LMA-DLMA Solutions in the light of astrophysical neutrinos observed at IceCube

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Vikram Discussions on Neutrino Astrophysics
(arXiv:2306.11653 [Universe 9 (2023) 380]; with M. Ghosh, S. Goswami, B. Pavlovic)

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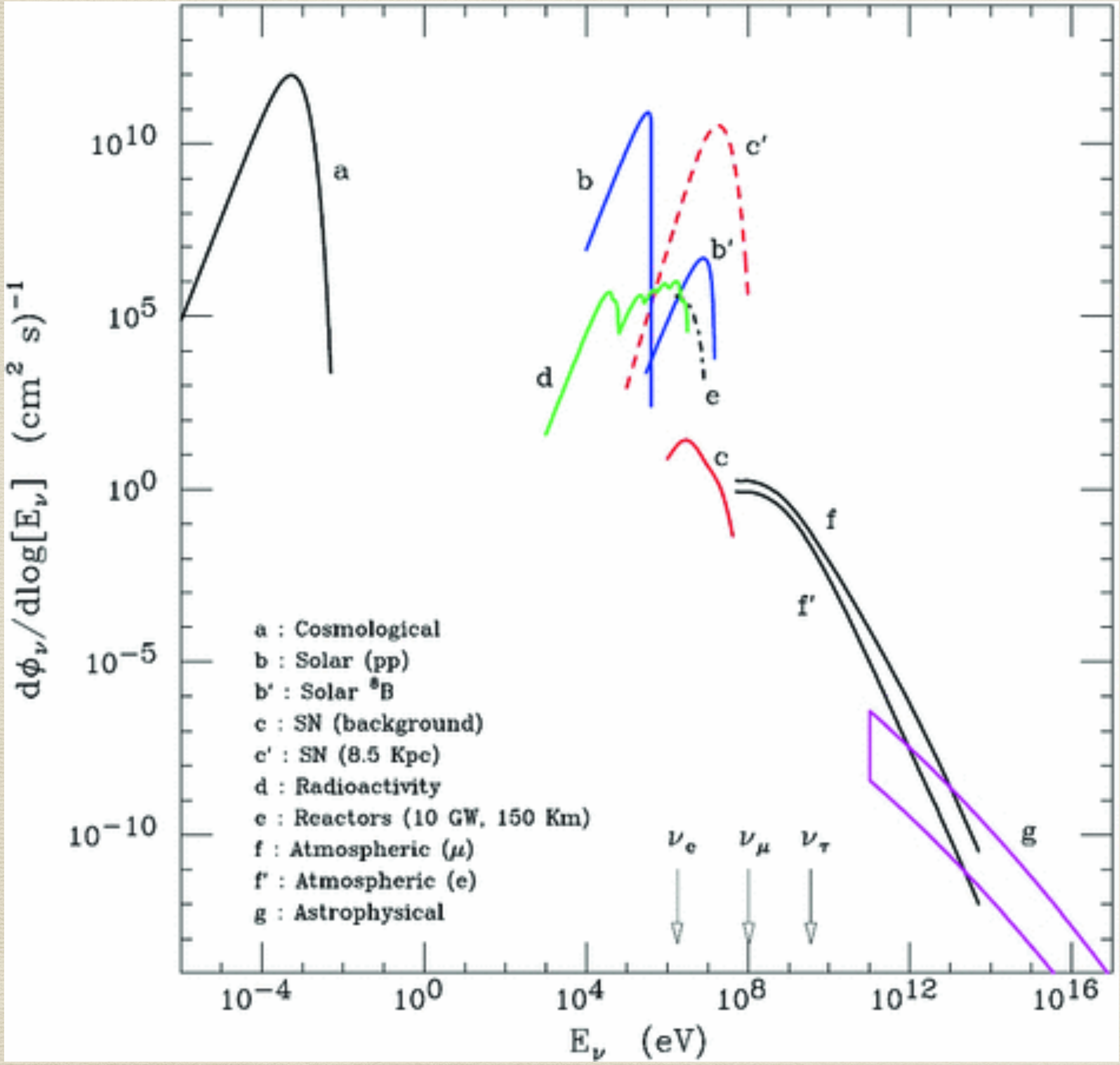
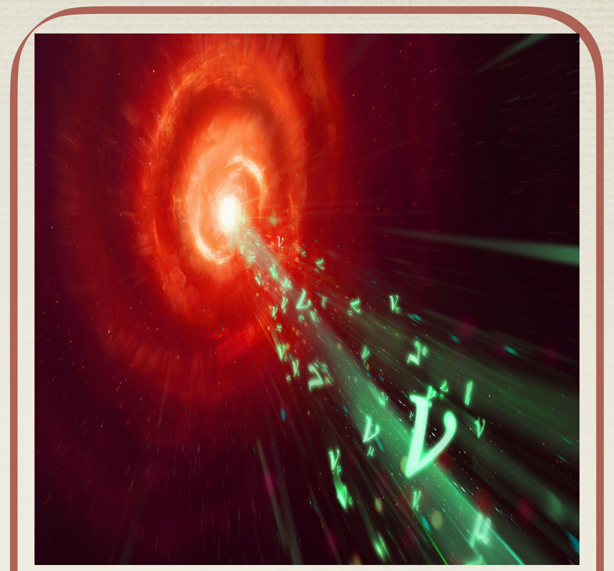
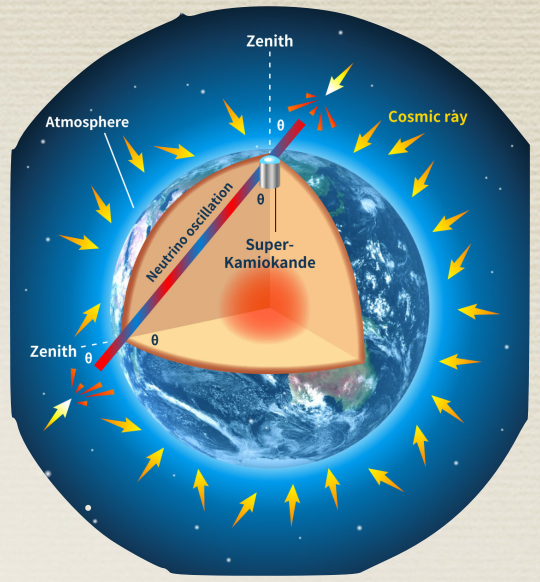
Sources of Neutrinos

