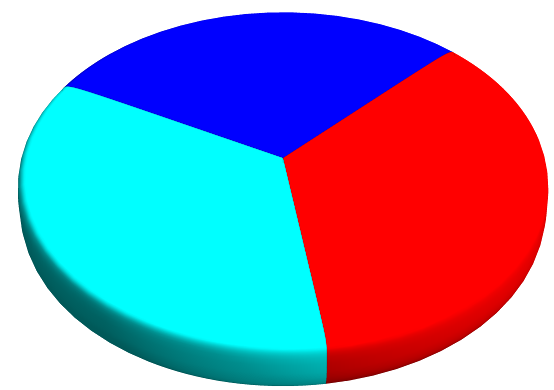
ν_1

most ν_e

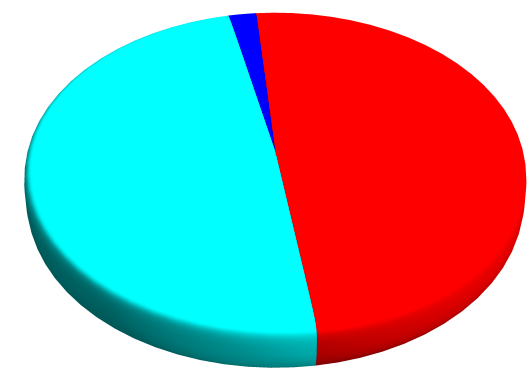


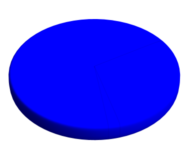
ν_2

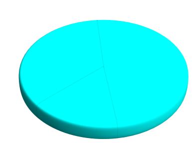


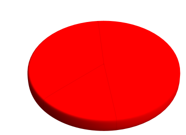
ν_3

least ν_e



$\nu_e =$ 

$\nu_\mu =$ 

$\nu_\tau =$ 

Solar Exp, SNO, SK,
KamiLAND
Daya Bay, RENO, …

Neutrino Mass EigenStates or Propagation States:

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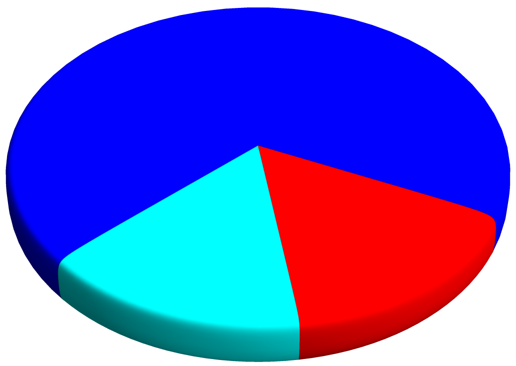
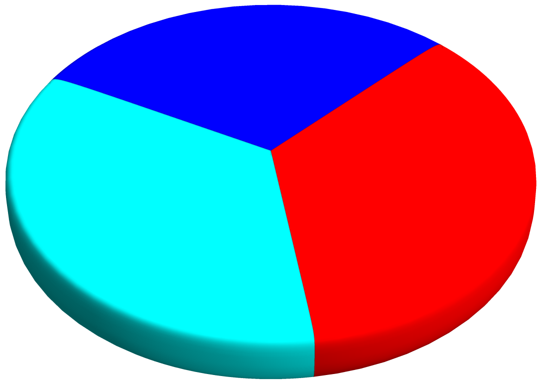
$\boldsymbol{\nu_1}$

most ν_e

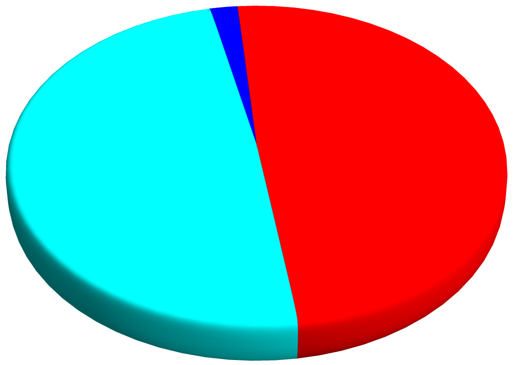


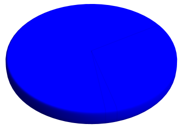
$\boldsymbol{\nu_2}$



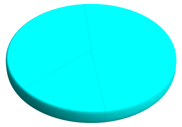
$\boldsymbol{\nu_3}$

least ν_e

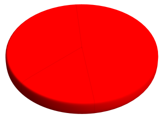


$\boldsymbol{\nu_e =}$ 

Solar Exp, SNO, SK,
KamiLAND
Daya Bay, RENO, …

$\boldsymbol{\nu_\mu =}$ 

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\boldsymbol{\nu_\tau =}$ 

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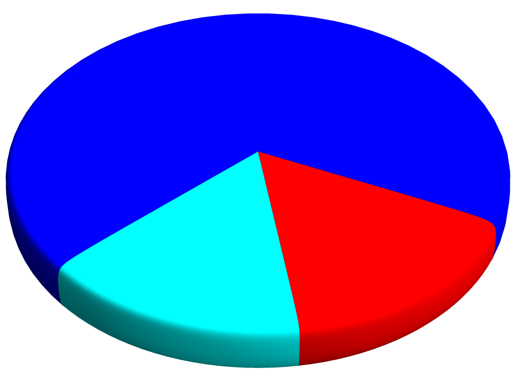
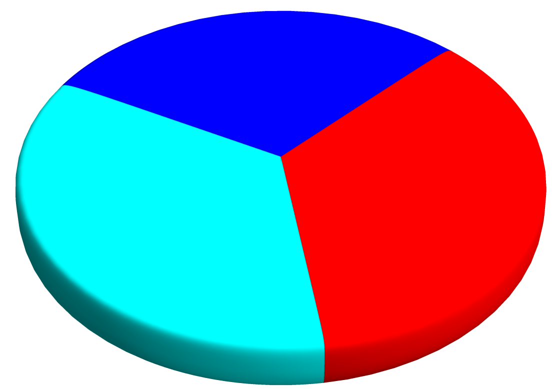
ν_1

most ν_e

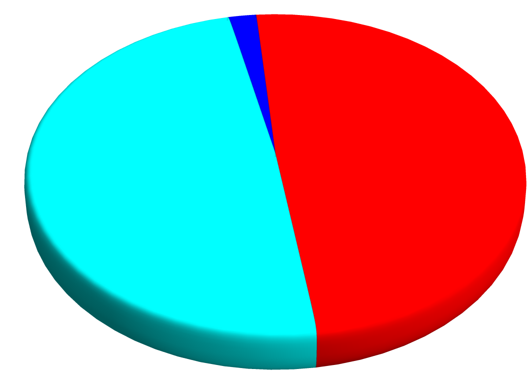


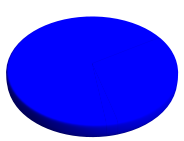
ν_2



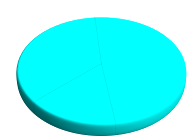
ν_3

least ν_e



$\nu_e =$ 

Solar Exp, SNO, SK,
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ 

SuperK, K2K, T2K
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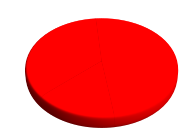
ICECUBE

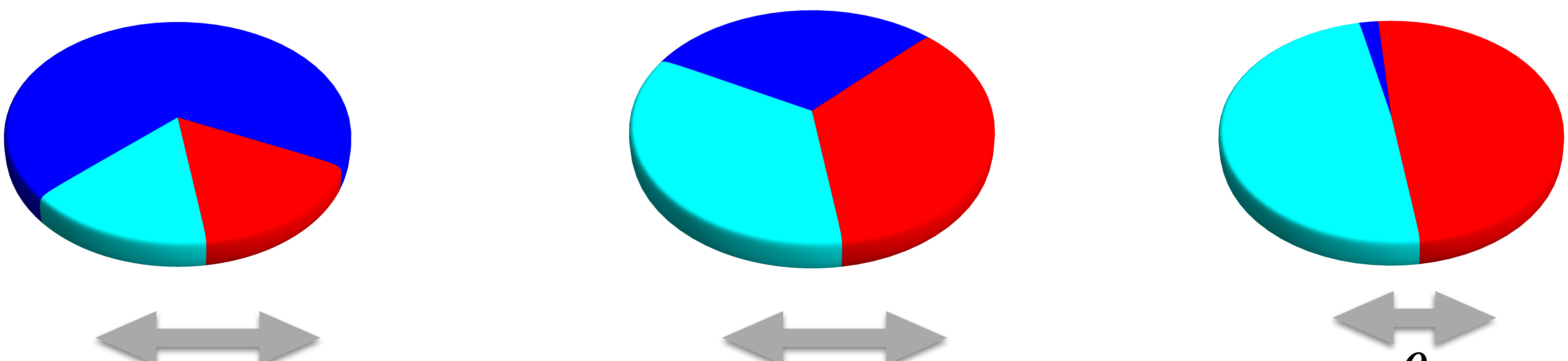
$\nu_\tau =$ 

Unitarity
SK, Opera
ICECUBE ?

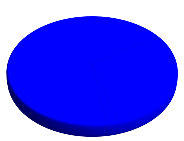
Neutrino Mass EigenStates or Propagation States:

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

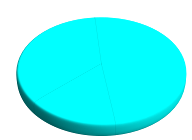
ν_1 most ν_e | ν_2 | ν_3 least ν_e



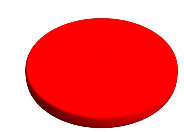
δ, θ_{23} | δ, θ_{23} | θ_{23}

$\nu_e =$ 

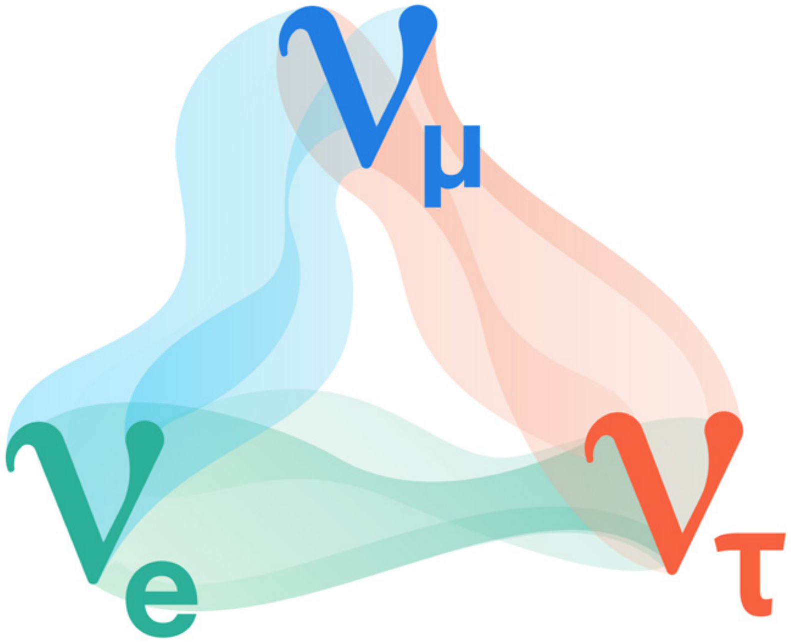
Solar Exp, SNO, SK,
KamiLAND
Daya Bay, RENO, …

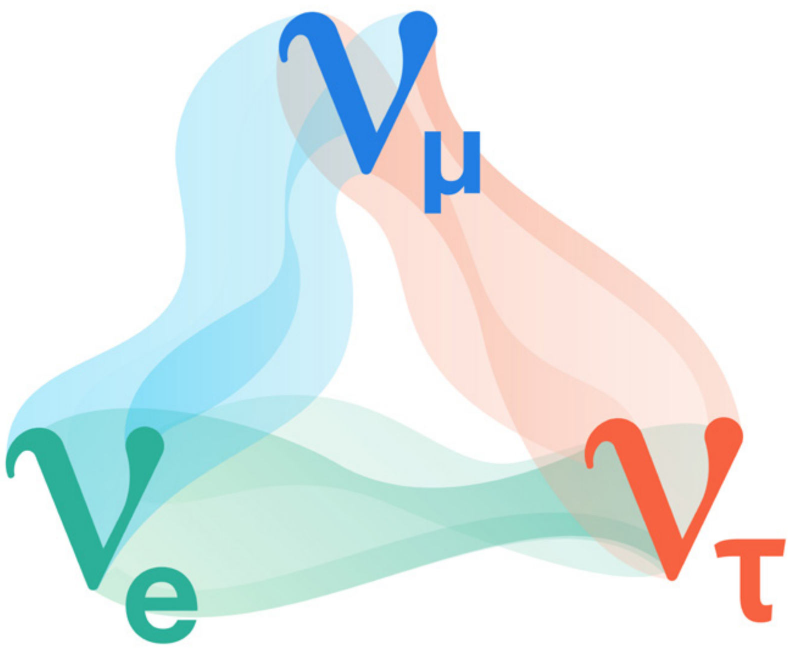
$\nu_\mu =$ 

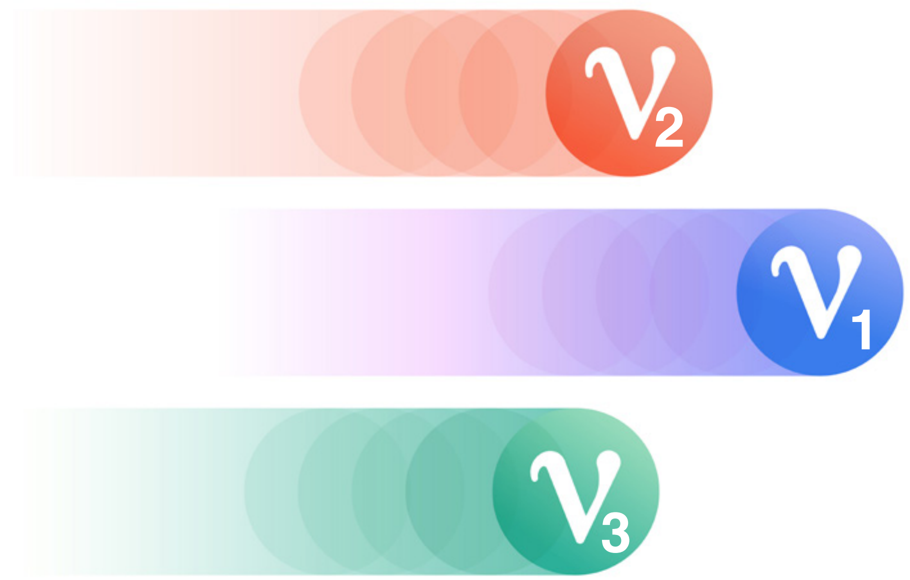
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ 

Unitarity
SK, Opera
ICECUBE ?

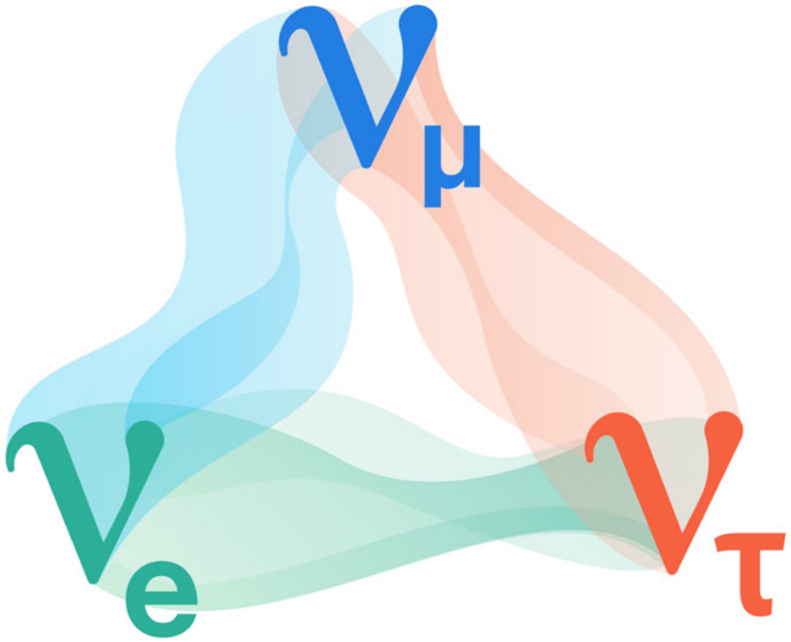

νμ
νe
ντ


ν_μ
ν_e
ν_τ

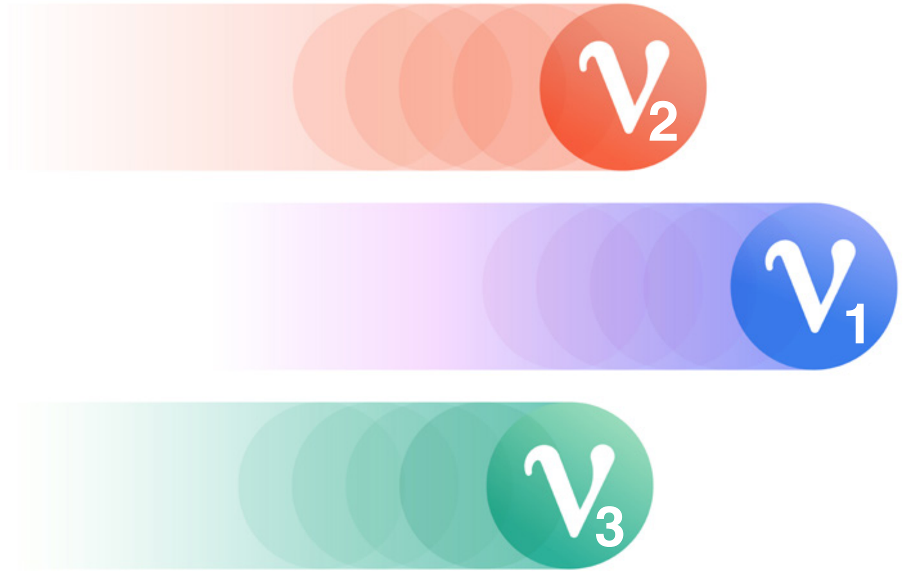

ν_2
ν_1
ν_3

Interactions:

simple

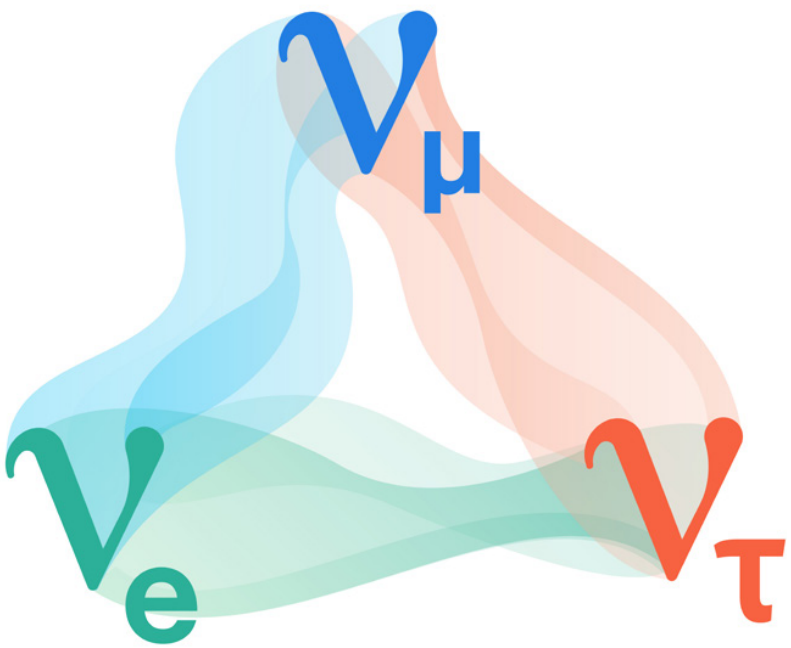


complicated



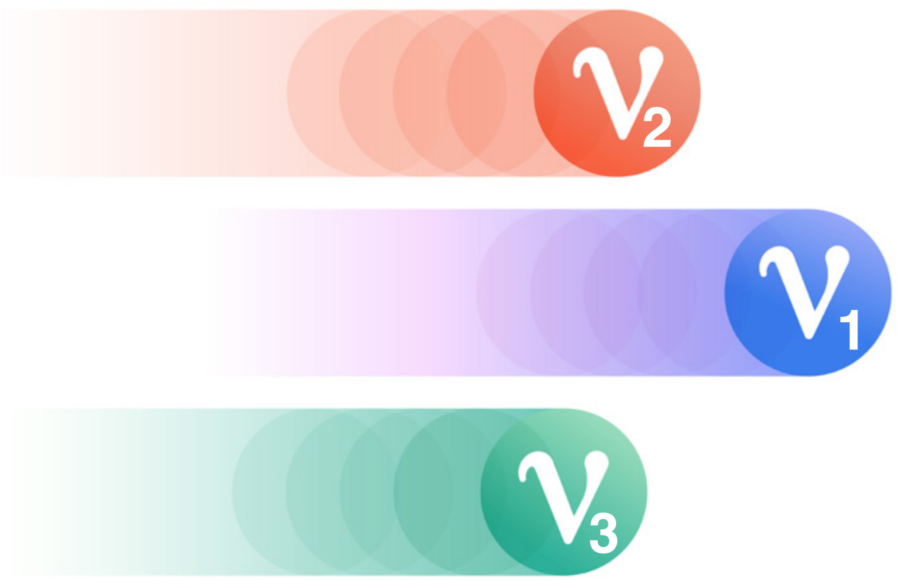
Interactions:

simple



complicated

complicated

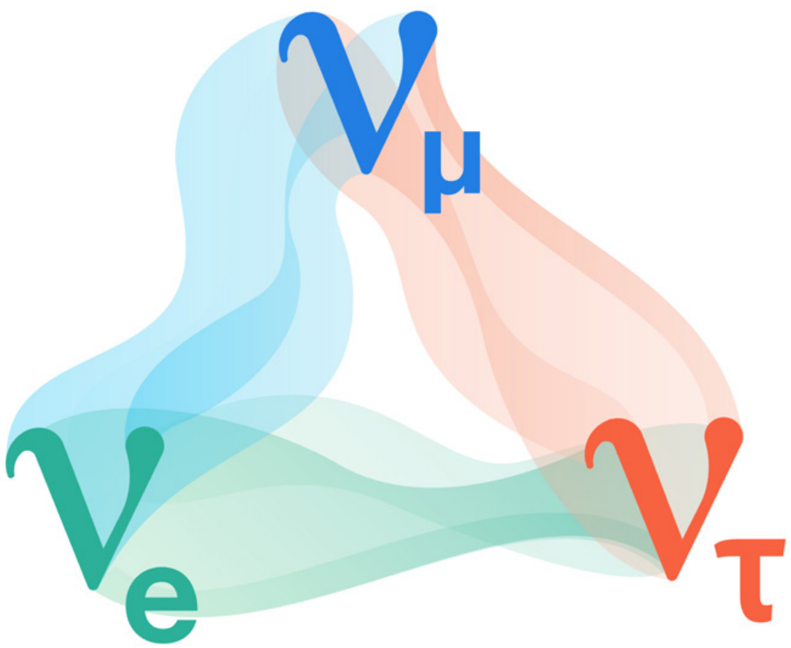


simple

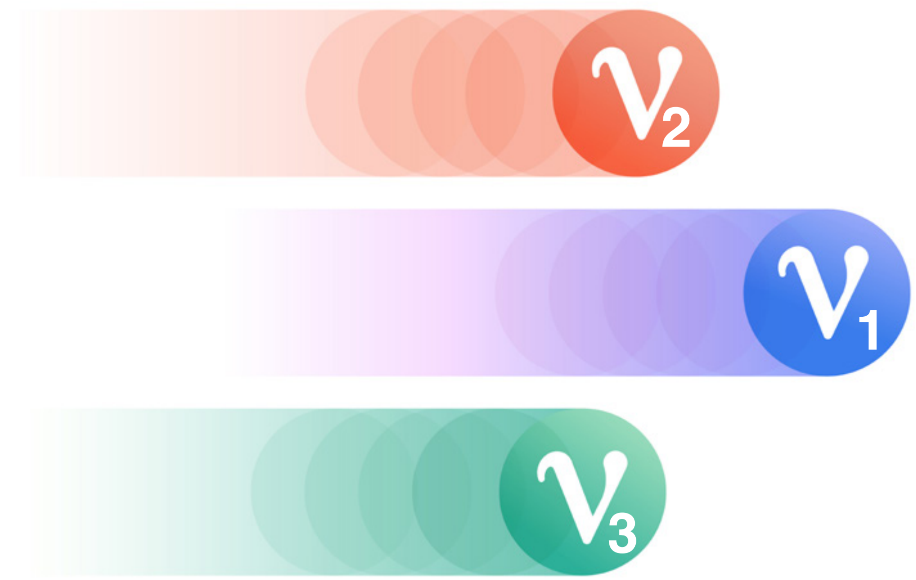
Propagation:

Interactions:

simple complicated



$= U$

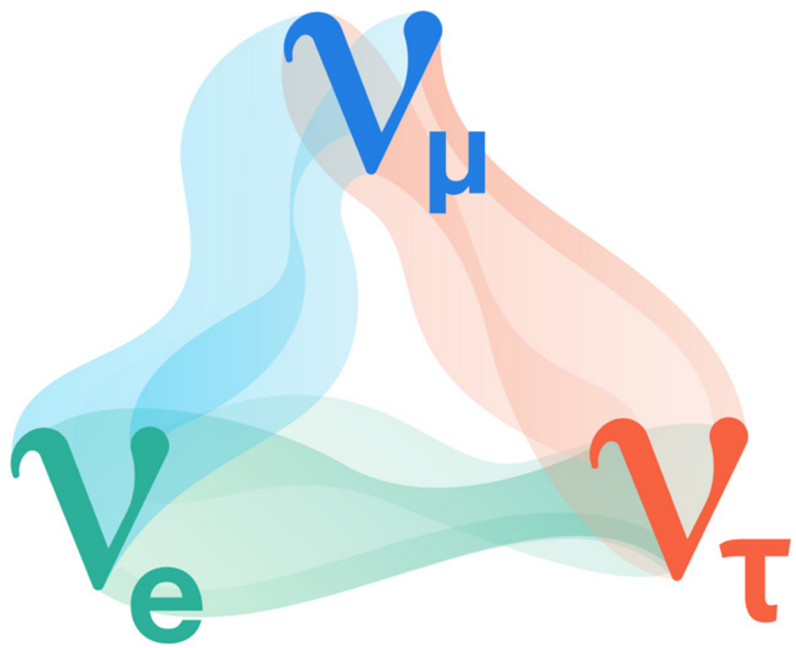


complicated simple

Propagation:

Interactions:

simple



complicated

$$=\mathbf{U}$$

unitary matrix ?

complicated

simple

masses ?

Propagation:

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

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

Why this order ???

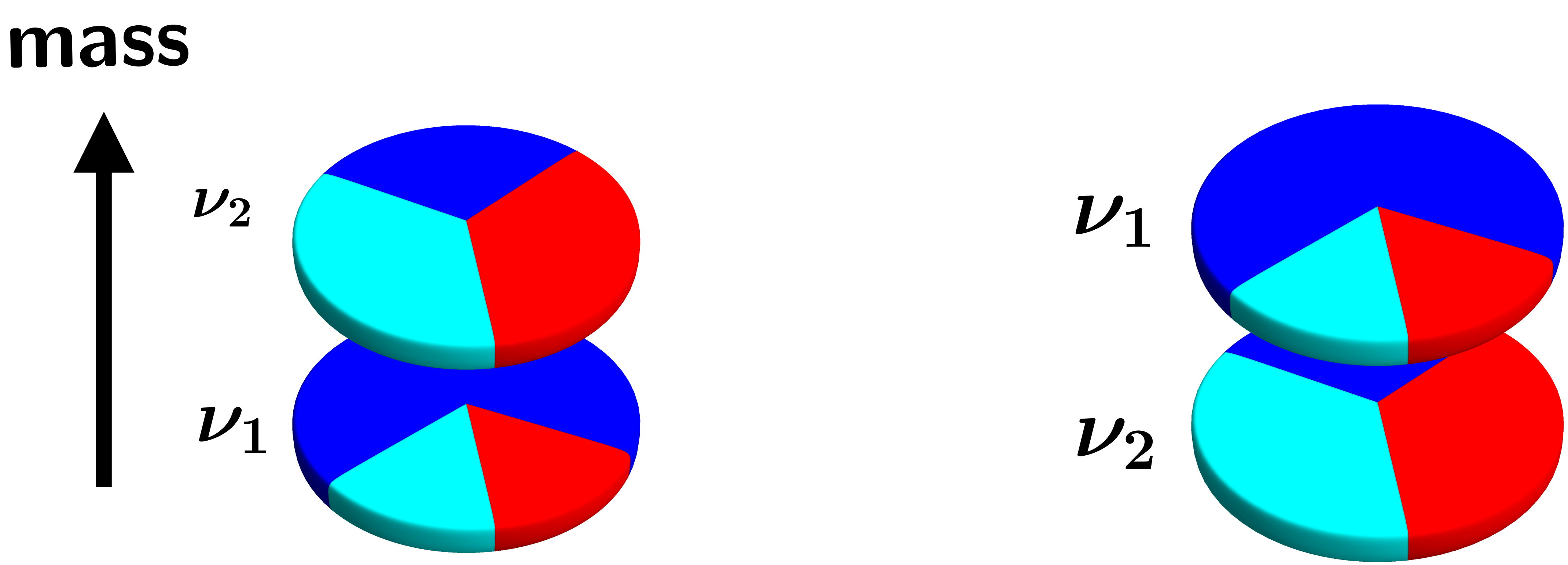
$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{+i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

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

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

$\nu_1, \ \nu_2$ Mass Ordering:

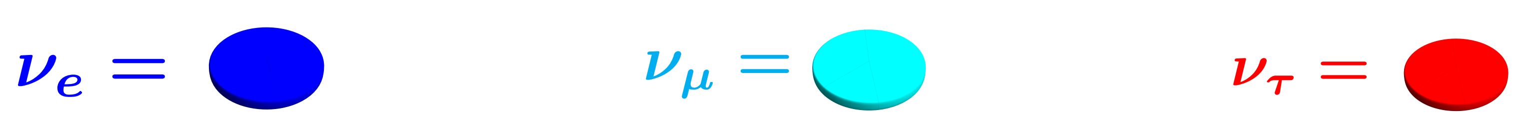
–solar mass ordering



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

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

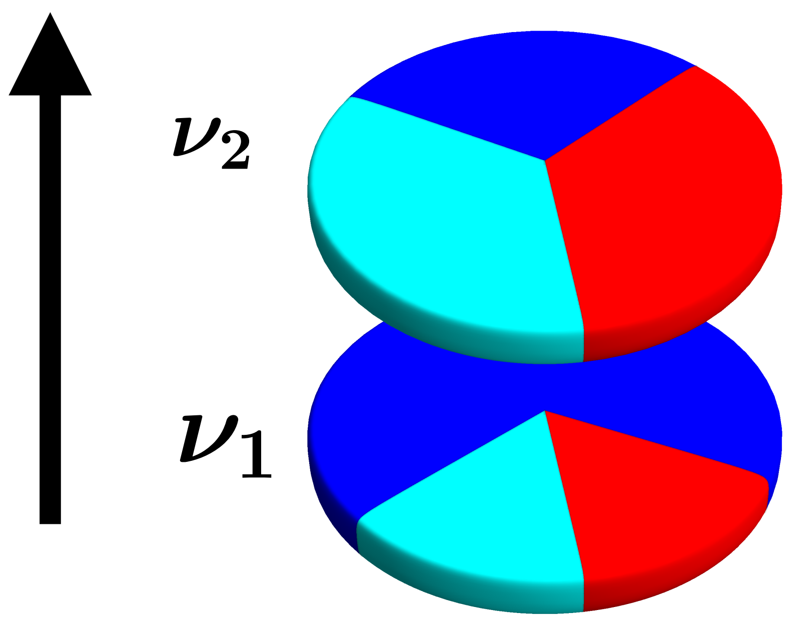
SNO $m_2 > m_1$



$\nu_1,\ \nu_2$ Mass Ordering:

–solar mass ordering

mass



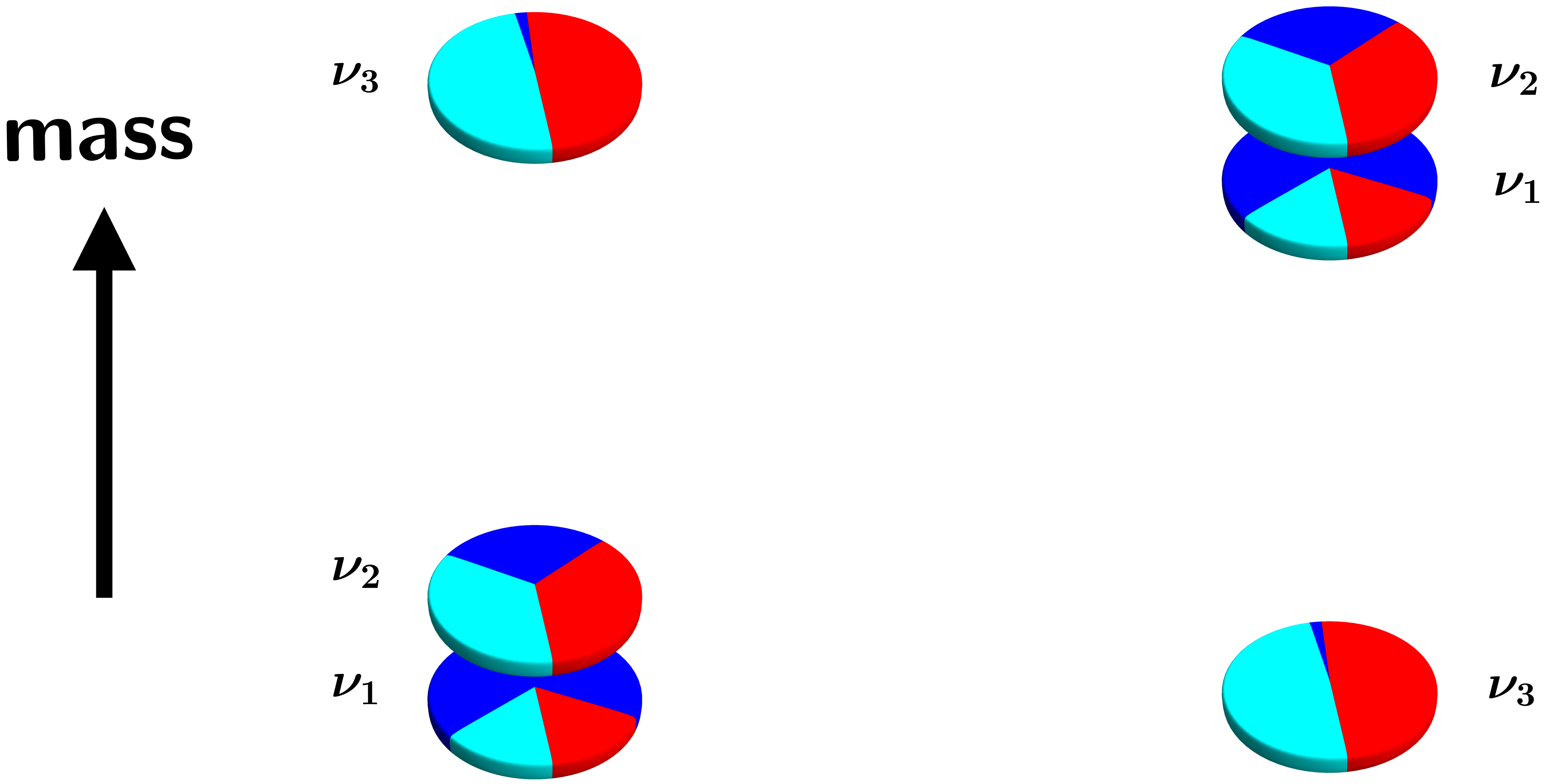
$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = \mathbf{7.5} \times \mathbf{10^{-5}}\ \mathrm{eV}^2$ $\quad$ $L/E = \mathbf{15}\ \mathrm{km/MeV} = \mathbf{15,000}\ \mathrm{km/GeV}$

SNO $\quad m_2 > m_1$

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

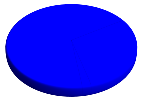
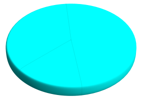
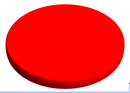
ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering



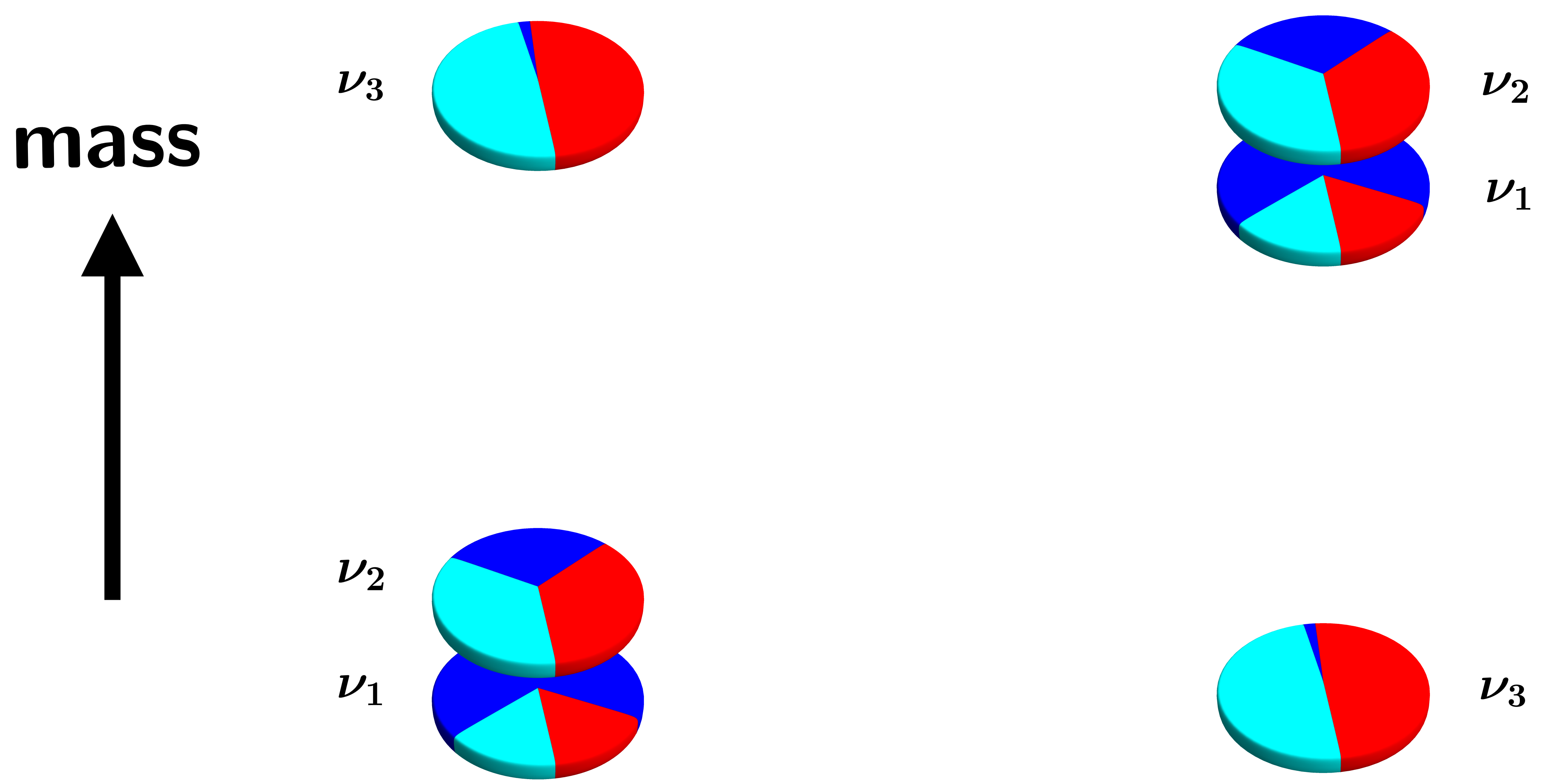
$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \text{eV}^2$

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

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

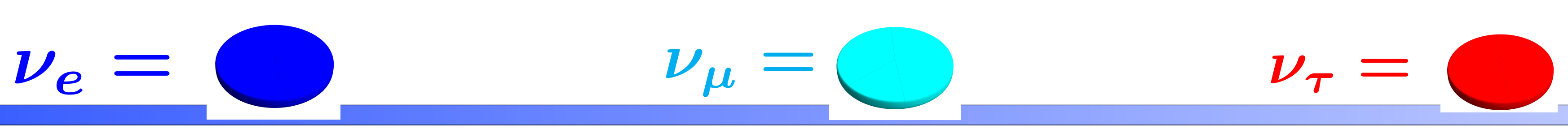
$\nu_3, \ \nu_1/\nu_2$ Mass Ordering:

–atmospheric mass ordering



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

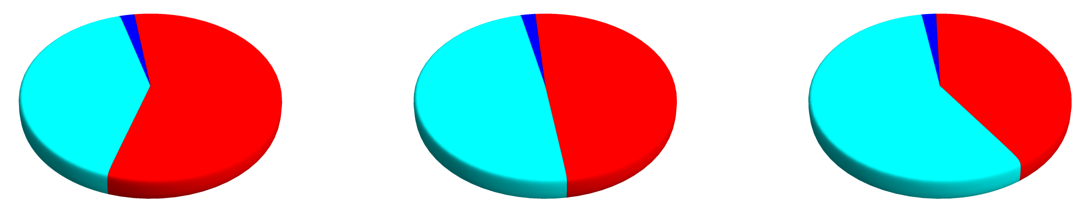
Unknown: NOνA, JUNO, ICECUBE, DUNE, T2HKK....