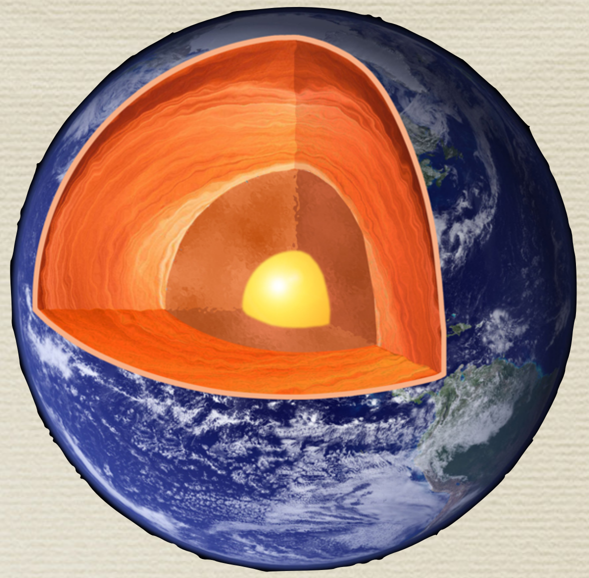




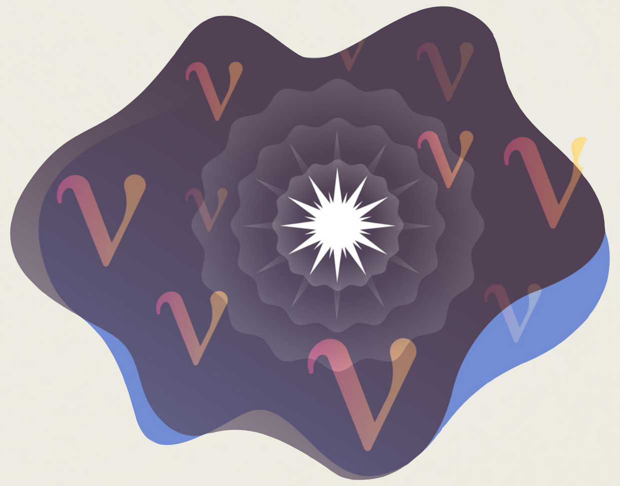
Astrophysical ν



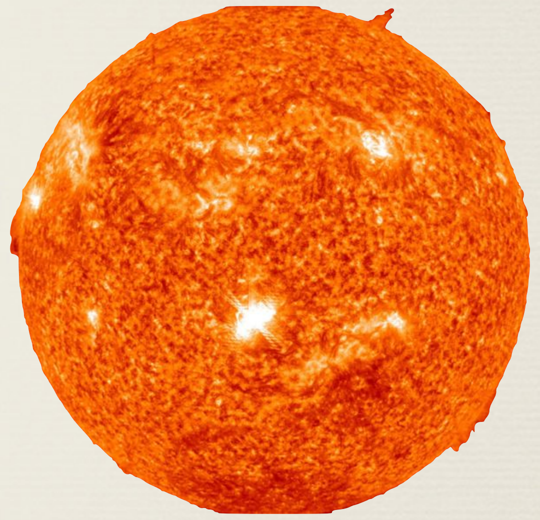
Atmospheric ν



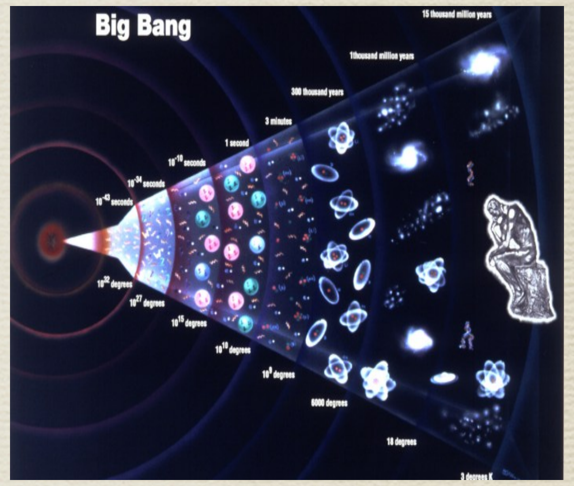
Terrestrial $\bar{\nu}_e$



Supernova ν

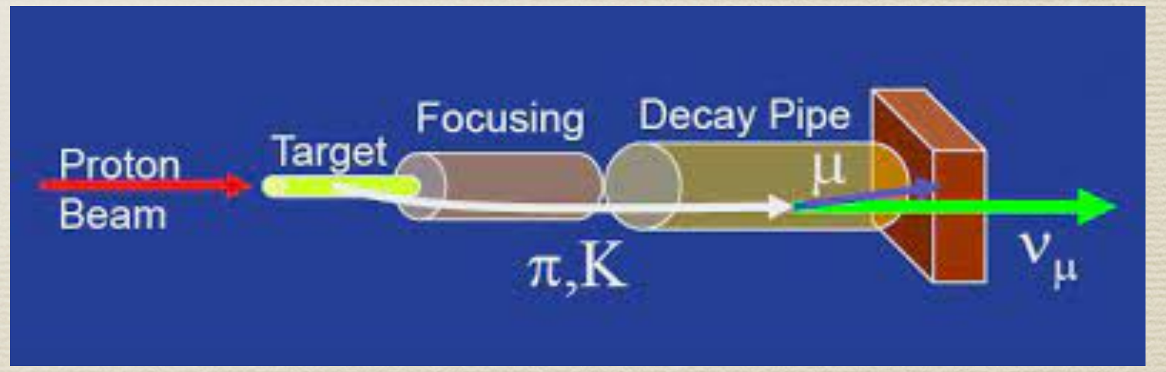


Solar ν_e



Big Bang ν

Reactor $\bar{\nu}_e$



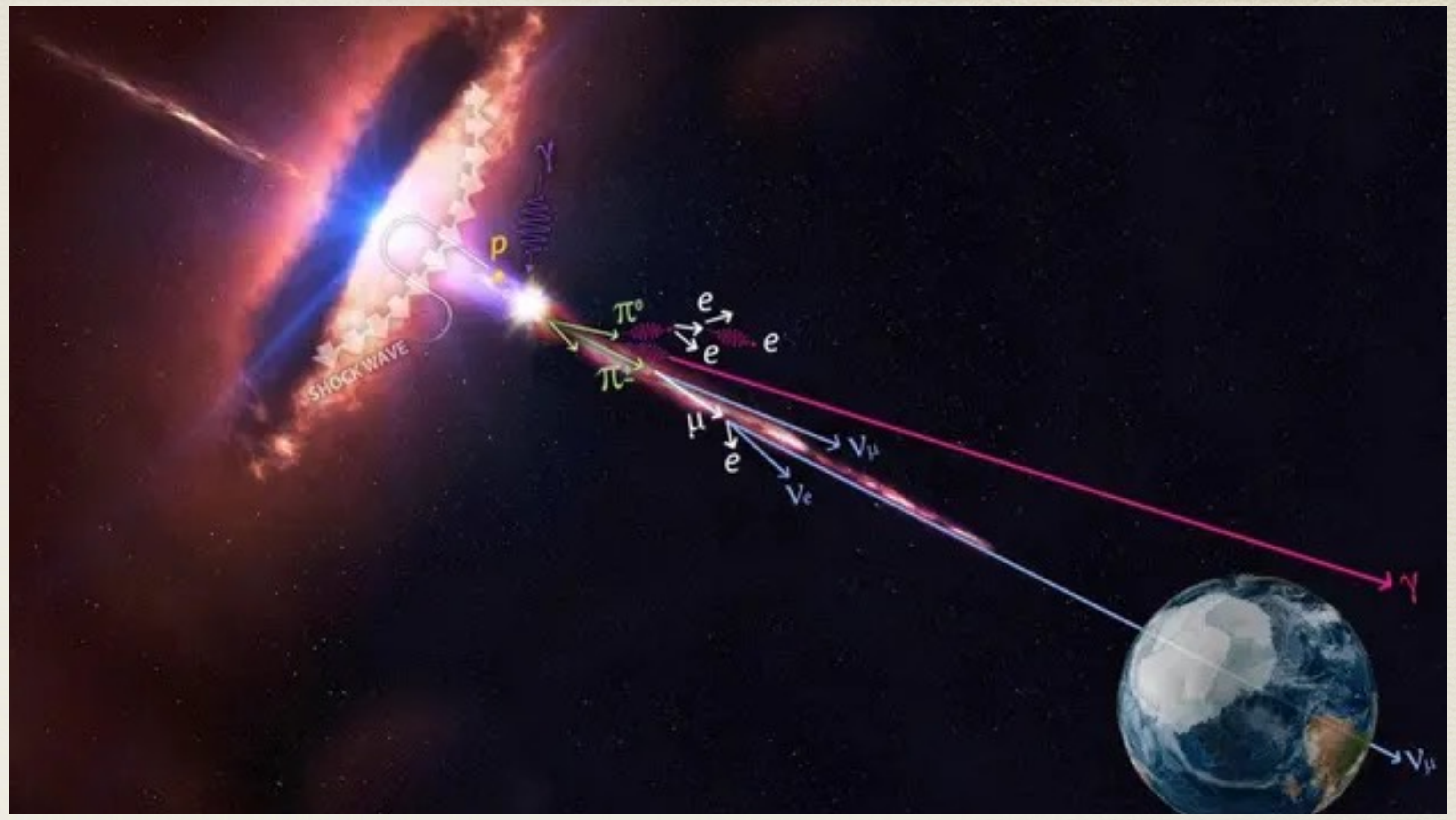
Accelerator ν_μ

Picture Source: Internet

Astrophysical Neutrino

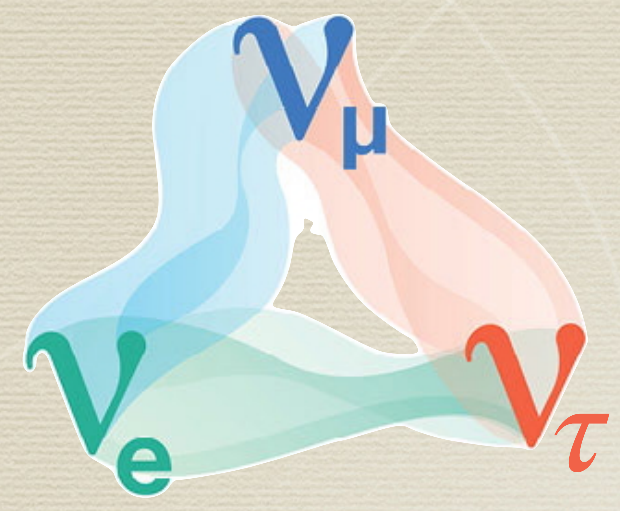
Source: AGNs, Blazer, GRB

Energy: $10^{11} - 10^{19} eV$



- π source : $\pi^+ \to \mu^+ + \nu_\mu ; \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu ; \phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau) = 1 : 2 : 0$