Summary: Octant of θ_{23}

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

ν_3

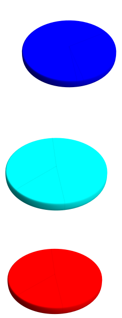


0

δ $\pm\pi/2$

π

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



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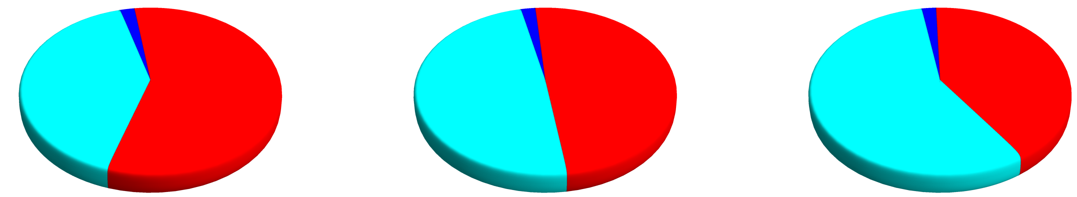
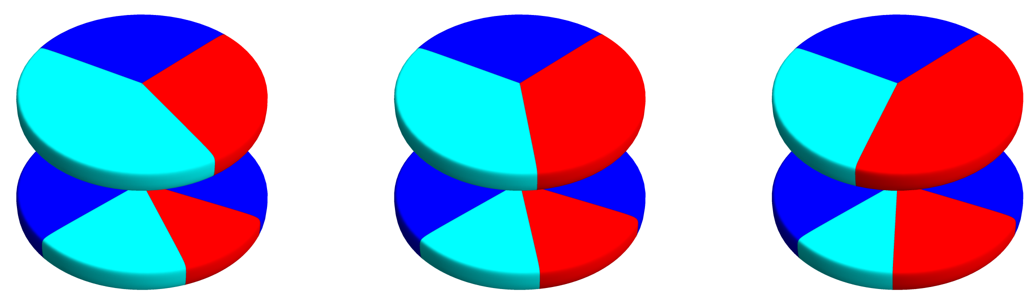


0

δ $\pm\pi/2$

ν_2

ν_1



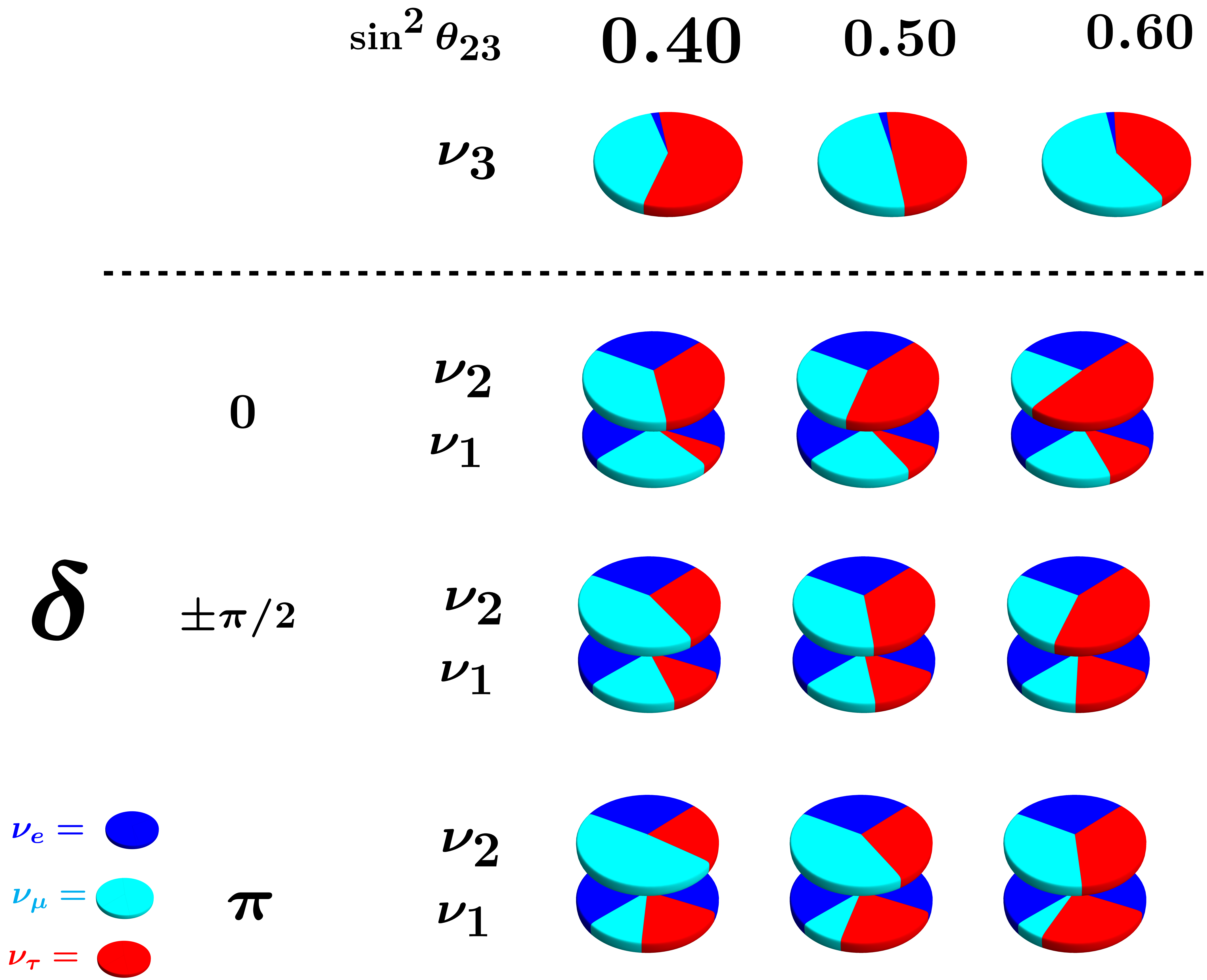
$\nu_e =$

$\nu_\mu =$

$\nu_\tau =$

π

Summary: Octant of θ_{23}

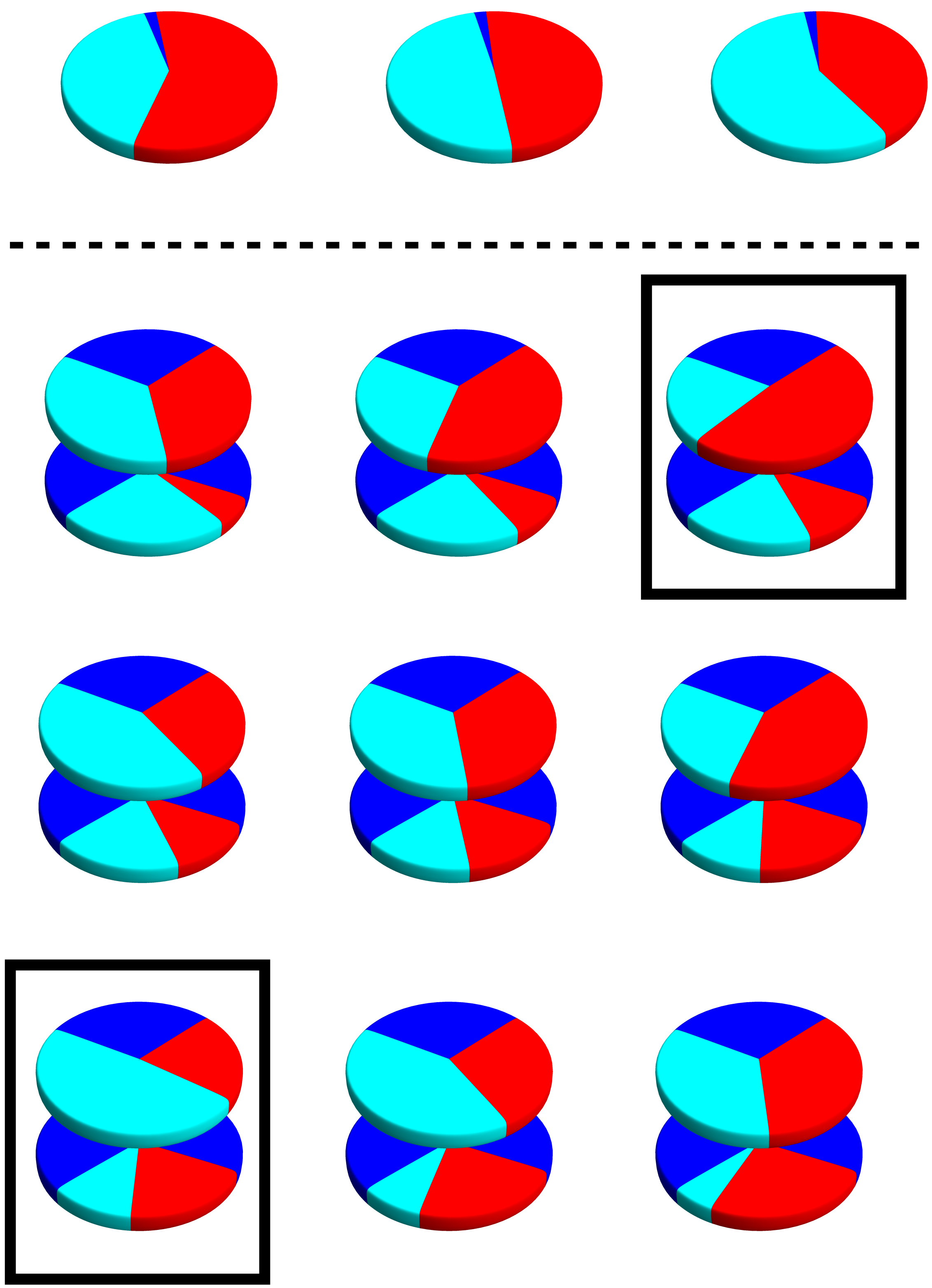


Summary:

Octant of θ_{23}

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

ν_3



ν_2 variation

δ

0: ν_2, ν_1

$\pm\pi/2$: ν_2, ν_1

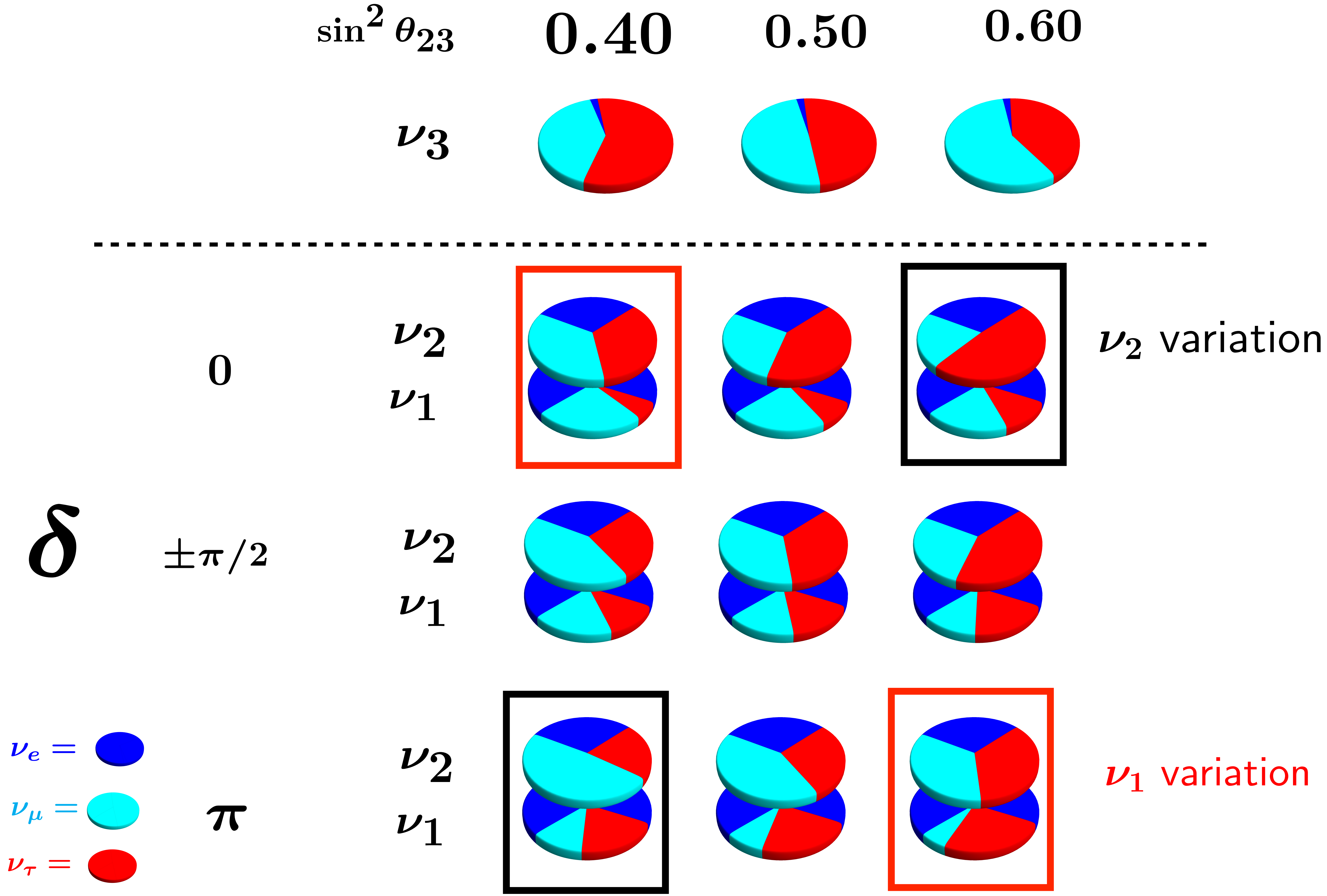
π: ν_2, ν_1

$\nu_e =$

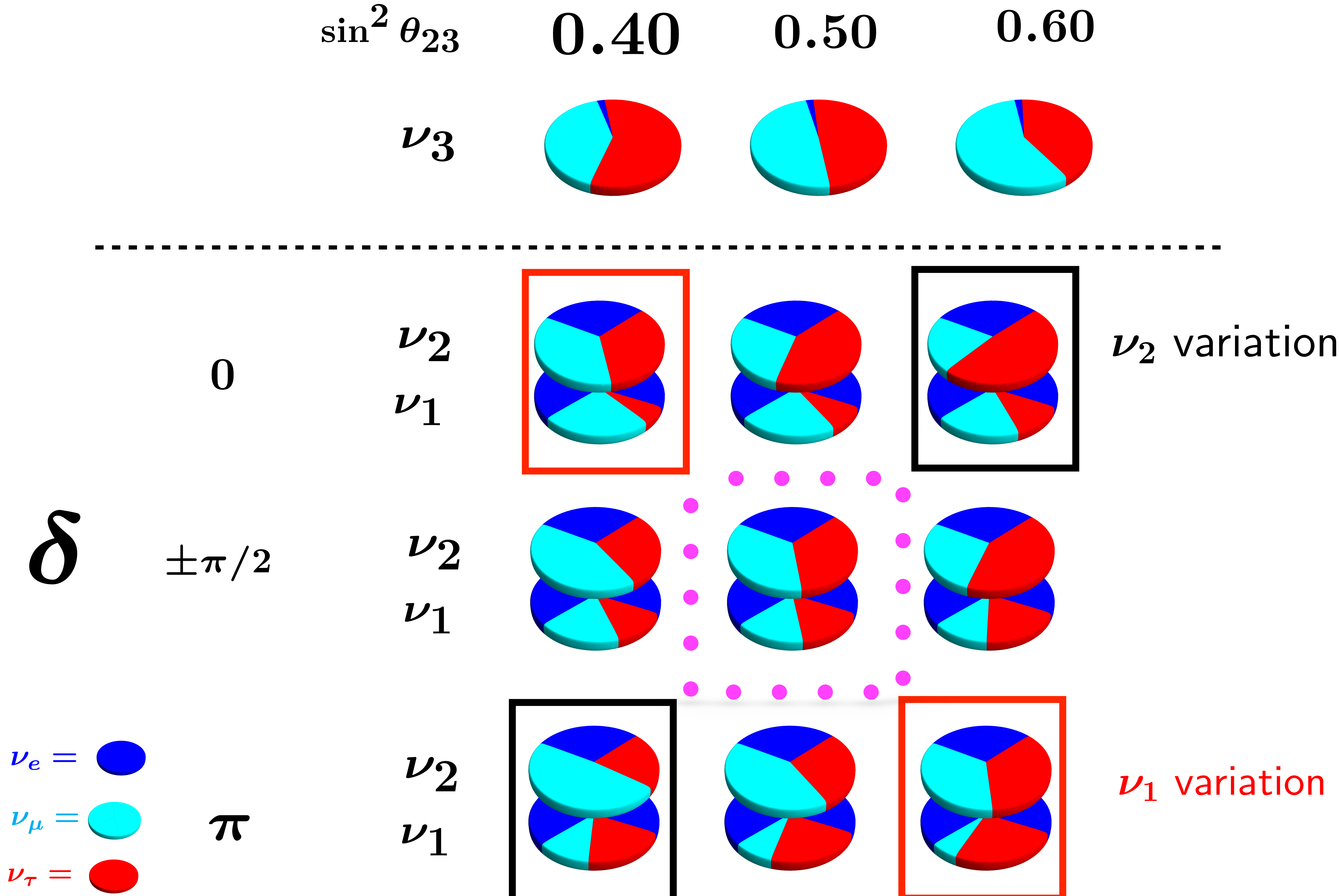
$\nu_\mu =$

$\nu_\tau =$

Summary: Octant of θ_{23}



Summary: Octant of θ_{23}



WHY?

Precision
Neutrino
Measurements:

WHY?

Precision Neutrino Measurements:

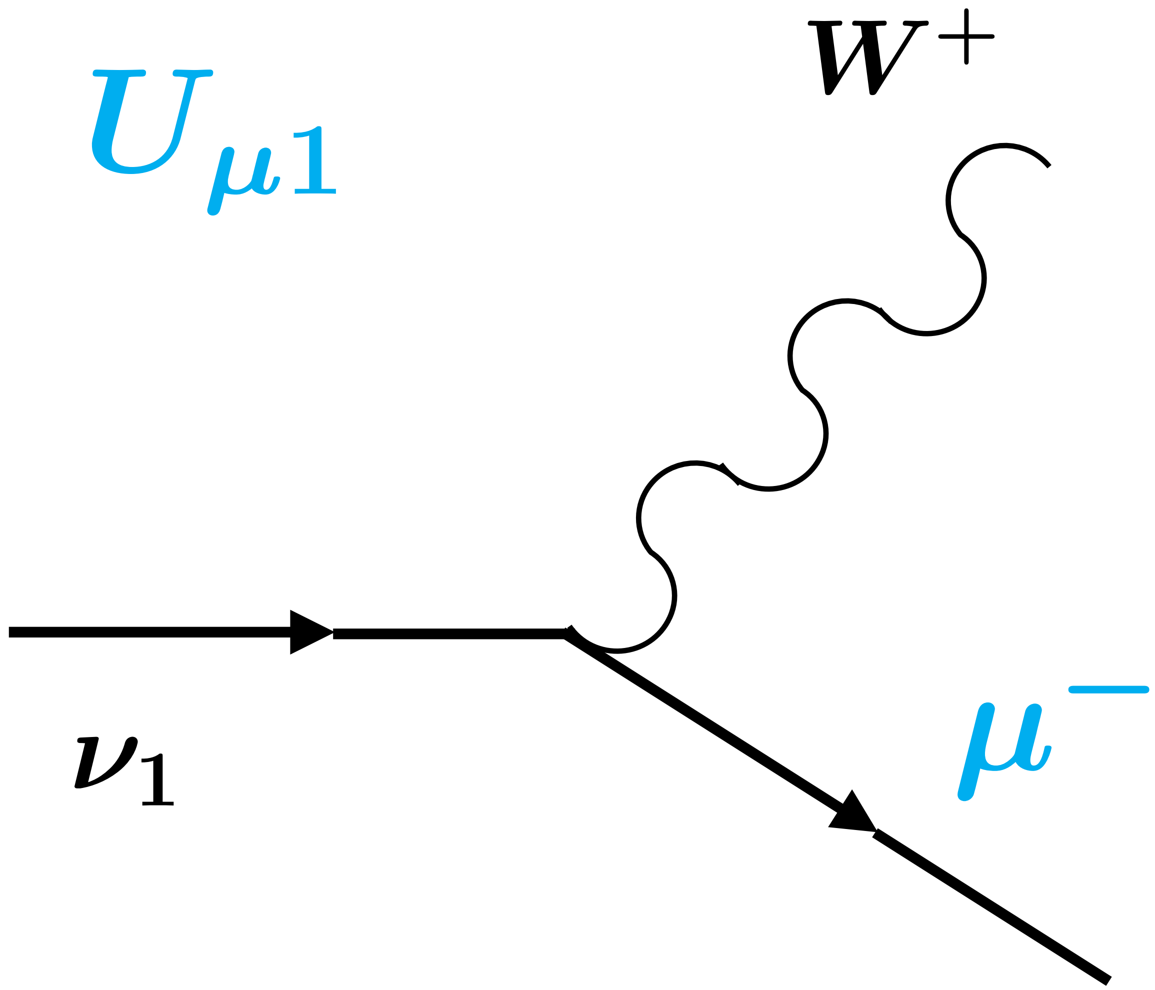
To discover neutrino BSM, one needs precision predictions for nuSM

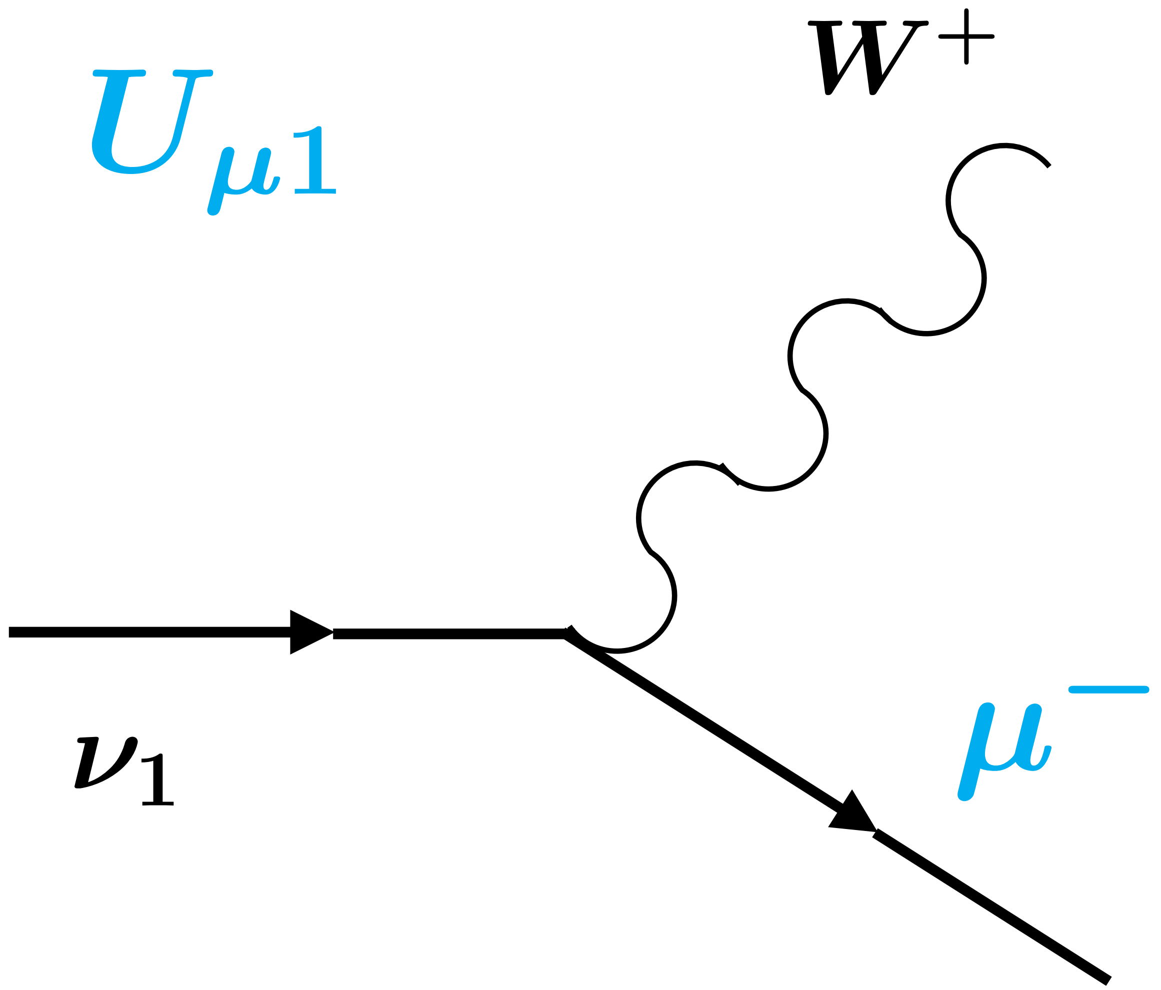
Determine flavor fractions of neutrino mass states

WHY?

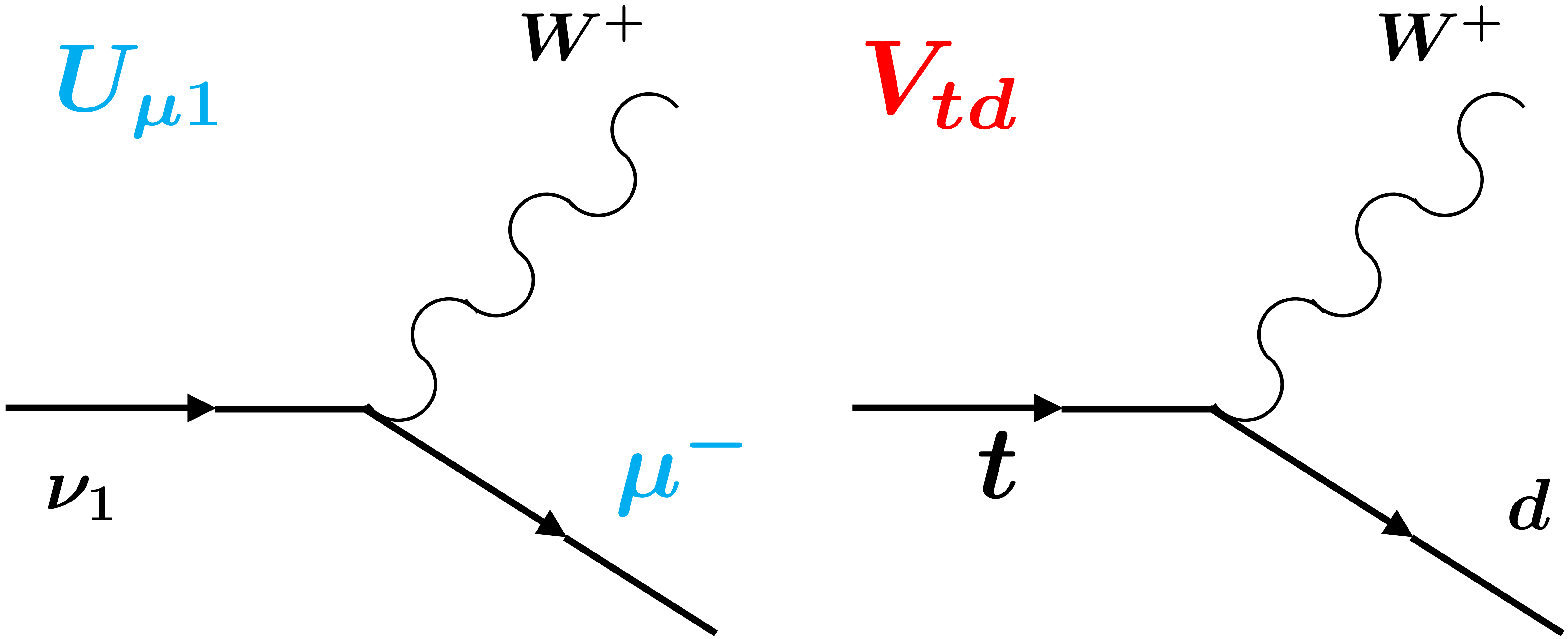
Precision Neutrino Measurements:

To discover neutrino BSM,
one needs precision predictions for nuSM


$U_{\mu 1}$
W^+
ν_1
μ^-

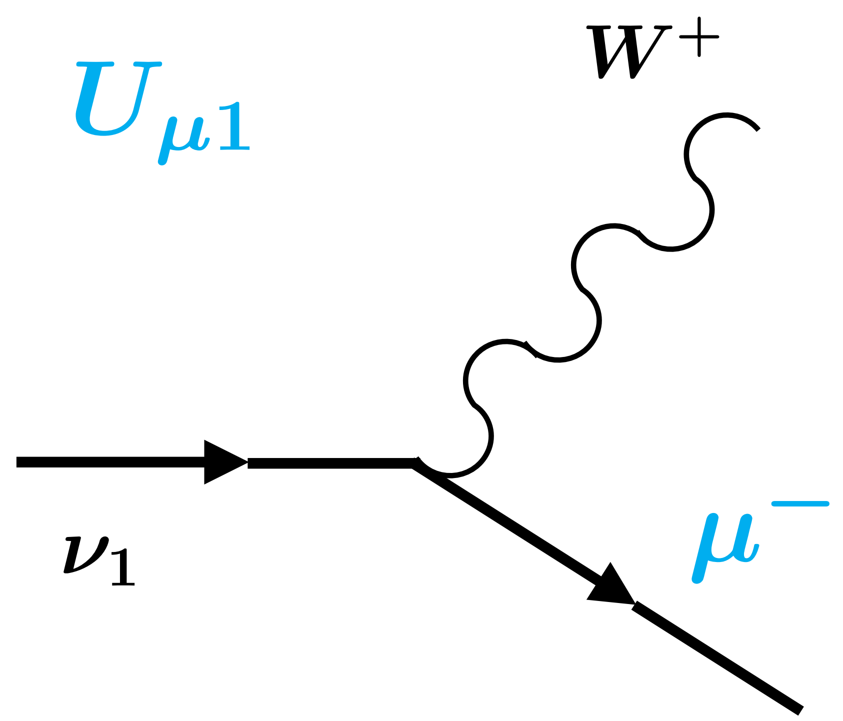


$U_{\mu 1}$
W^+
ν_1
μ^-
V_{td}
W^+
t
d



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

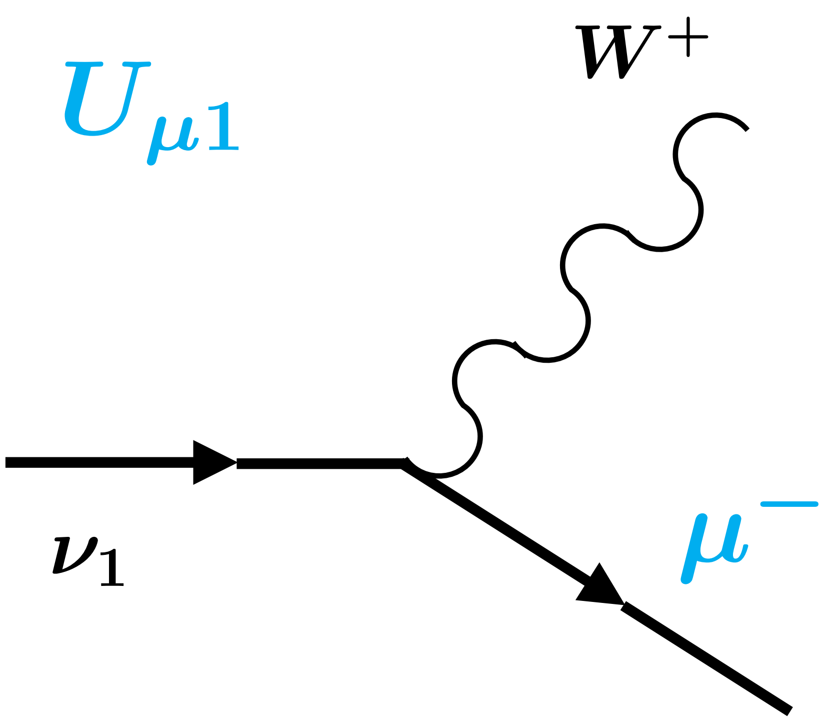
Leptons:



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

variation in δ only !

Leptons:



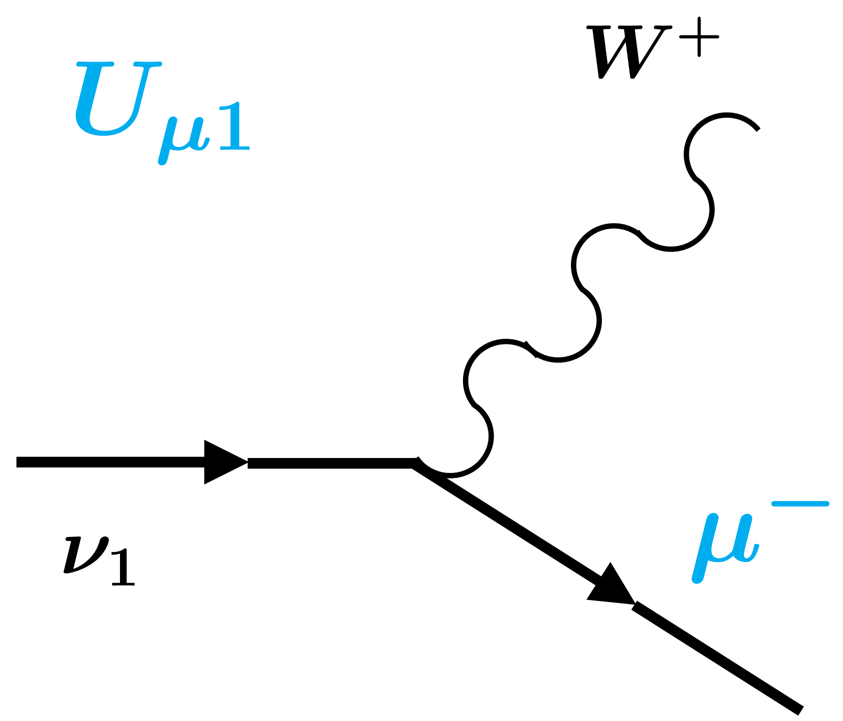
$$0.08 < |U_{\mu 1}|^2 < 0.24$$

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:



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Quarks:

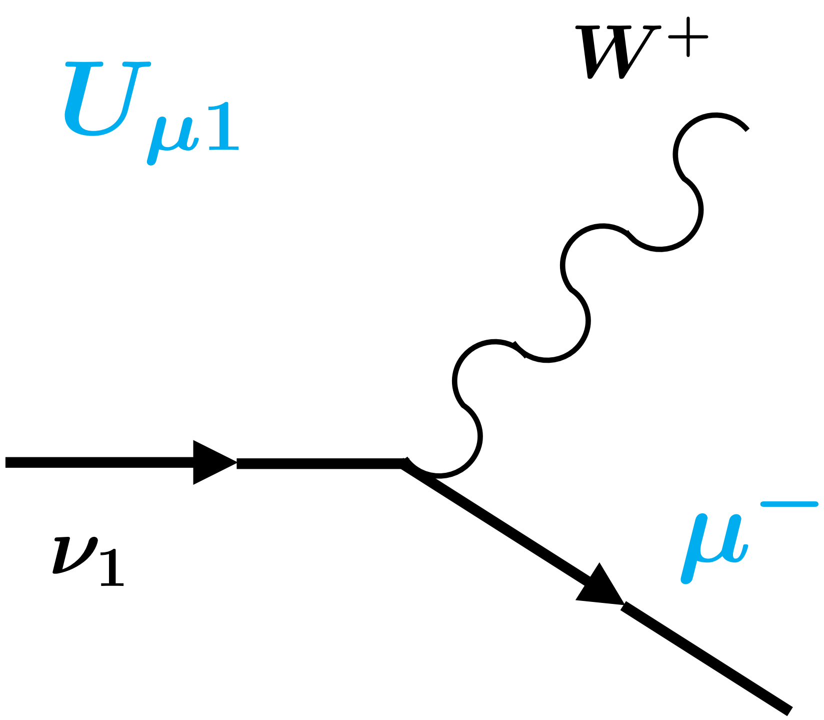
$|V_{ij}|^2$ essentially independent of δ_q !

Leptons:

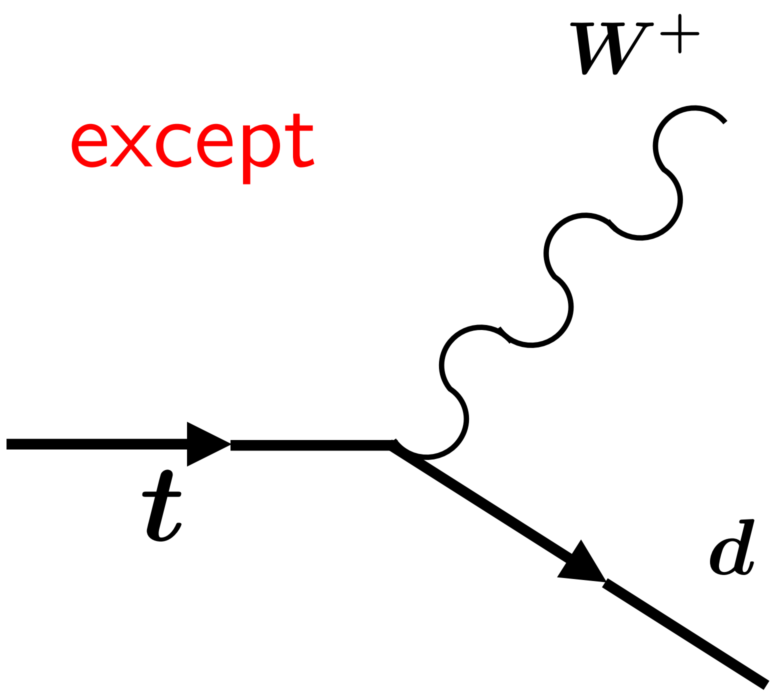
Quarks:

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

$U_{\mu 1}$



except



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

variation in δ only !

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

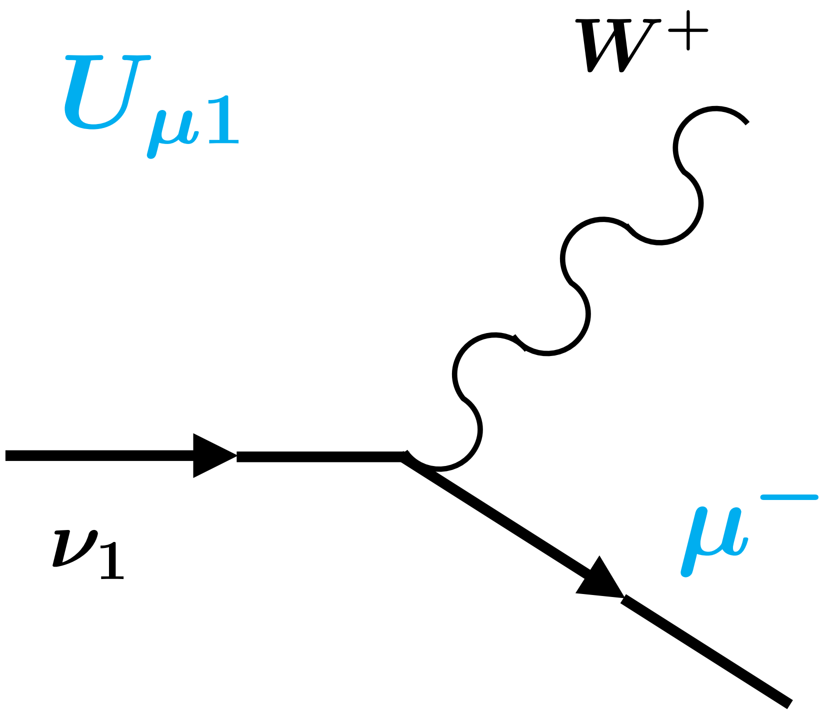
$$|V_{td}|^2 \approx 10^{-4}$$

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:

$U_{\mu 1}$



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

variation in δ only !

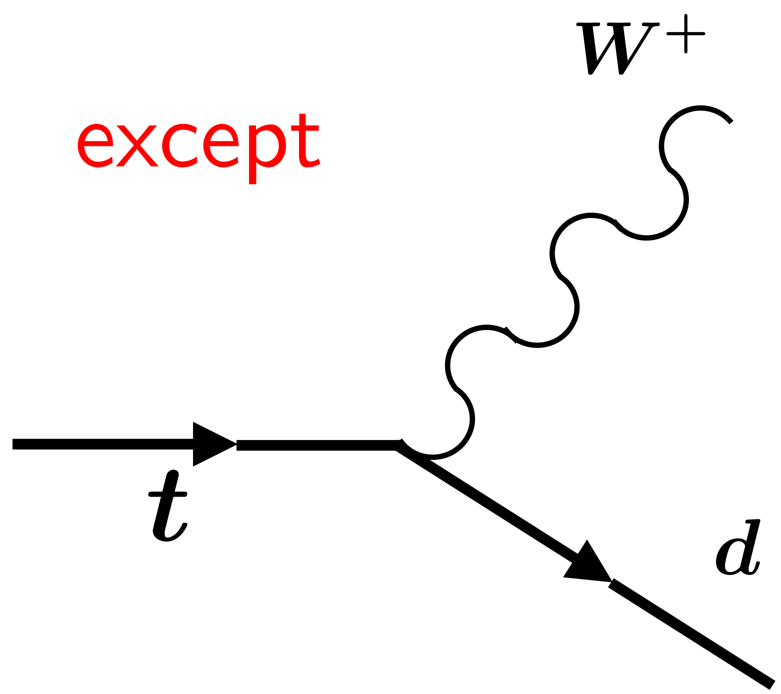
factor of 3 diff.