- μ source : $\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau) = 0 : 1 : 0$
- n source: $n \to p^+ + e^- + \bar{\nu}_e ; \phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau) = 1 : 0 : 0$

Oscillation of Astrophysical Neutrinos



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

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

PMNS mixing matrix

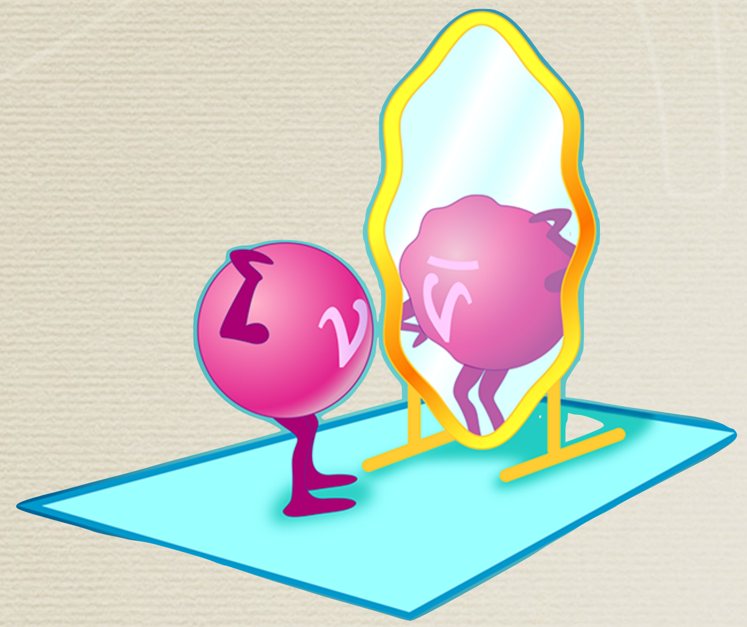
$$U = U(\theta_{23})U(\theta_{13}, \delta_{CP})U(\theta_{12})$$

$$\begin{bmatrix} \phi(\nu_e) \\ \phi(\nu_\mu) \\ \phi(\nu_\tau) \end{bmatrix} = \begin{bmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{bmatrix} \begin{bmatrix} \phi_0(\nu_e) \\ \phi_0(\nu_\mu) \\ \phi_0(\nu_\tau) \end{bmatrix}$$

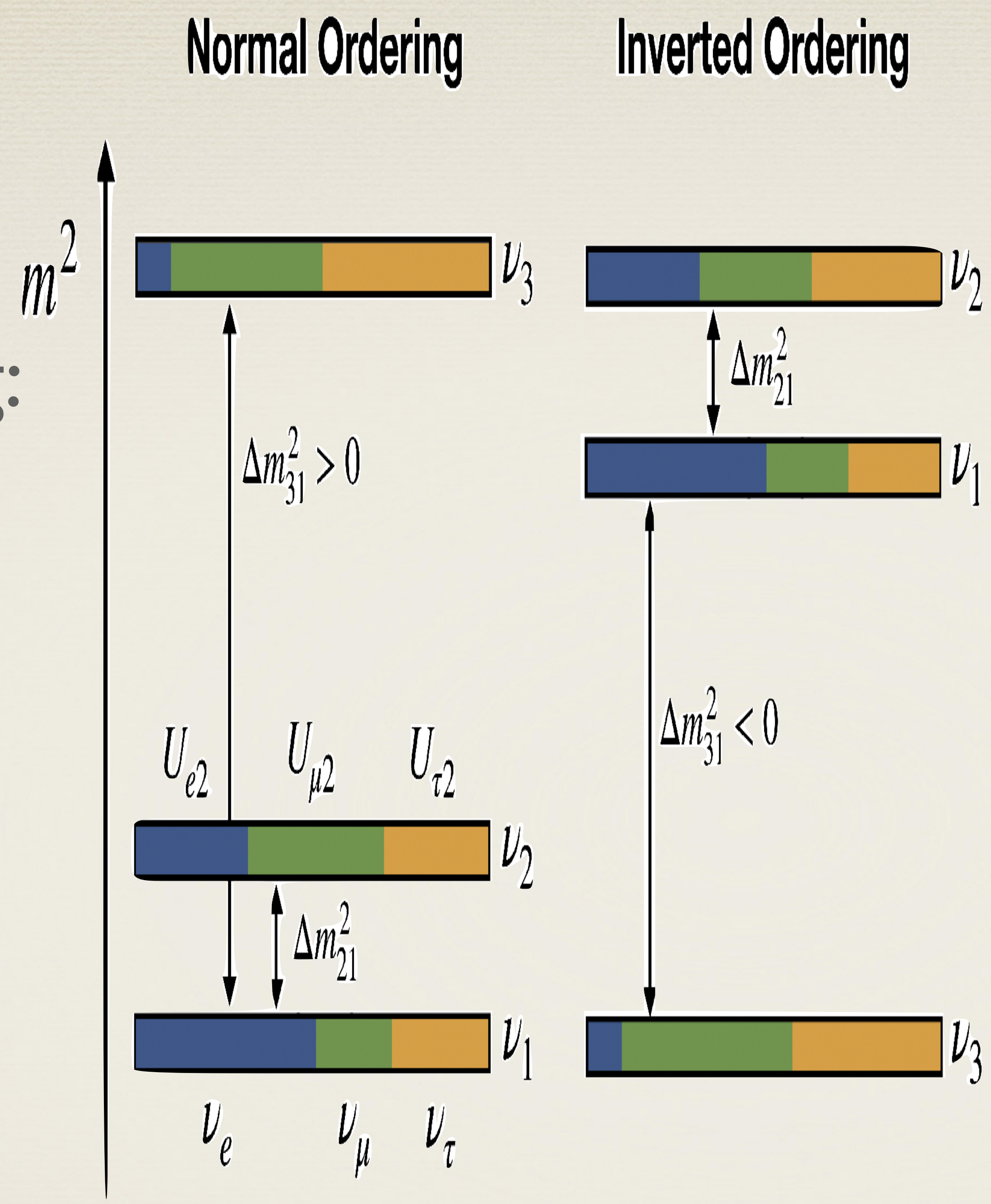
- π Source: $\phi_e : \phi_\mu : \phi_\tau = 1 : 2 : 0$ [PRD,59,023002]
- μ Source: $\phi_e : \phi_\mu : \phi_\tau = 0 : 1 : 0$ [PRL,108,231101]
- n Source: $\phi_e : \phi_\mu : \phi_\tau = 1 : 0 : 0$ [PRD, 82, 023003]

$P_{ee}, P_{e\mu}, P_{e\tau}, P_{\mu\mu}, P_{\mu\tau}$ are relevant

Current Status of Oscillation Parameters



Mass Ordering: Sign of Δ_{31}



https://doi.org/10.3390/psf2023008007

Value of δ_{13}

Octant of θ_{23}

Higher Octant($> 45°$)
Lower Octant($< 45°$)

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/°$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$
	$\theta_{23}/°$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$
	$\theta_{13}/°$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$
	$\delta_{CP}/°$	212^{+26}_{-41}	$124 \to 364$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$