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

Quarks:

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

except

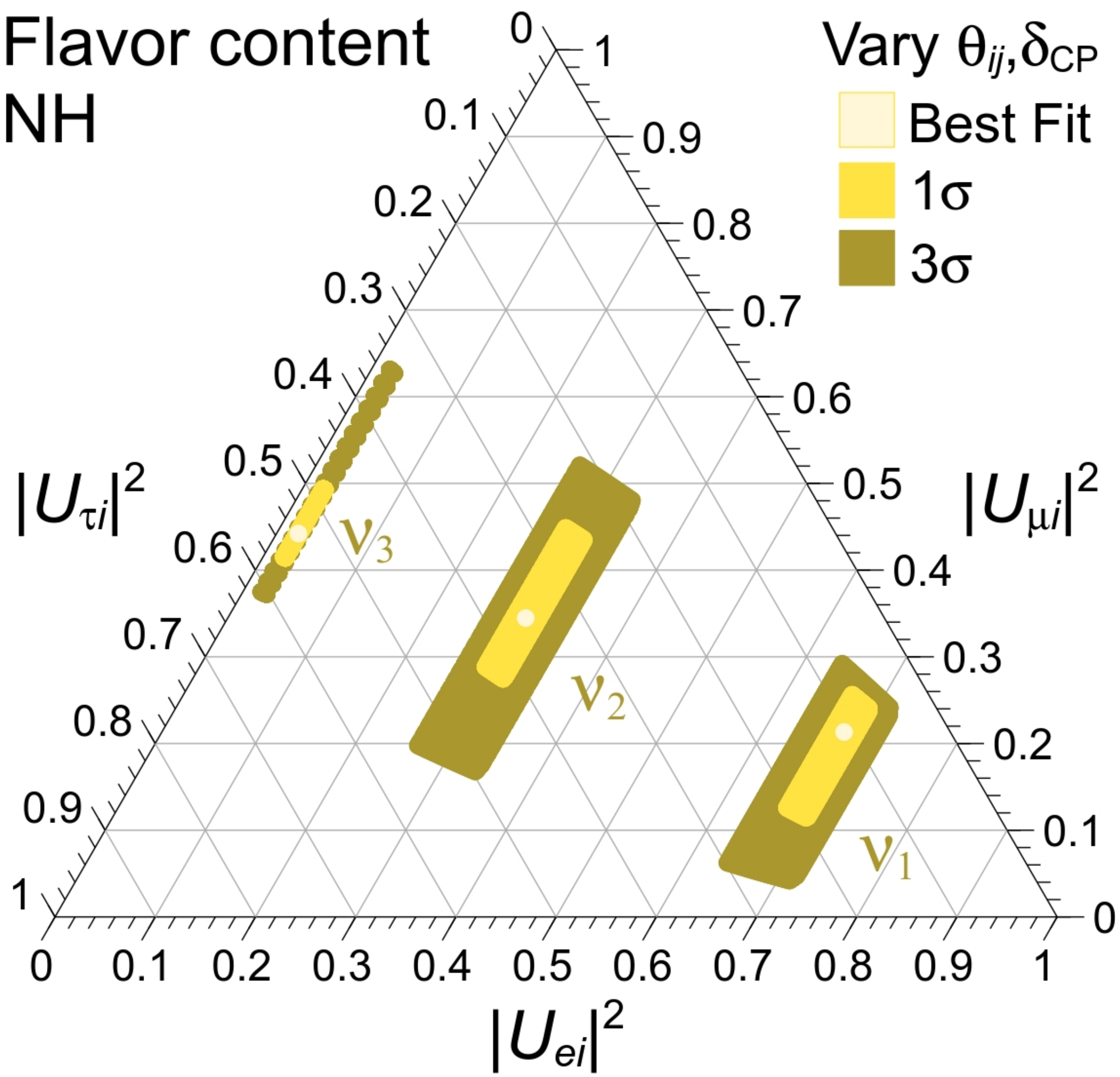


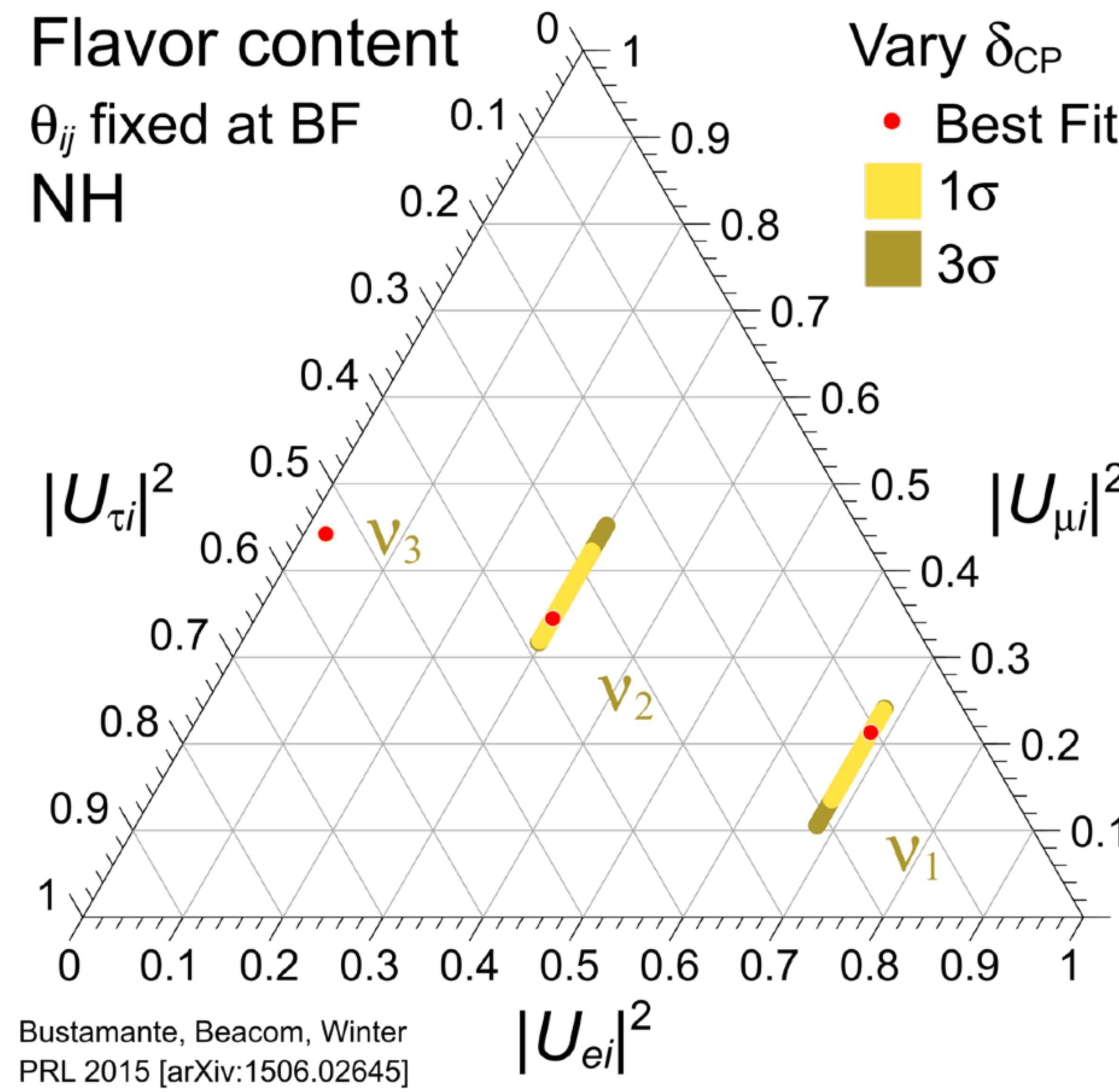
$$V_{td} \approx A\lambda^3(1 - 0.37e^{i\delta_q})$$

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

$$\begin{aligned} |V_{tb}|^2 &\approx 1 \\ |V_{ts}|^2 &\sim \lambda^4 \approx 2 \times 10^{-3} \\ |V_{td}|^2 &\sim \lambda^6 \approx 8 \times 10^{-5} \end{aligned}$$

δ_q → $|V_{td}|^2$

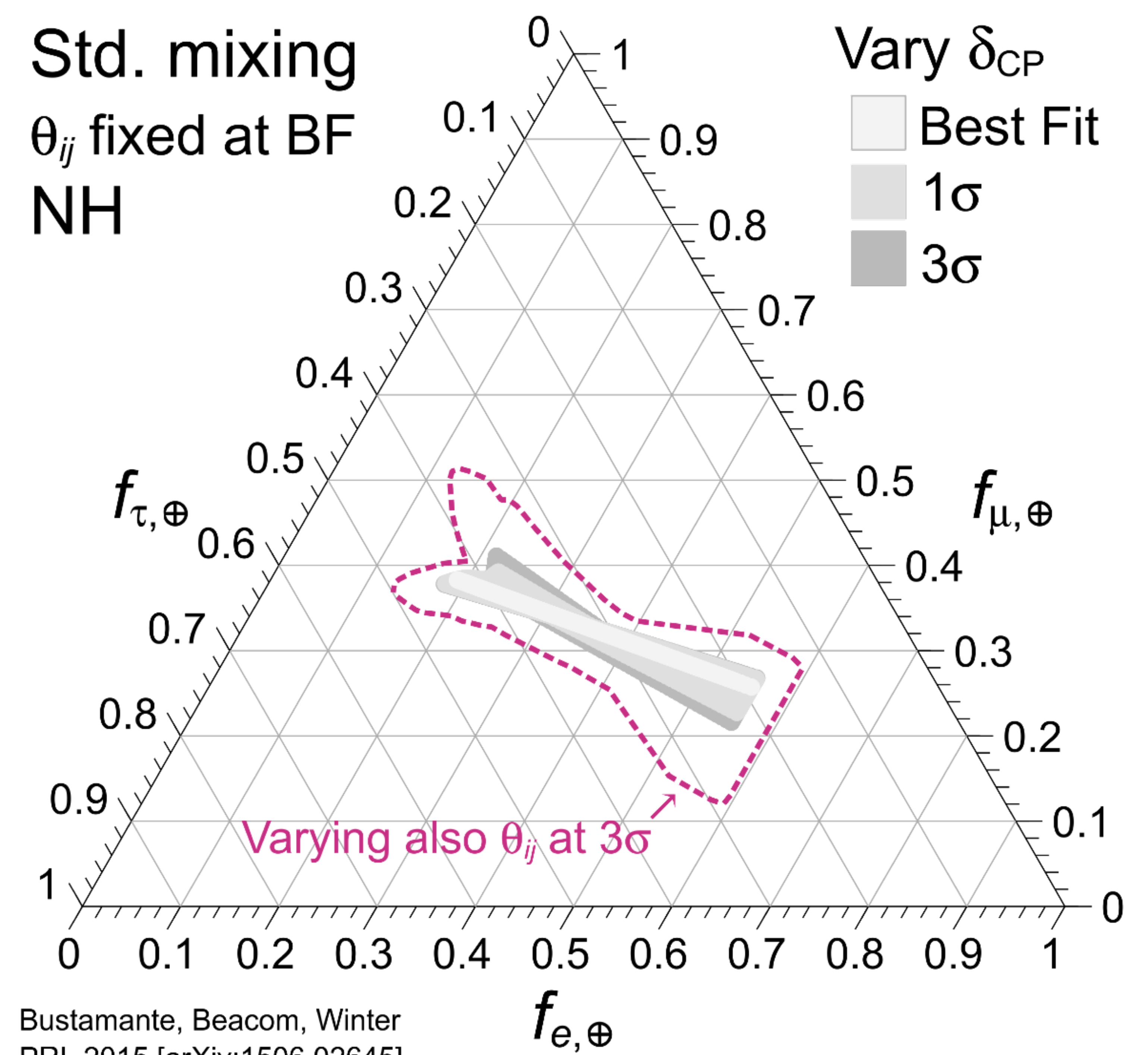




δ & θ_{23} uncertainty

no θ_{23} uncertainty

Determine flavor fractions of neutrino mass states



Bustamante, Beacom, Winter
PRL 2015 [arXiv:1506.02645]

Precision Predictions for flavor ratios at ICECUBE.

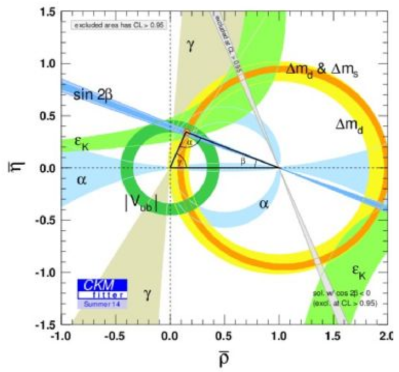
WHY?

Determine flavor fractions of neutrino mass states

Stress Test Neutrino paradigm search for new physics

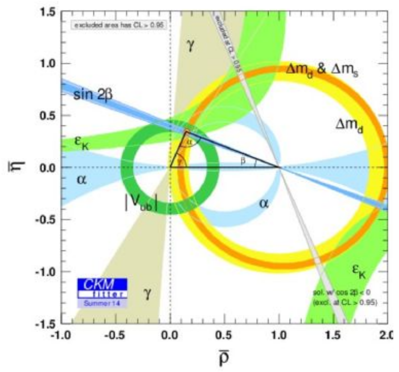
Precision Neutrino Measurements:

Quark



Stress Test
Neutrino paradigm
search for new physics

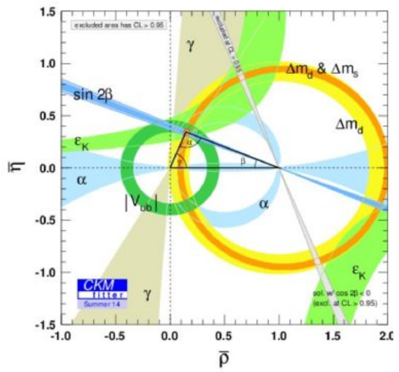
Quark



$A\lambda^3$

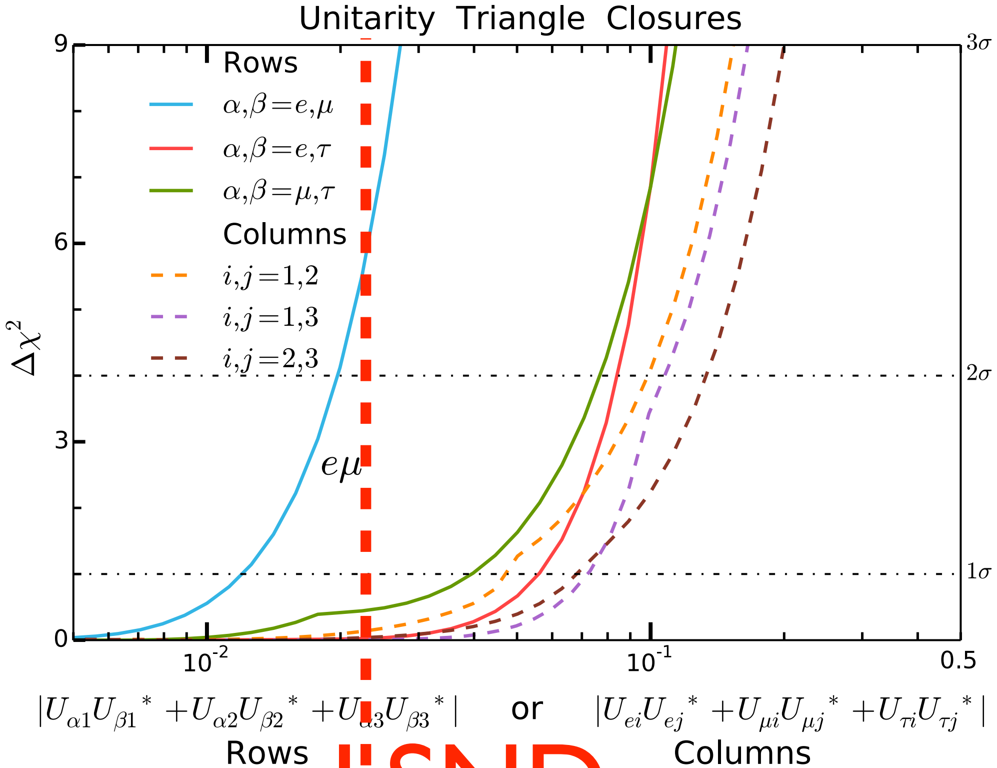
Stress Test
Neutrino paradigm
search for new physics

Quark



$A\lambda^3$

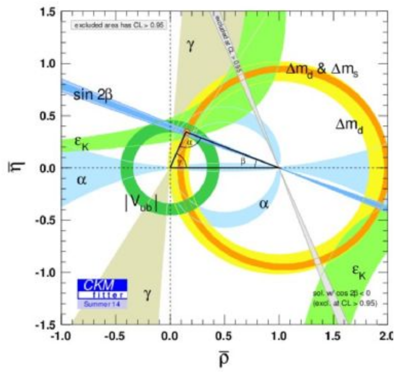
Stress Test
Neutrino paradigm
search for new physics



LSND

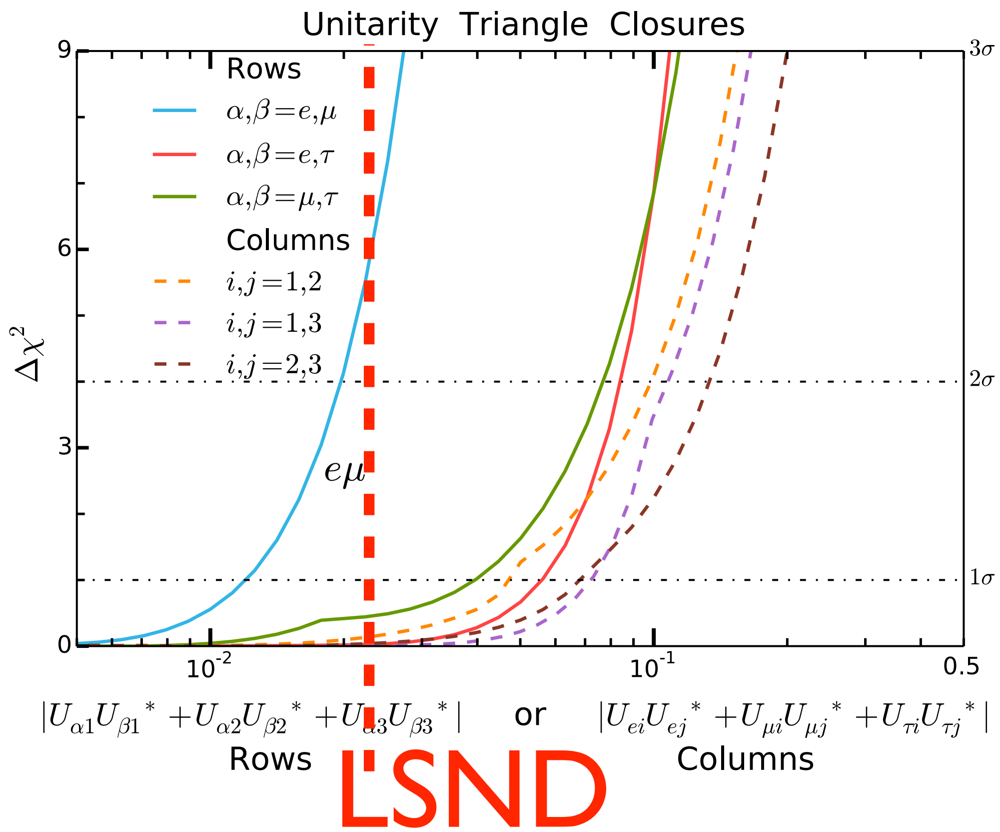
M. Ross-Lonergan + SP
arXiv:1508.05095

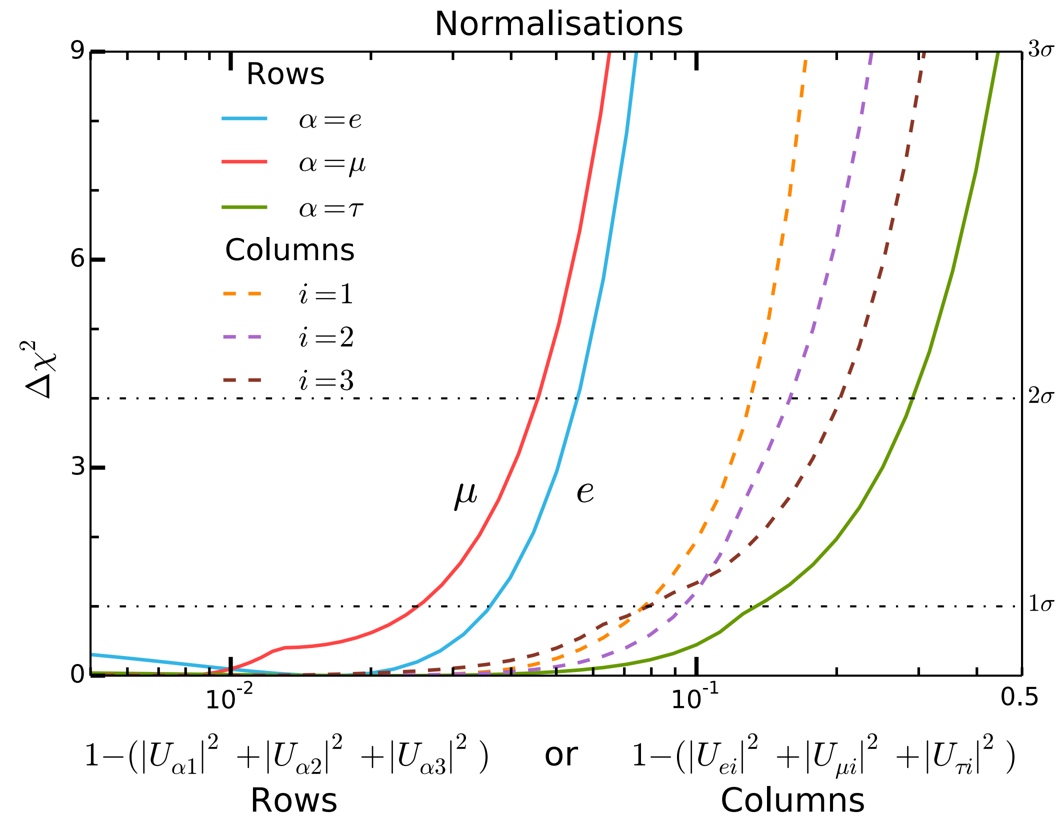
Quark



$A\lambda^3$

Stress Test
Neutrino paradigm
search for new physics





M. Ross-Lonergan + SP
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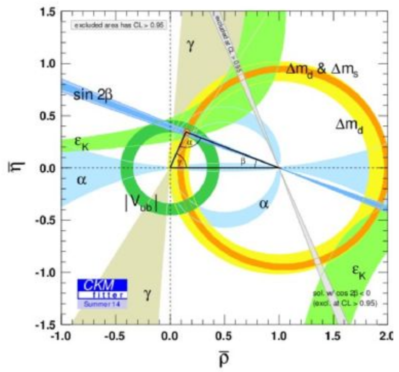
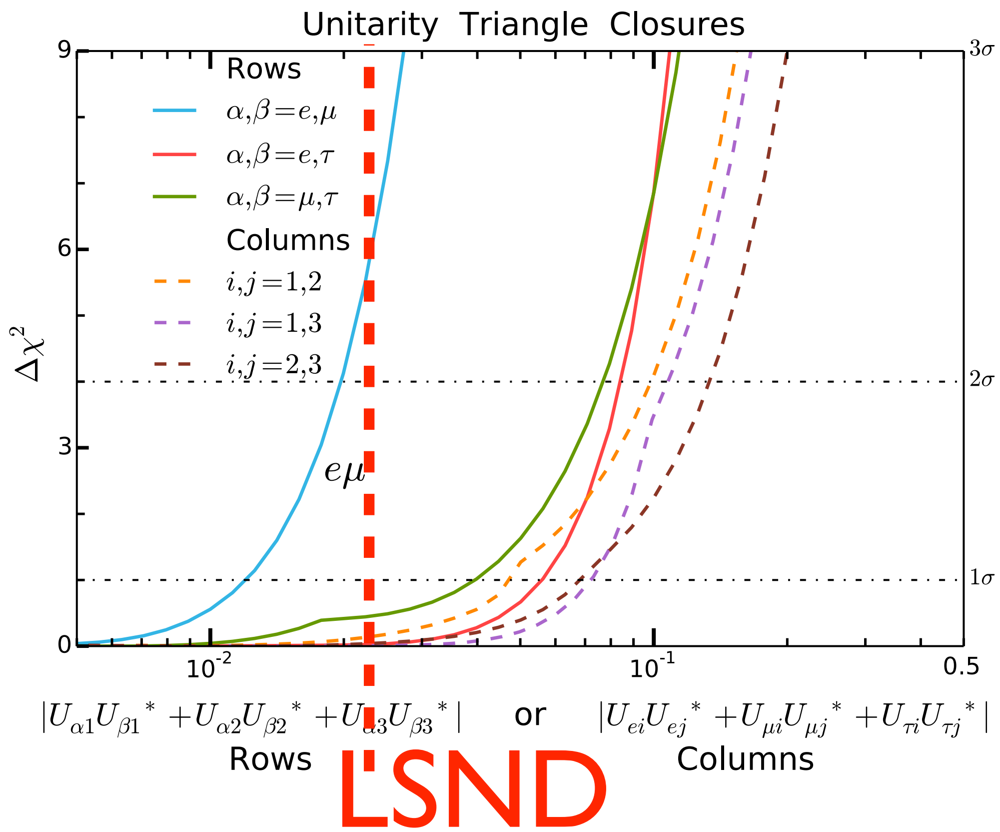
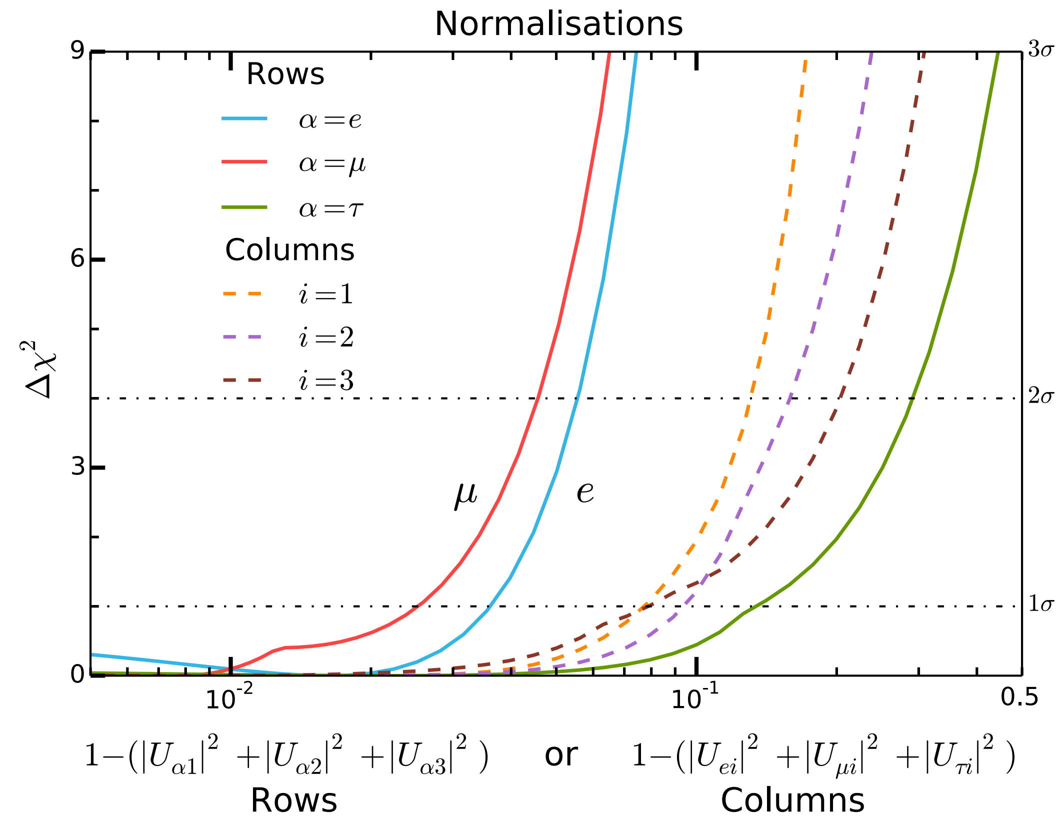
Quark



$A\lambda^3$

Stress Test
Neutrino paradigm
search for new physics



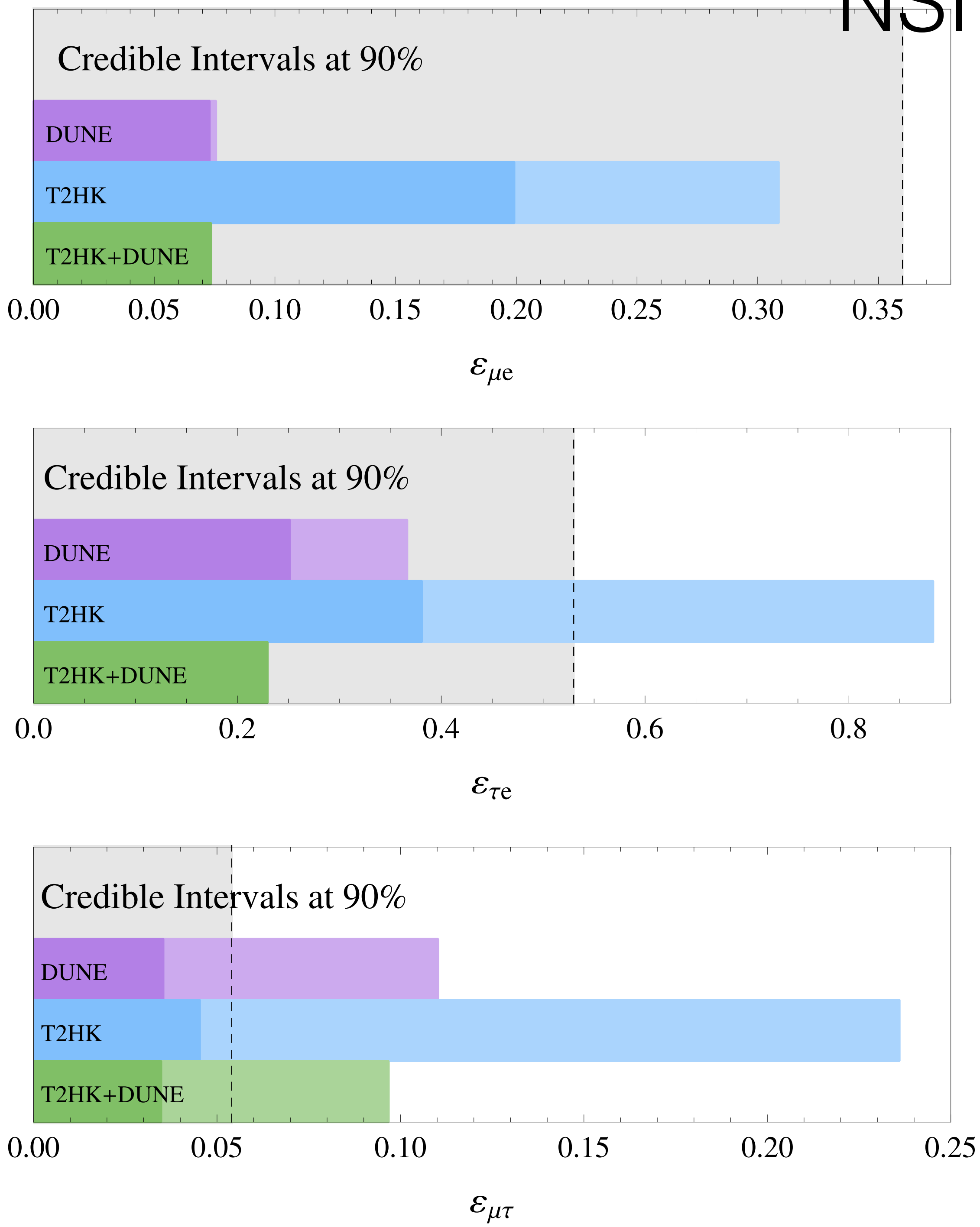


M. Ross-Lonergan + SP
arXiv:1508.05095

9 out of 12 involve nu_tau !!!

Stress Test
Neutrino paradigm
search for new physics

NSI

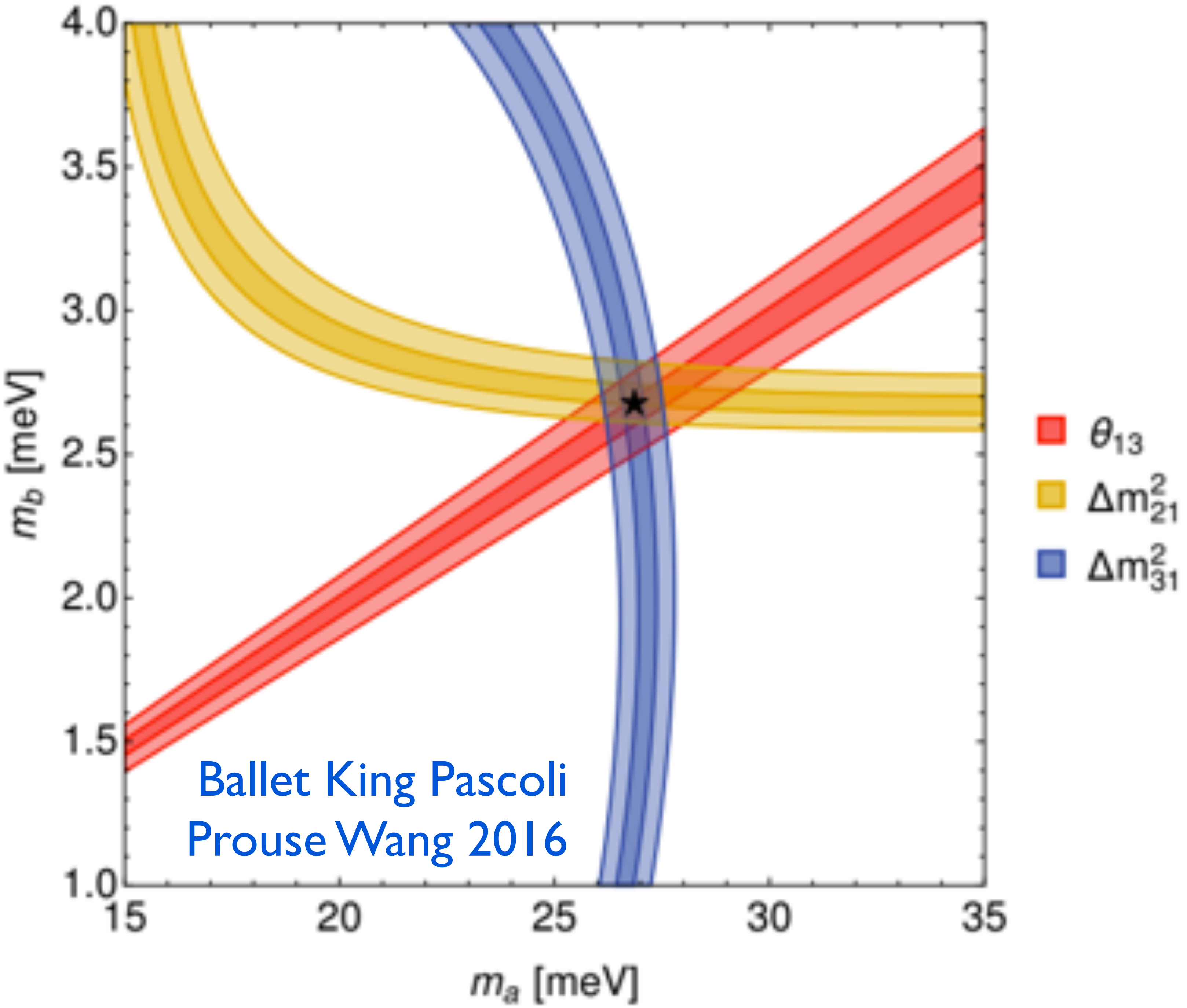


P.Coloma
arXiv:1511.06357

WHY?

Precision Neutrino Measurements:

- Determine flavor fractions of neutrino mass states
- Stress Test Neutrino paradigm search for new physics
- Connection to Leptogenesis Understanding Universe



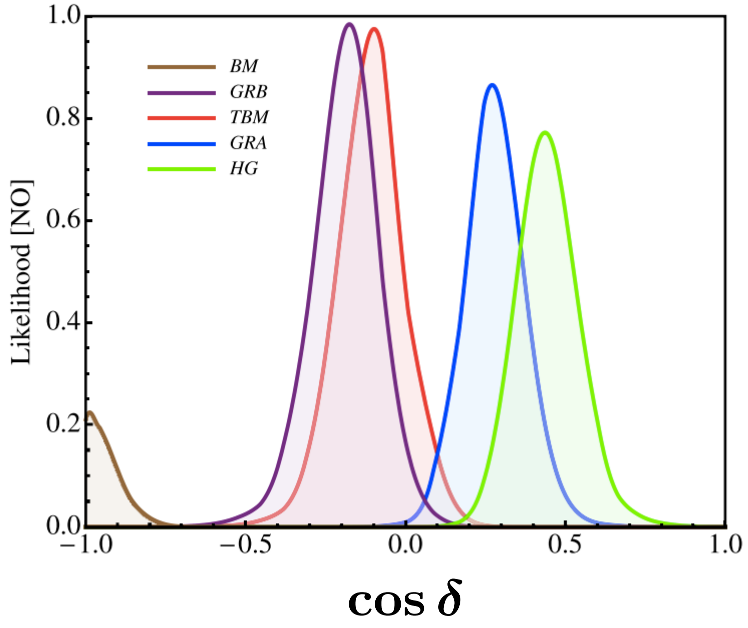
Connection to
Leptogenesis
Understanding Universe

WHY?

Precision Neutrino Measurements:

- Determine flavor fractions of neutrino mass states
- Stress Test Neutrino paradigm search for new physics
- Test Theoretical Neutrino Models
- Connection to Leptogenesis Understanding Universe