LMA-DLMA Solutions of θ_{12}

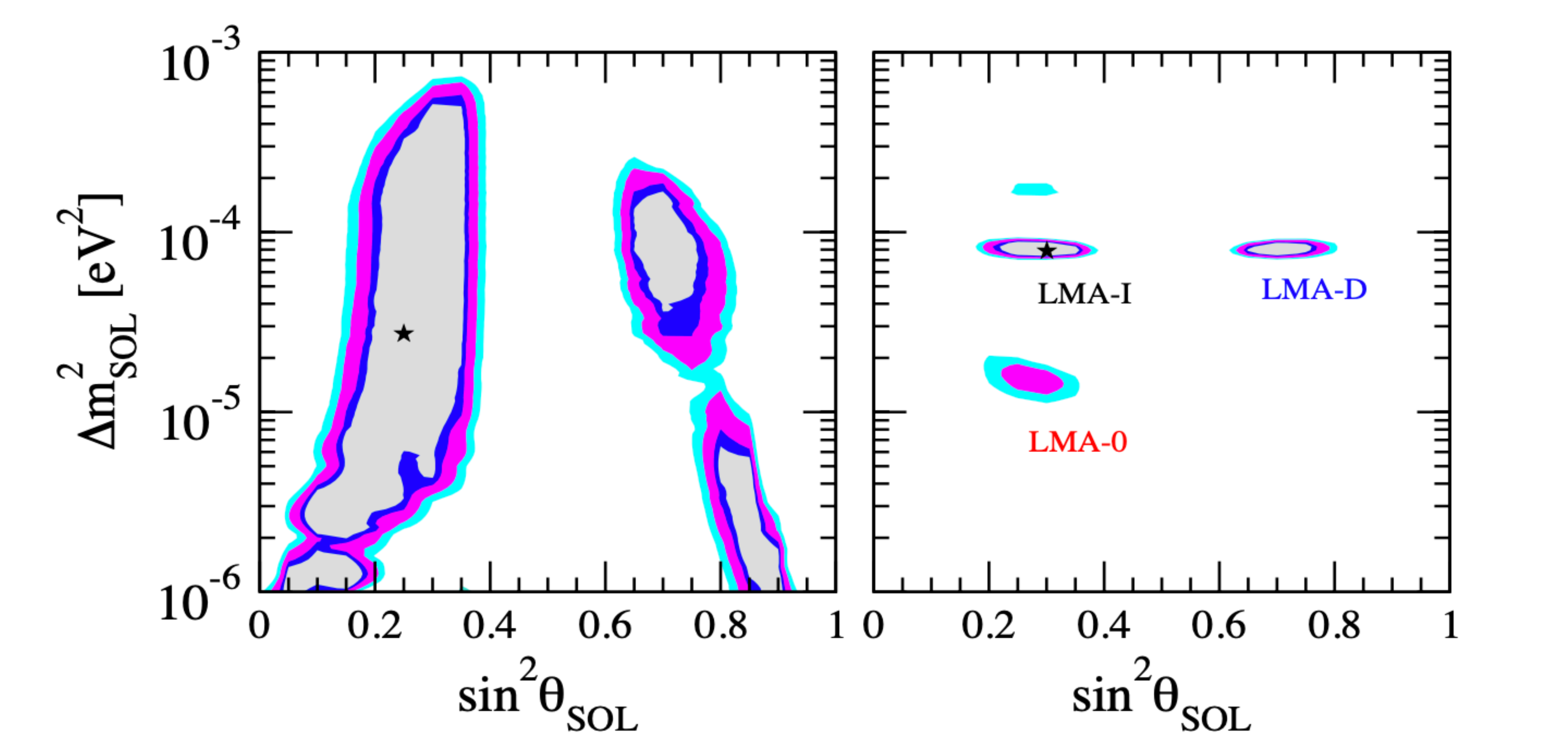
DLMA: $\theta_{12}^{DLMA} = 90° - \theta_{12}^{LMA}$; [de Gouvea, Friedland, Murayama, Phy.Lett.B. 490(2000)]

Degenerate solutions for $\sin\theta_{12}$

Large mixing angle (LMA): $\sin\theta_{12} \sim 0.3$

Dark-LMA (DLMA): $\sin\theta_{12} \sim 0.7$

The DLMA sol is rejected from solar data for standard neutrino oscillations



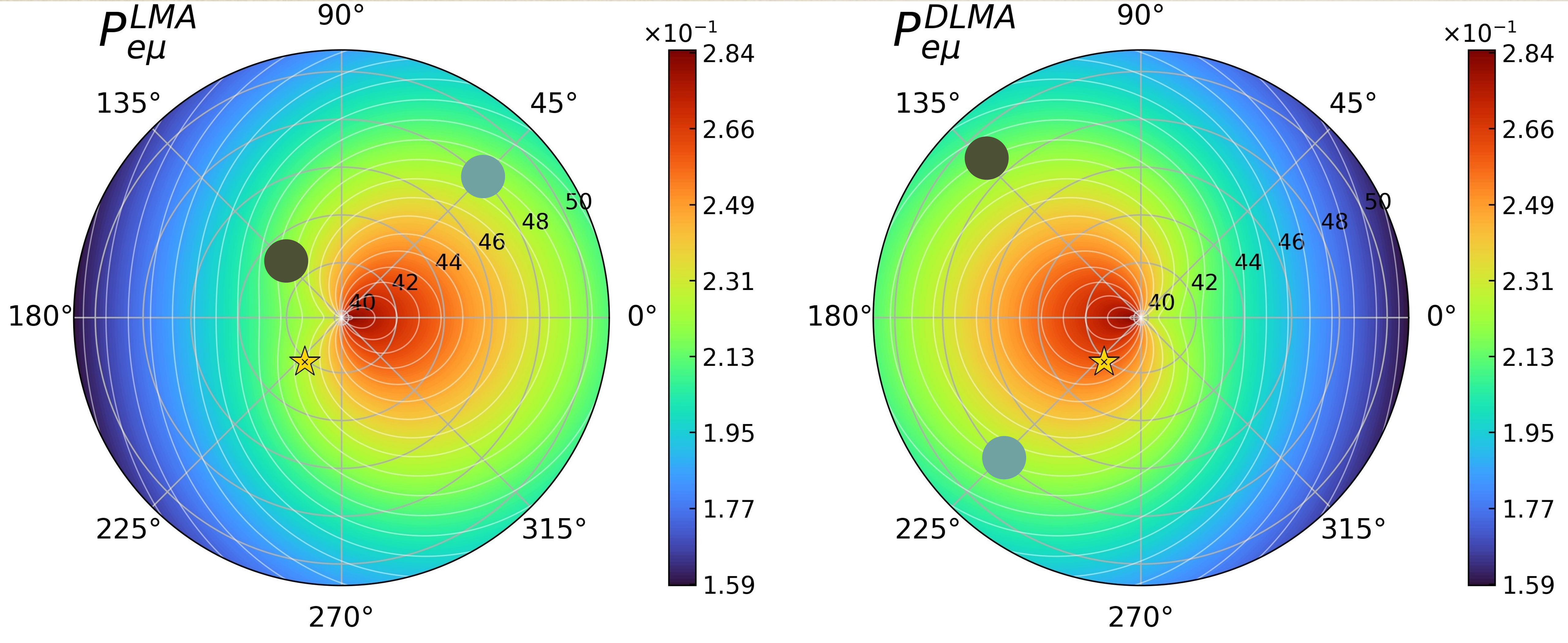
Source: Miranda, Tortola, Valle, JHEP. 10 (2006) 008.

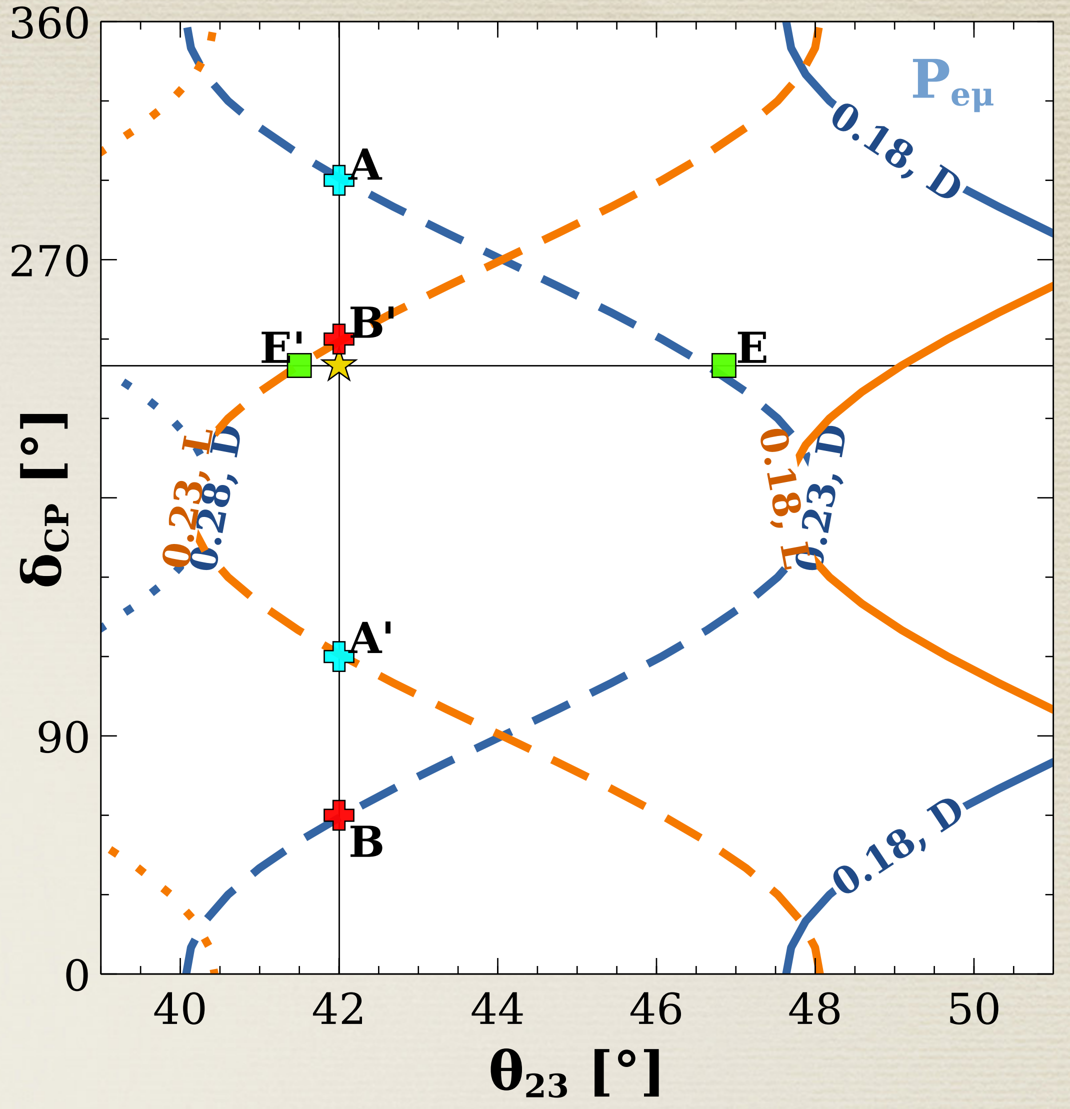
In presence of NSI, DLMA-LMA degeneracy gets revived

Probability Invariant: $\Delta_{31} \to -\Delta_{31}$; $\sin\theta_{12} \to \cos\theta_{12}$; $\delta_{CP} \to 180° - \delta_{CP}$; $\epsilon_{ee} \to -\epsilon_{ee} - 2$

[Coloma, Schwetz, PRD 95 079903 (2017)]

Degeneracies in $P_{e\mu}$





$$P_{e\mu} = \left[\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{23} + \sin^2\theta_{13}\sin^2\theta_{23}(2 - \frac{1}{2}\sin^2 2\theta_{12}) + \frac{1}{2}\sin 2\theta_{23}\sin\theta_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta_{CP}\right]\cos^2\theta_{13}$$

- Fixed θ_{23}: $P_{\alpha\beta}(\theta_{12}^{LMA}, \delta_{CP}) = P_{\alpha\beta}(\theta_{12}^{DLMA}, 180^\circ \pm \delta_{CP})$; A-A' , A'-B, A-B'
- Fixed δ_{CP}: $P_{e\mu}(\theta_{12}^{LMA}, \theta_{23}^{L}) = P_{e\mu}(\theta_{12}^{DLMA}, \theta_{23}^{D})$; E-E'
- $\delta_{CP} = -\delta_{CP}$; within LMA and DLMA solutions; A-B, A'-B'

Degenerate Solutions

$$\Delta P_{\alpha\beta} = P_{\alpha\beta}(\theta_{12}) - P_{\alpha\beta}(90^\circ - \theta_{12})$$