Predictions from flavor symmetry forms
with current measurement precision

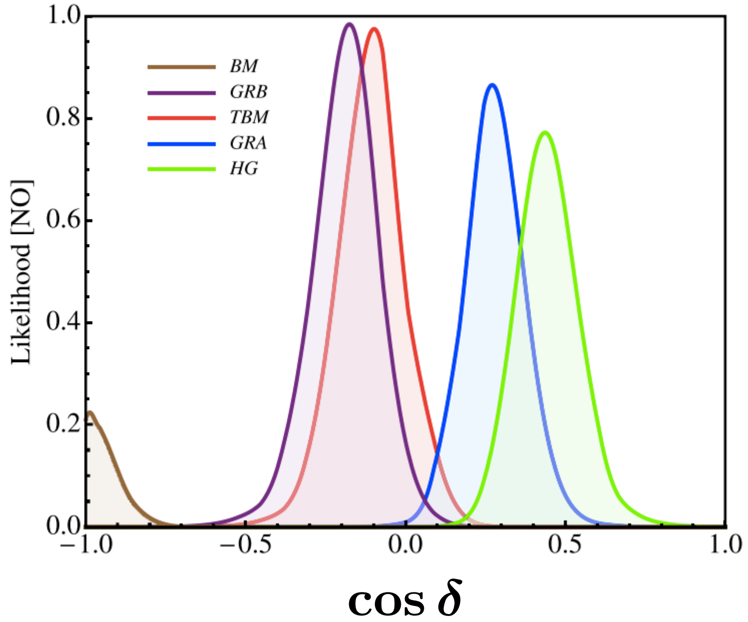


Test Theoretical Neutrino Models

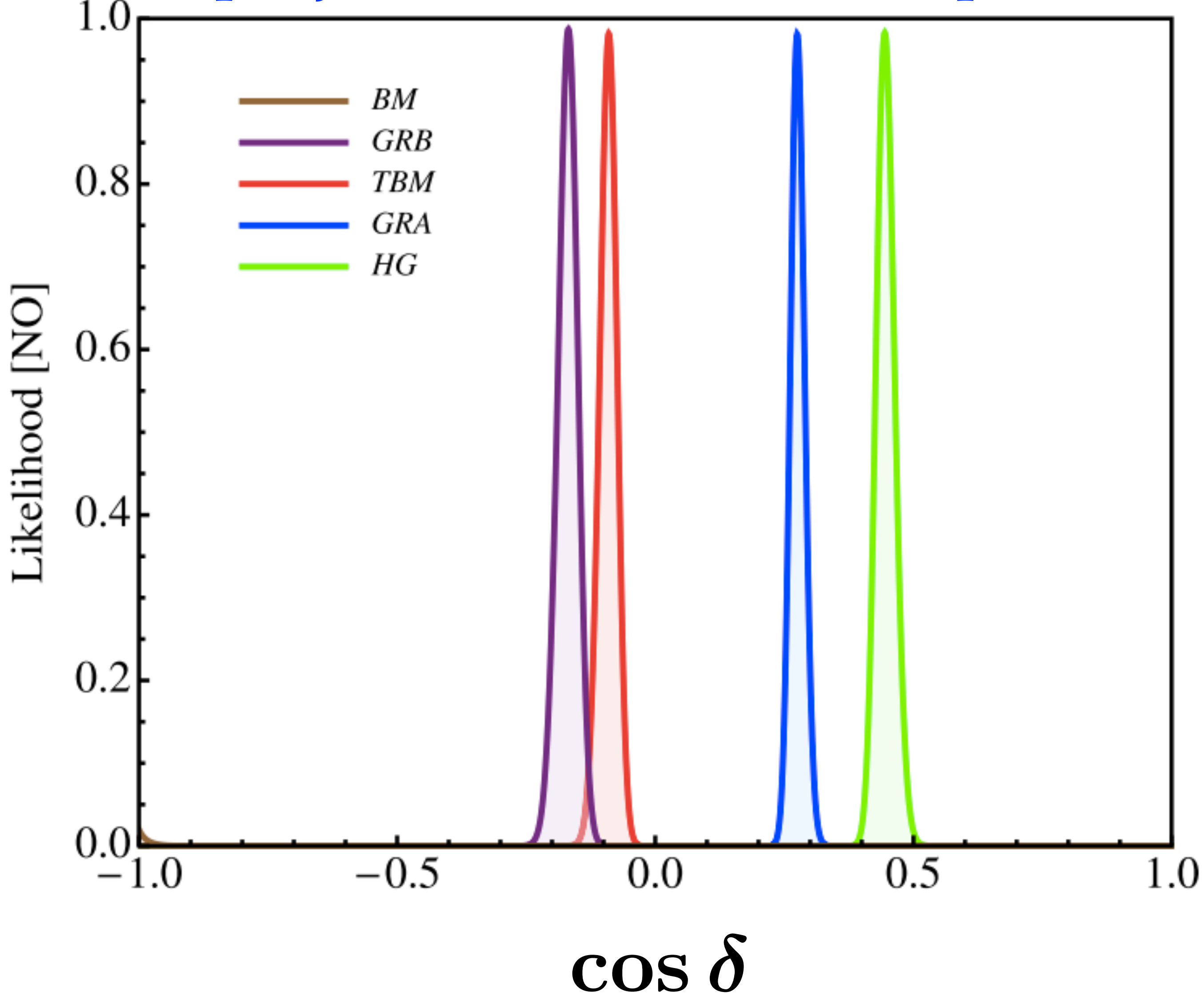
Girardi, Petcov, Titov, arXiv:1410.8056

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



Test Theoretical Neutrino Models

Girardi, Petcov, Titov, arXiv:1410.8056

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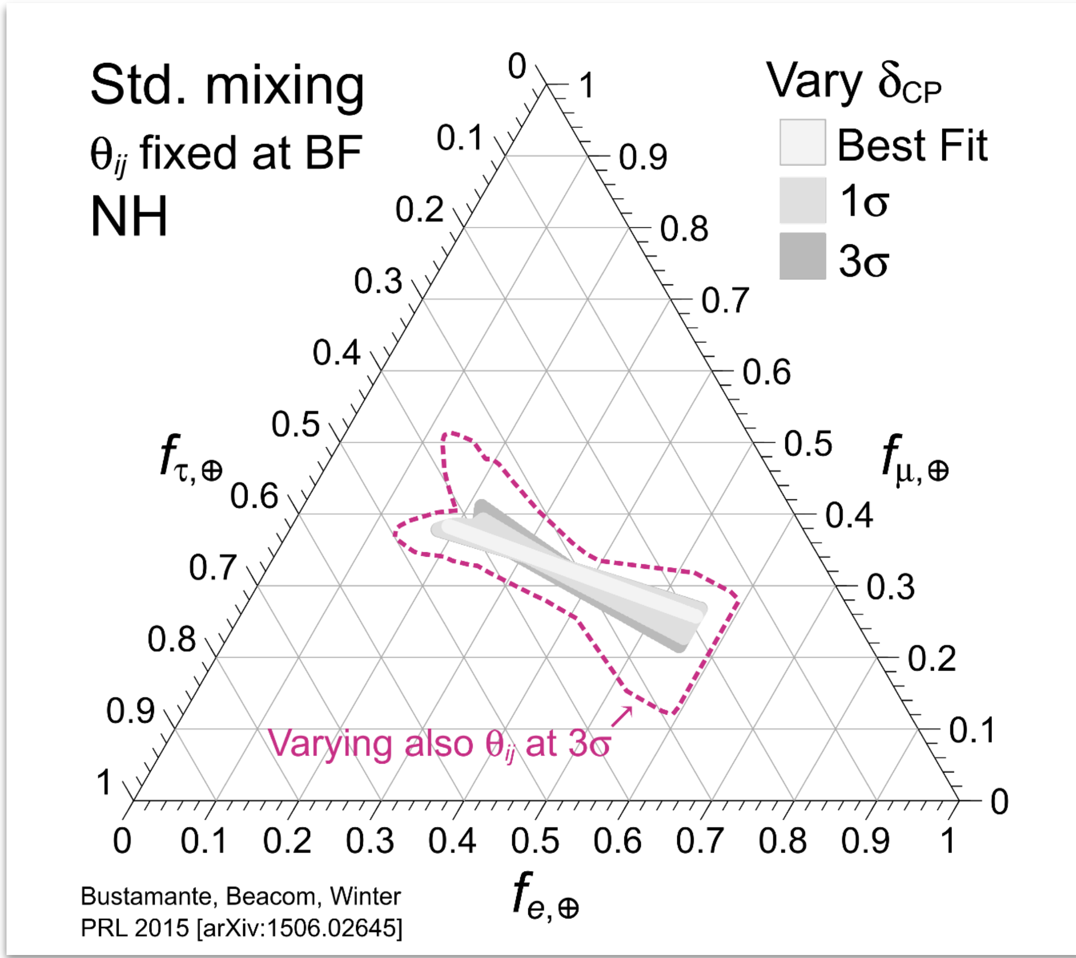
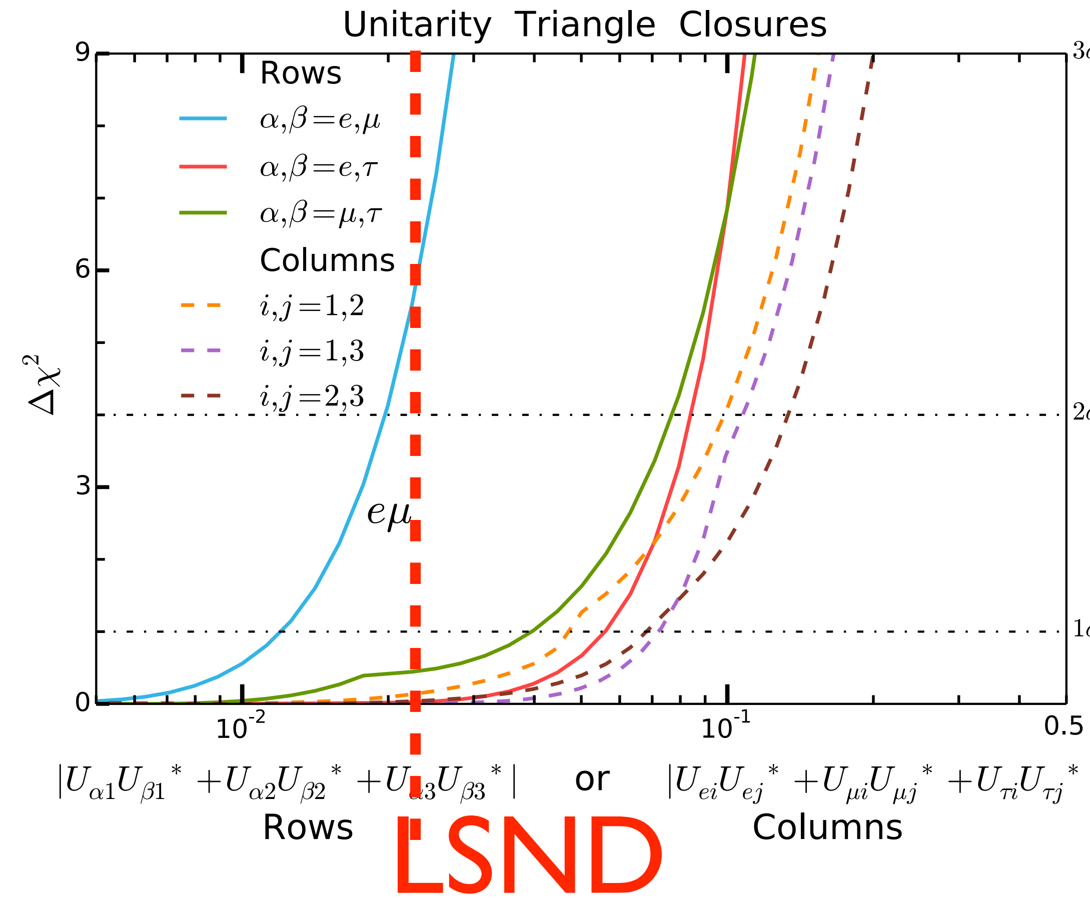
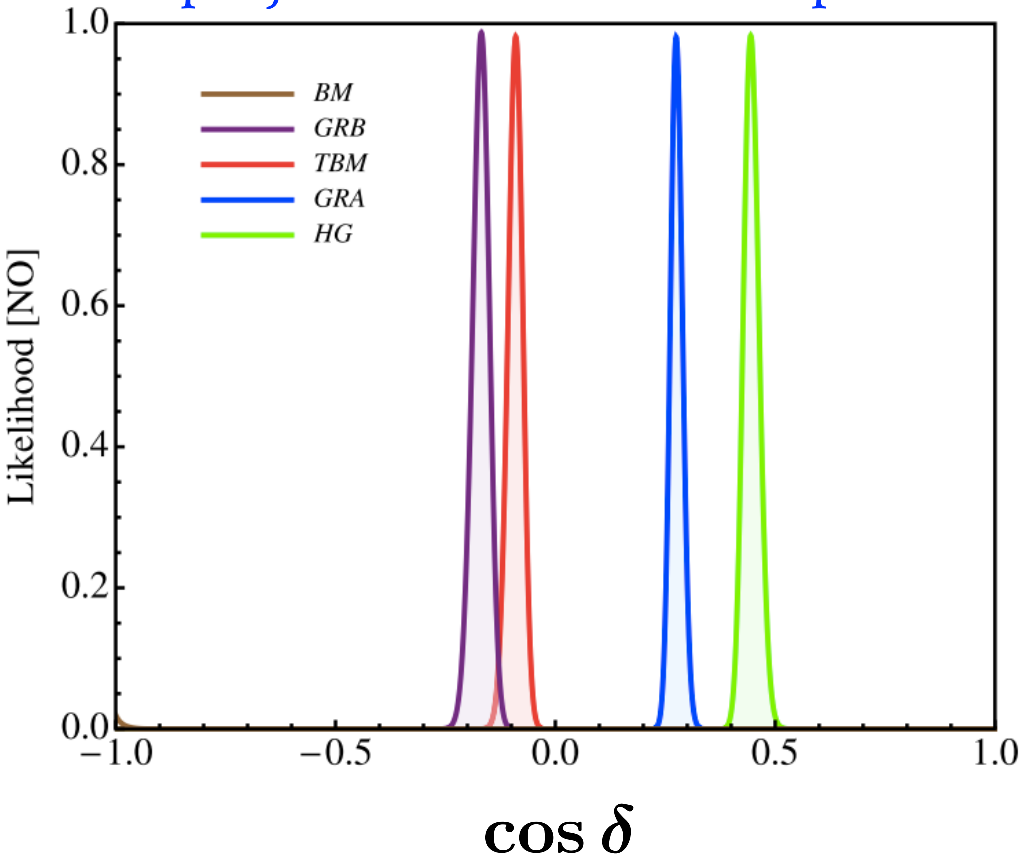
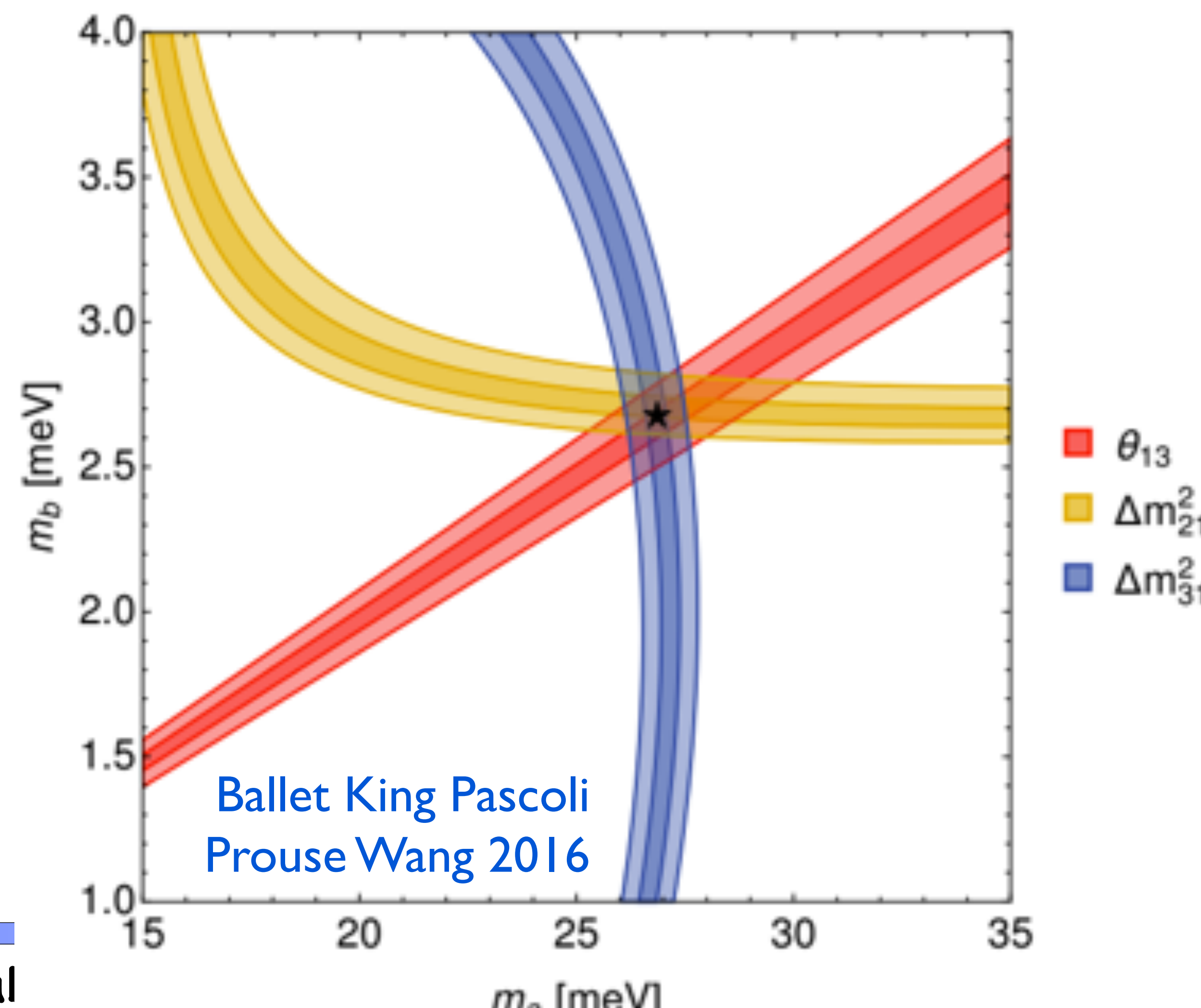




Predictions of flavor symmetry forms with projected measurement precision





ARE THERE LIGHT STERILE

$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\rm PMNS}^{\rm 3x3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

ARE THERE LIGHT STERILE

$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\mathrm{PMNS}}^{3\mathrm{x}3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} & \begin{matrix} \ddots & \vdots \end{matrix} \\ \begin{matrix} U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

Cauchy-Schwartz

$$\left| \sum_{i=1}^{3} U_{ei} U_{\mu i}{}^{*} \right|^2 \leq \left(1 - \sum_{i=1}^{3} |U_{ei}|^2\right) \left(1 - \sum_{i=1}^{3} |U_{\mu i}|^2\right)$$

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- ν_μ Disappearance

- ν_μ Disappearance

MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

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Daya Bay, RENO, many $\sim$10m Reactor experiments & source experiments.

ARE THERE LIGHT STERILE

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- $\nu_\mu \to \nu_e$ Appearance
- ν_e Disappearance
- ν_μ Disappearance

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MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

- ν_e Disappearance

Daya Bay, RENO, many $\sim$10m Reactor experiments & source experiments.

- $\nu_\mu \to \nu_e$ Appearance

Fermilab SBN Program, T2K and NOvA: DUNE & HyperK

CP violation ???

What about Nu_tau ???

Cosmology & Neutrinos

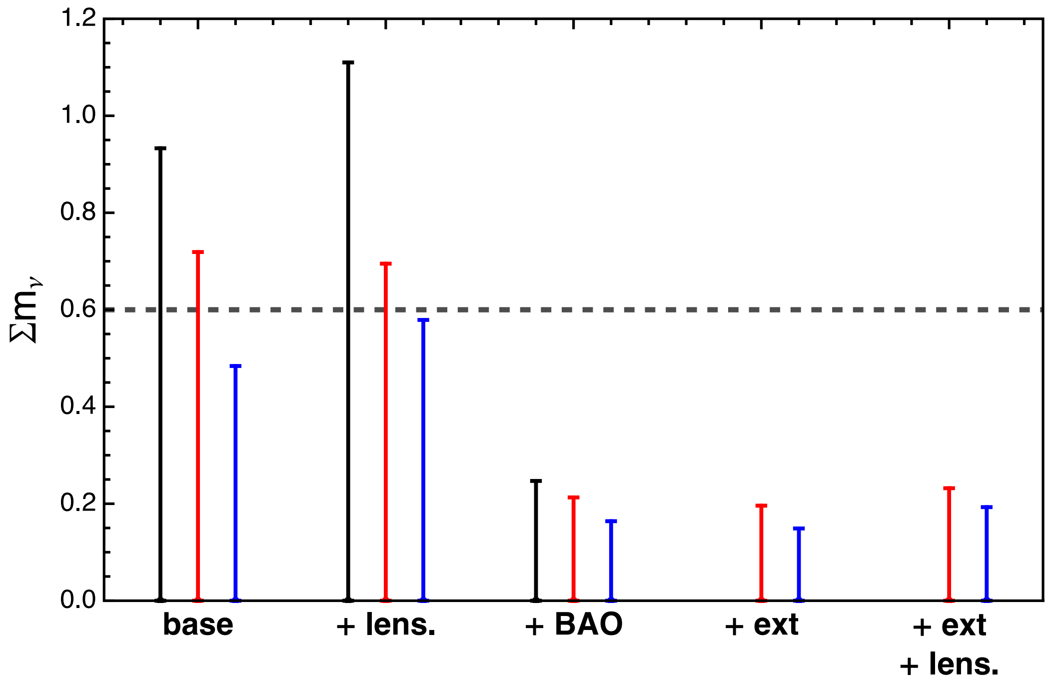
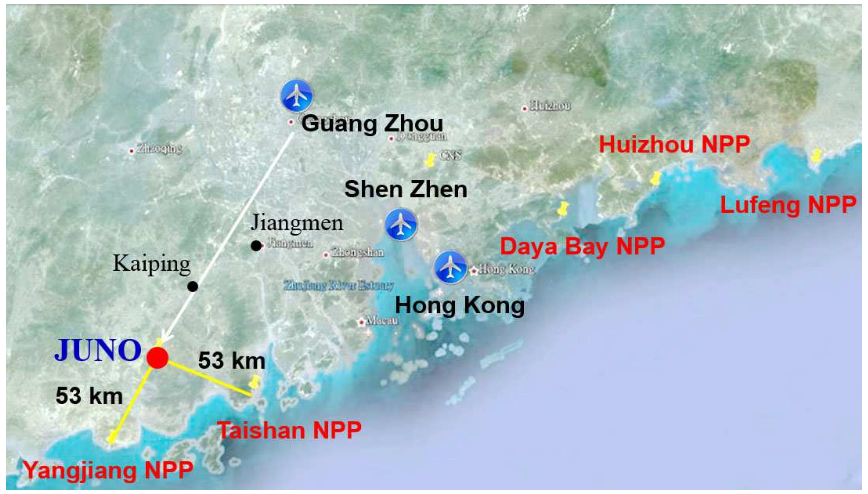


Figure 1. Comparison between constraints on $\sum m_\nu$ from *Planck* 2013 (black) and *Planck* 2015 without (red) and with (blue) small-scale polarization. The baseline always includes the full TT spectrum and the low-ell polarization (taken from WMAP in 2013). The dashed line represents KATRIN sensitivity to the effective electron neutrino mass, translated in terms of $\sum m_\nu$.

$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\rm TT + lowP, \tag{1a}$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\rm TT + lowP + BAO, \tag{1b}$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\rm TT, TE, EE + lowP, \tag{1c}$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\rm TT, TE, EE + lowP + BAO. \tag{1d}$$

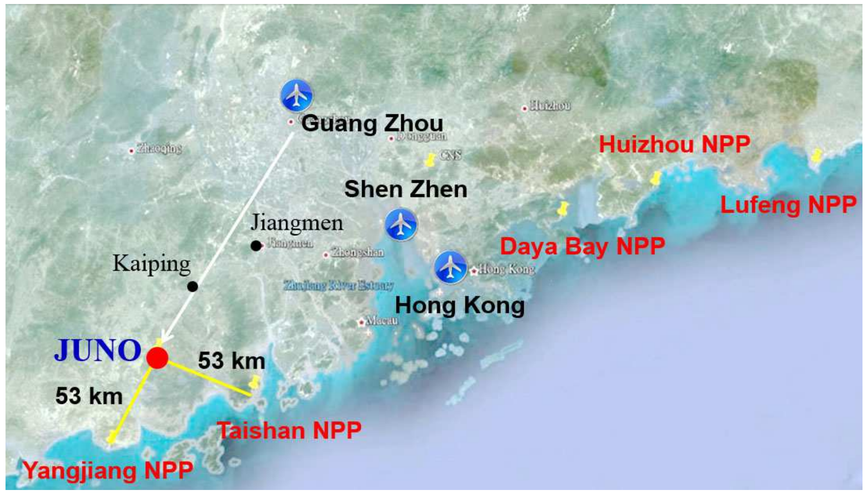
Planck is consistent with the standard value of $N_{\rm eff}$, and excludes $N_{\rm eff} = 4$ (*i.e.*, a fully-thermalized fourth neutrino state) at a level between 2.7 and 5.3σ; however, sizeable amounts

Reactor:



	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

Reactor:



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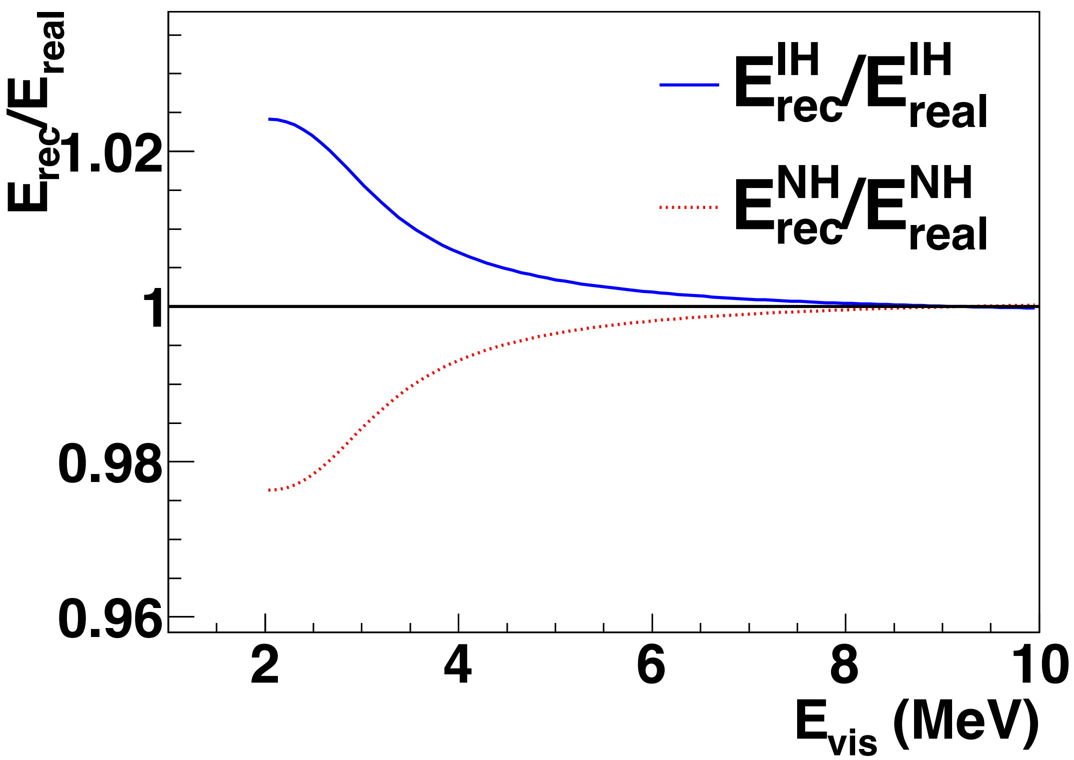
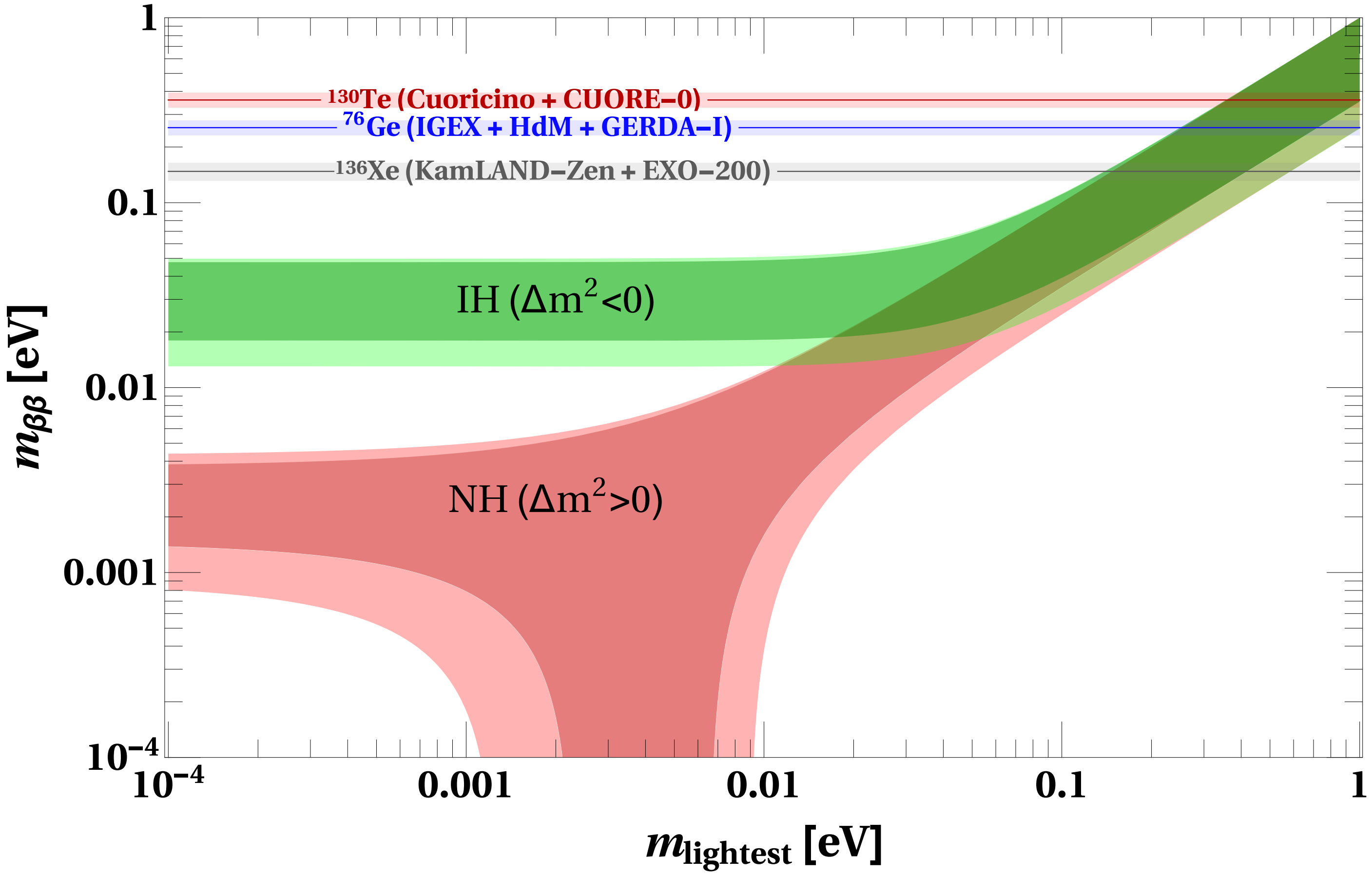
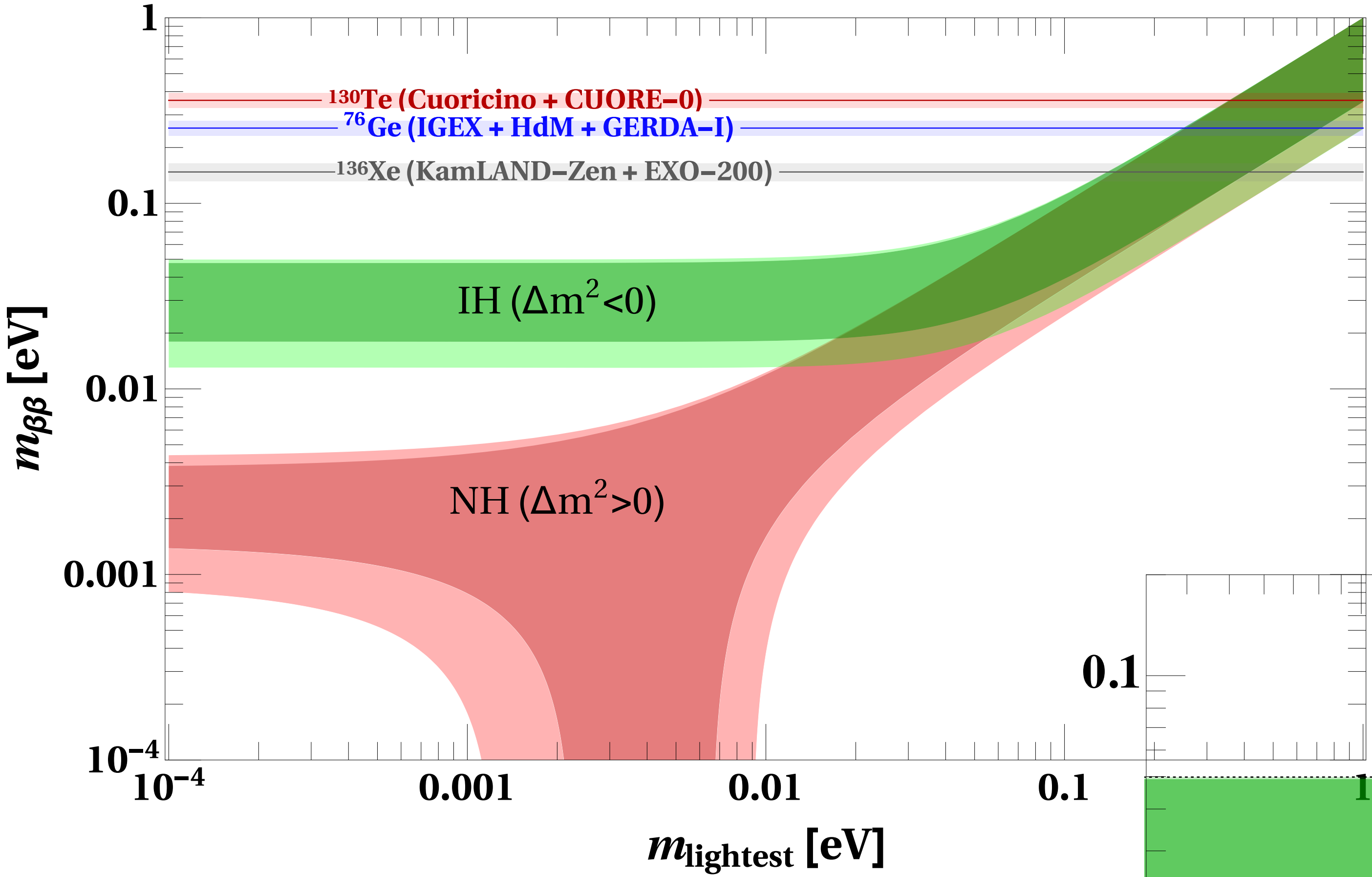
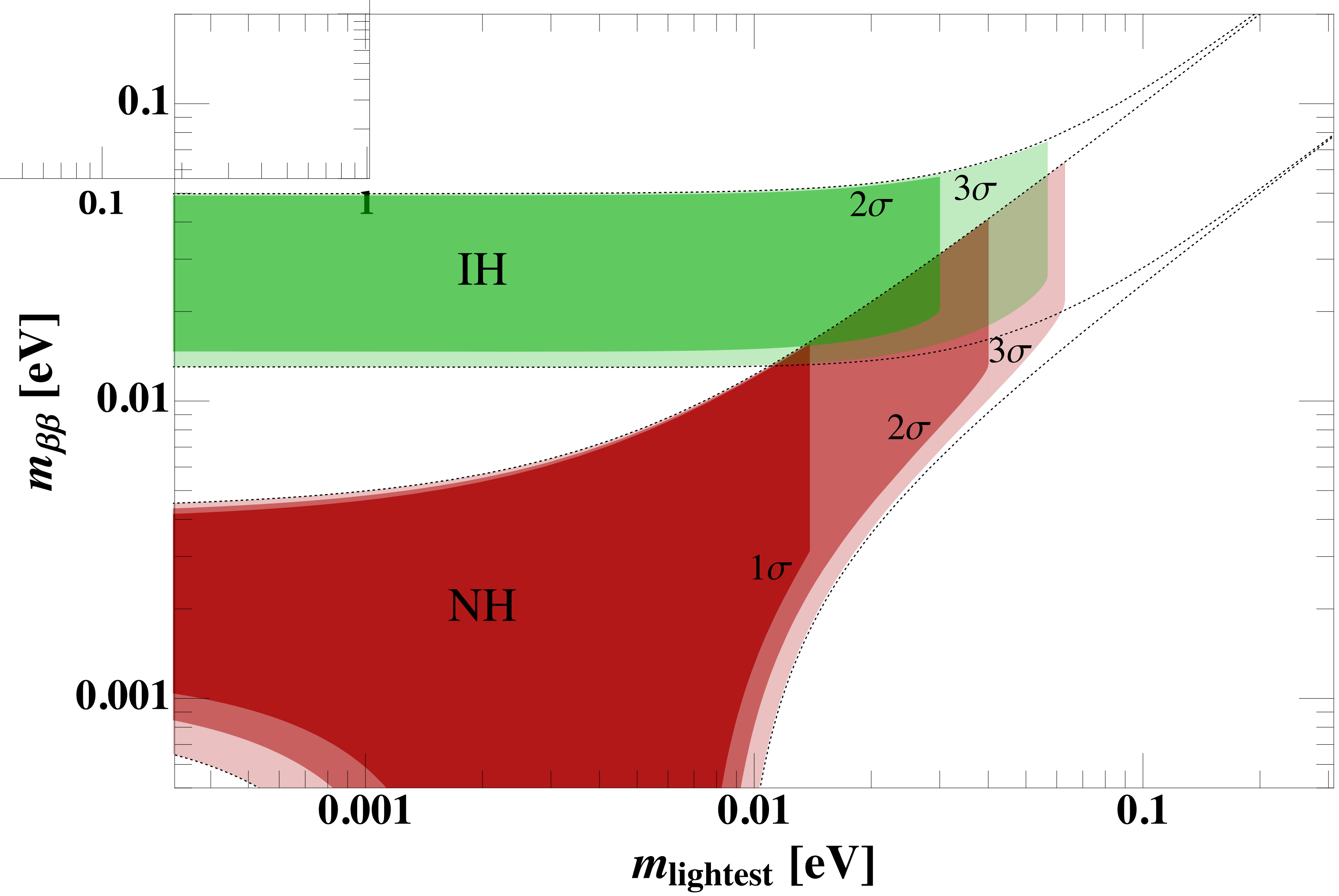


Neutrinoless Double Beta decay



Neutrinoless Double Beta decay





QCD & Nuclear Physics:

- Reactor Flux and Spectrum
- Matrix elements for neutrinoless double beta decay
- Cross Sections for neutrino nucleon AND nucleus scattering
- ……

Recent highlights from neutrino theory

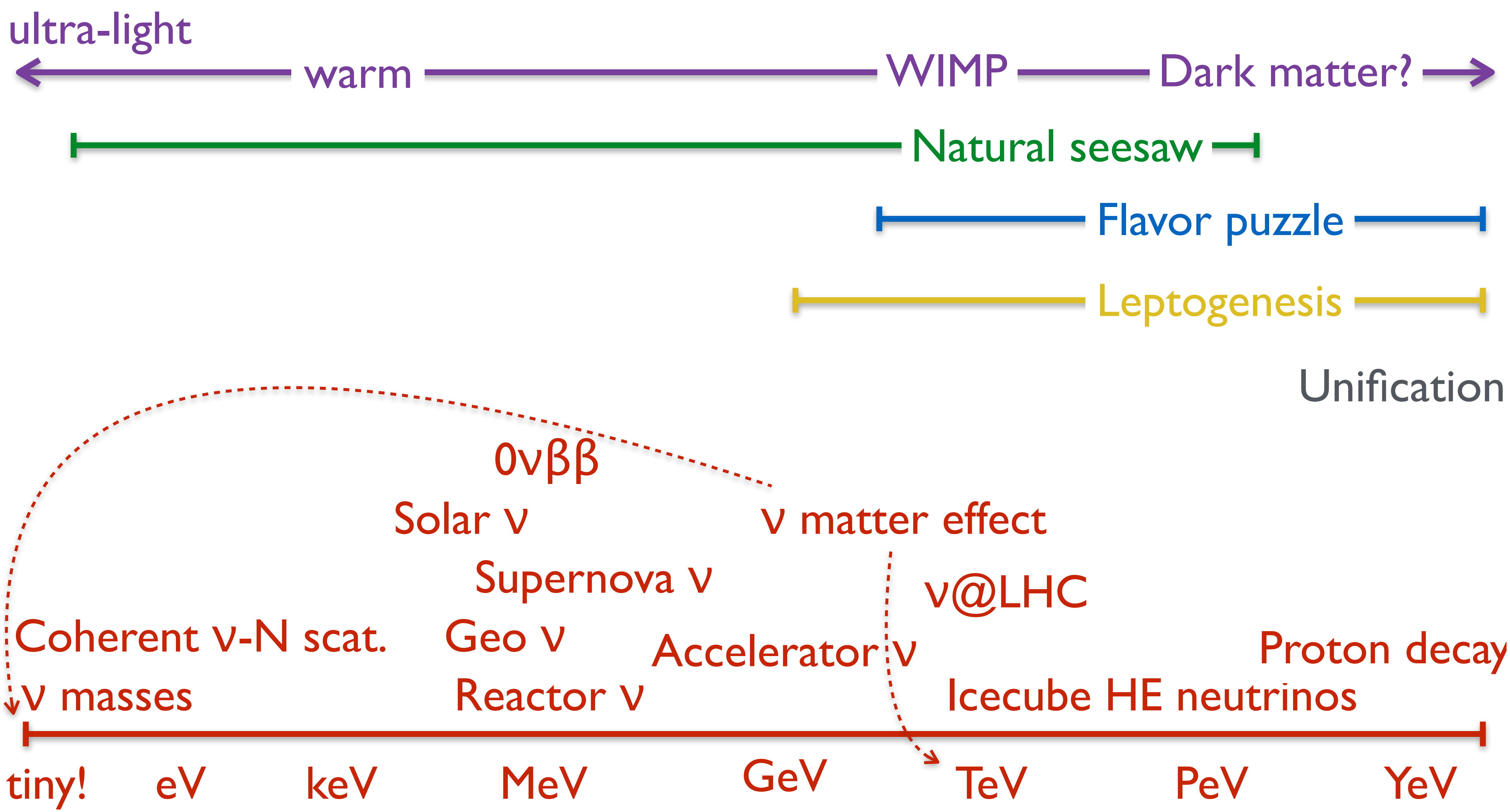
Pedro A. N. Machado

Fermilab *soon to be at LANL as junior staff member*

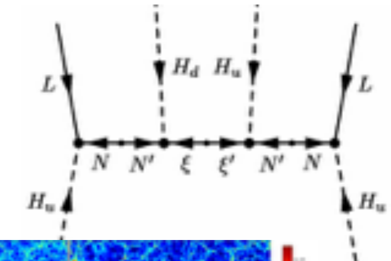
Aug/2017

pmachado@fnal.gov

Neutrinos as a portal to new Physics



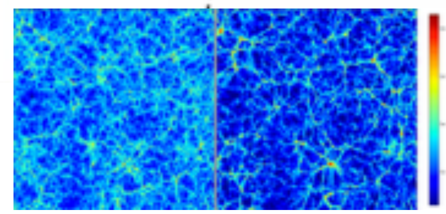
Many many many other fronts!



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,…

Neutrino cross sections (NuSTEC effort)



Dark matter in neutrino detectors: light DM and light mediators

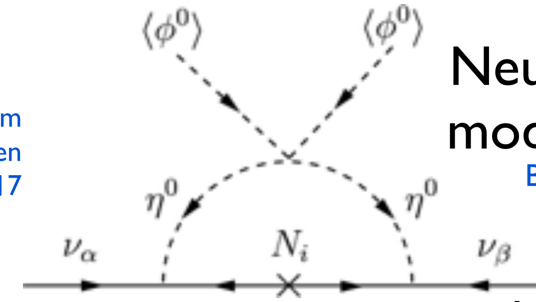
Ballett, Batell, Chen, Coloma, deNiverville, Dobrescu, Frugiuele, Harnik, McKeen, Pascoli, Pospelov, Ritz, Ross-Lonergan

Neutrinos 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



Neutrinos and the standard solar model: CNO cycle and metallicity

Bailey, Busoni, Christensen-Dalsgaard, Krief, Simone, Serenelli, Scott, Vincent, Vilante, Vissani, Vynioli, …

Supernova evolution: non-linear effects from collective oscillations

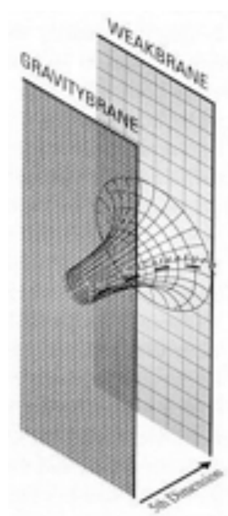
Friedland 2010, Cherry Carlson Friedland Fuller Vlaesnko 2012, Chakraborty Hansen Izaguirre Raffeelt 2016, Capozzi Basudeb Dasgupta 2016, Izaguirre Raffelt Tamborra 2016, Capozzi Dasgupta Lisi Marrone Mirizzi 2017

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

Chen Ratz Trautner 2015

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



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 , …

Type II, type III and radiative seesaw

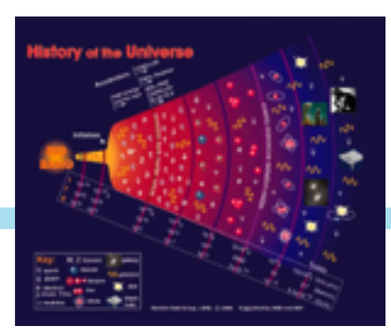
Akhmedov, Bonnet, Babu, Barbieri, Barger, Berezhiani, Ellis, Gaillard, Glashow, Hirsch, Keung, Ma, Mohapatra, Ota, Pakvasa, Schechter, Senjanovic, Valle, Yanagida, Winter, Wolfenstein, Zee, and many others

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

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, …



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!

Leptogenesis

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

Circa 2025+

- from Nu1998 to now, tremendous exp. progress on Neutrino SM: more at Nu2018 and much more before 2025 ! - nu_3 mass ordering and dominant flavor, size CP violation phase.

- Unitarity ? 12 constraints, only 3 will be tested with reasonable precision !!! All with nu-tau poorly constrained except thru Cauchy-Schwartz.

- LSND Sterile Nu's neither confirmed or ruled out at acceptable CL: - CP violation ? and role of Nu_tau ?

- Neutrinoless Double beta decay will be probing below IO scale.

Circa 2025+

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

- Convincing model of Neutrino masses and mixings: with testable and confirmed predictions !

- Connections to other sectors

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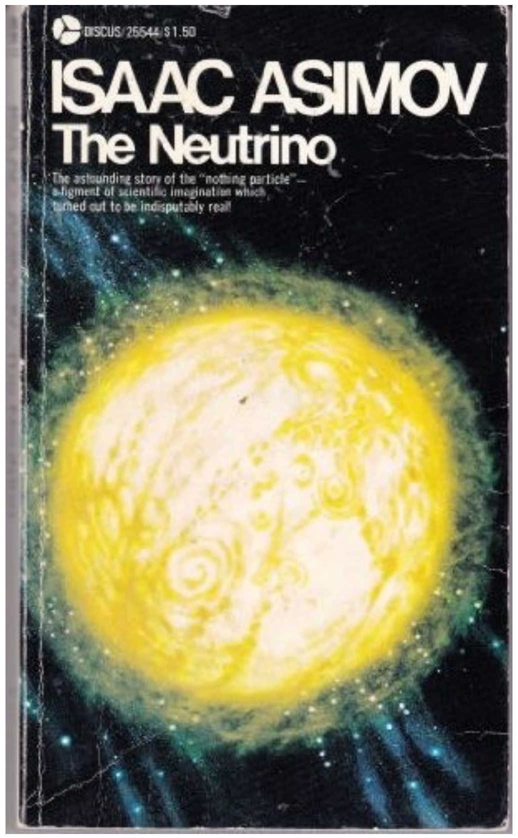
- Connections to other sectors

- Surprises !!!



"And yet the nothing-particle is not a nothing at all."

– Isaac Asimov 1966