For Degenerate Solutions: $\Delta P_{\alpha\beta} = 0$

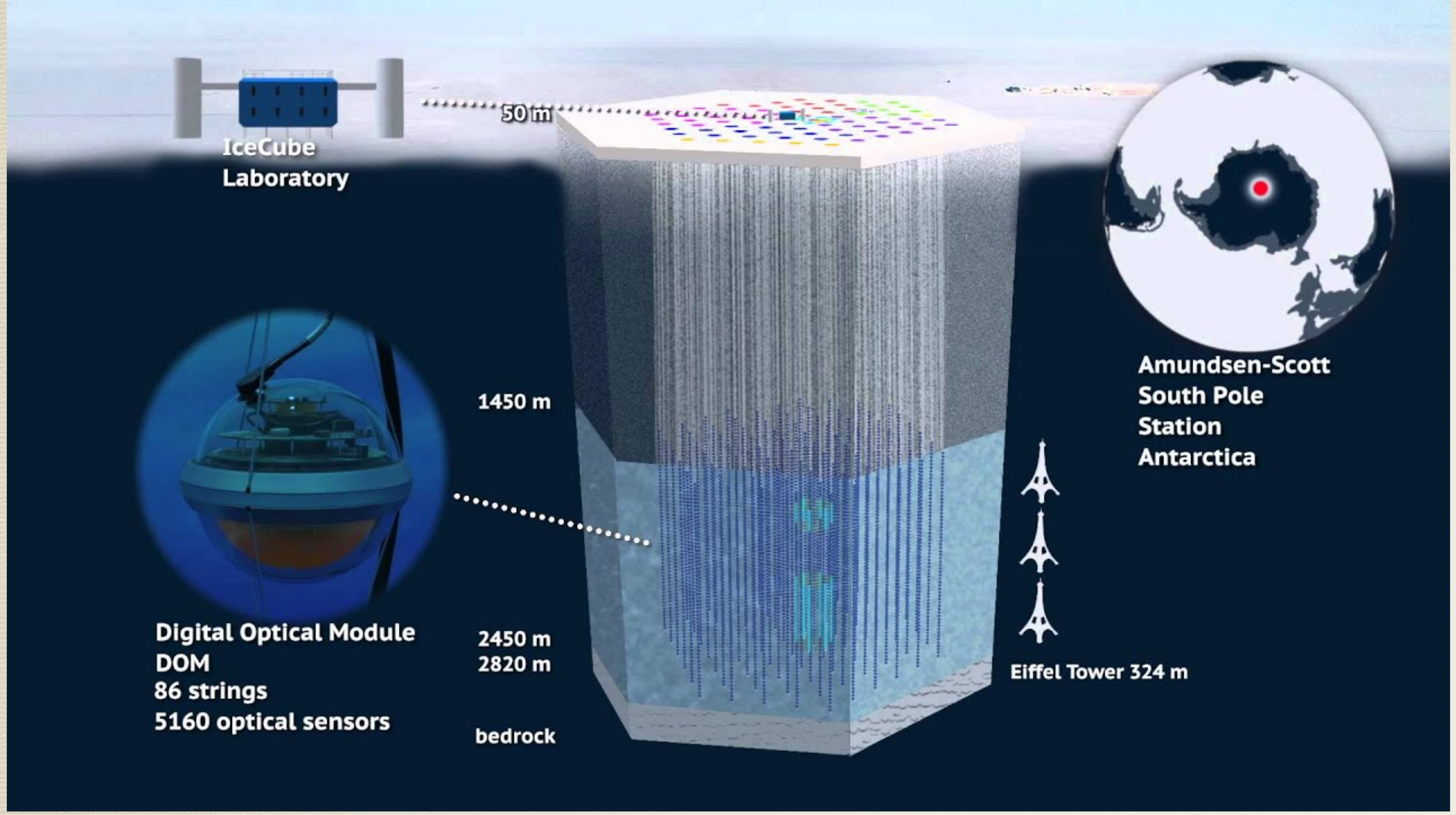
$$\Delta P_{\mu\mu} = \Delta P(\sin^2\theta_{23}\sin^2\theta_{13} - \cos^2\theta_{23}),\ \Delta P_{\mu\tau} = \Delta P\cos 2\theta_{23}(1 + \sin^2\theta_{13})$$

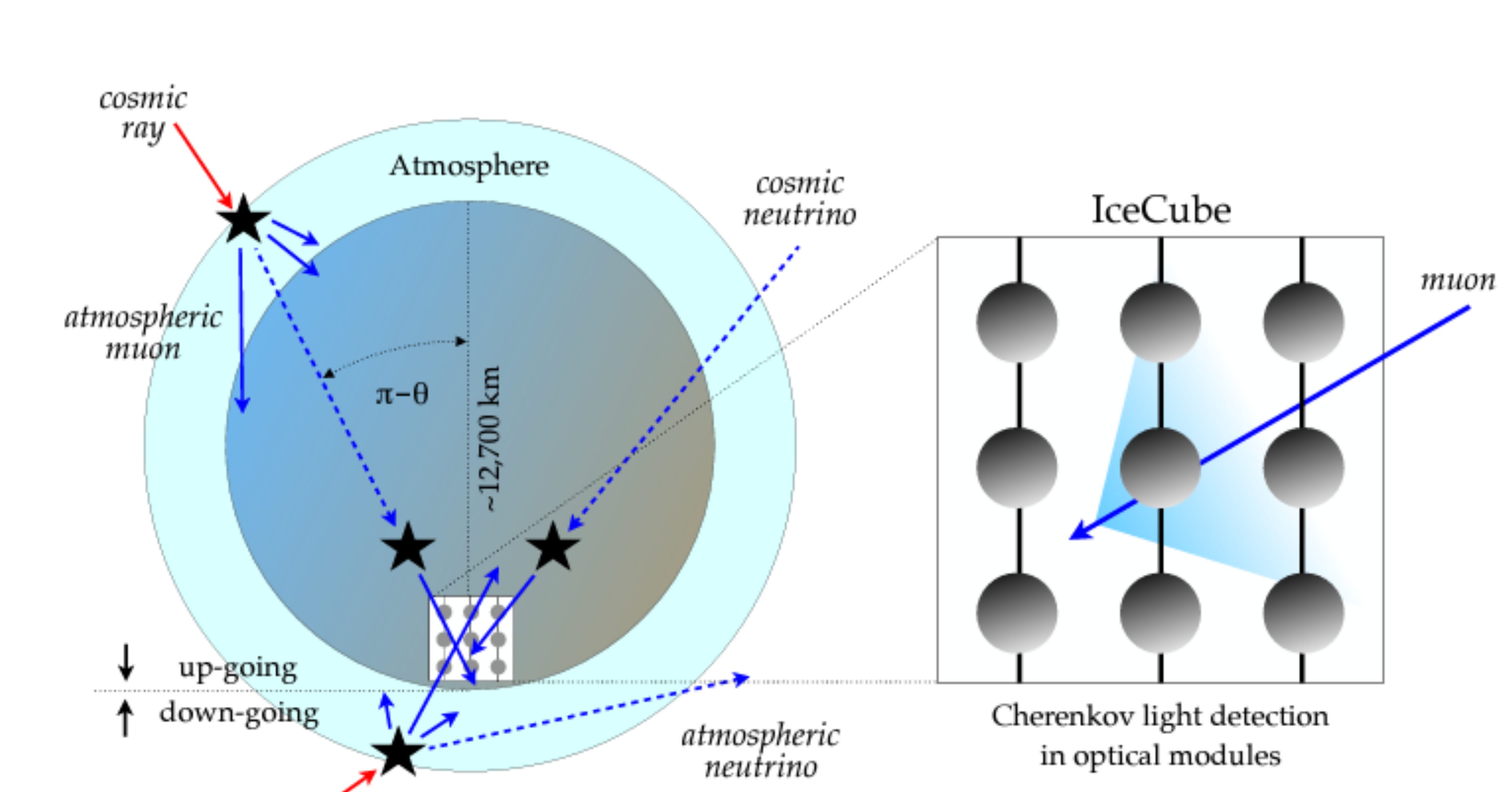
$$\Delta P_{e\mu} = \Delta P,\ \Delta P_{e\tau} = -\Delta P$$

$$\Delta P = \sin 2\theta_{12}\cos 2\theta_{12}\sin\theta_{13}\cos^2\theta_{13}\sin 2\theta_{23}\cos\delta_{CP}$$

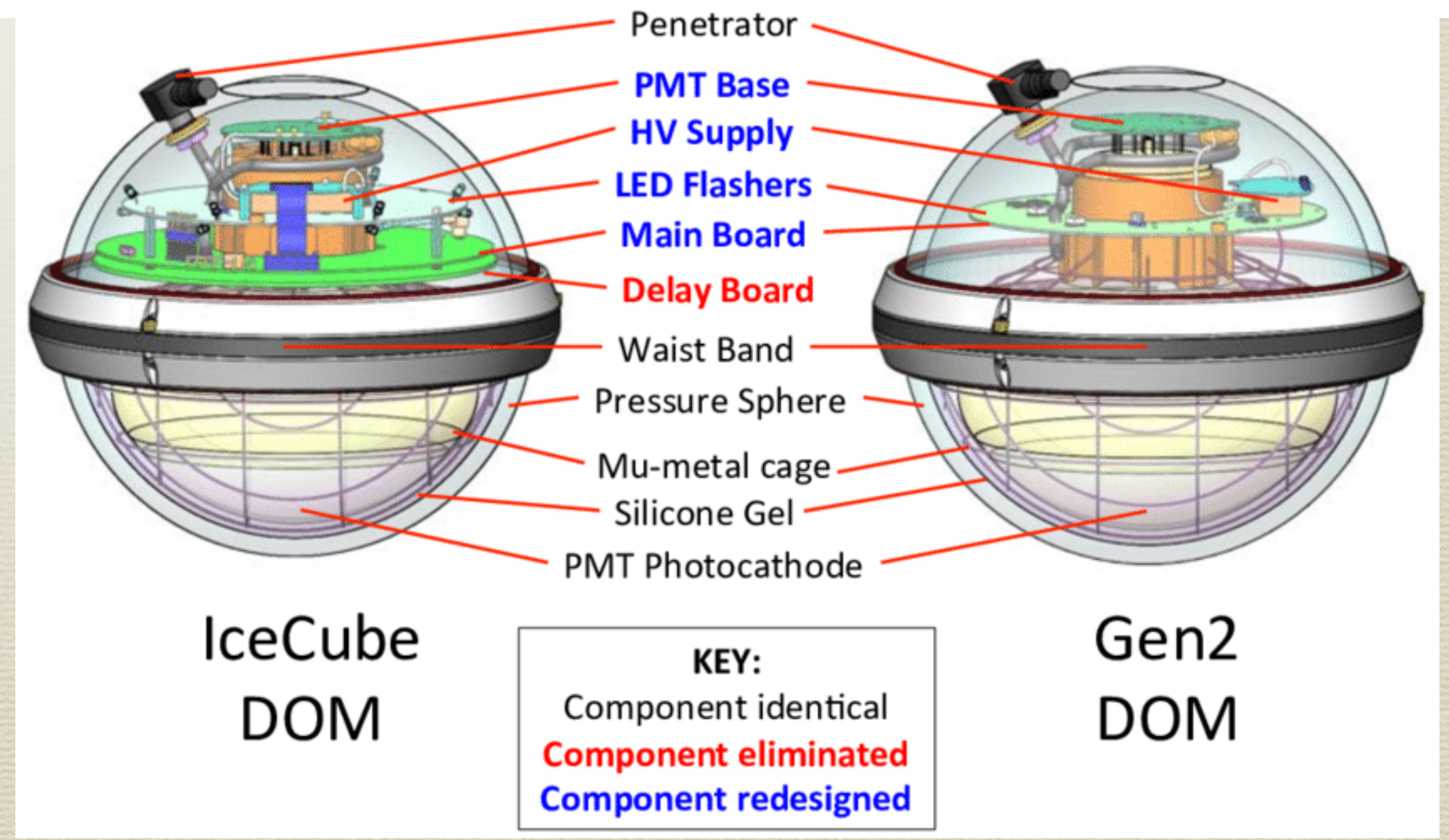
- I. $\Delta P = 0$ for $\delta_{CP} = 90^\circ, 270^\circ$
- II. $\Delta P = 0$: At fixed θ_{23}, $\delta_{CP}^{LMA} = 180^\circ - \delta_{CP}^{DLMA}$
- III. $\Delta P = 0$: At fixed δ_{CP}, $\sin\theta_{23}^D + \sin\theta_{23}^L = 0 => \theta_{23}^L = 360^\circ - \theta_{23}^D$
  $M_1\cos\delta_{CP}(\sin^2\theta_{23}^L - \sin\theta_{23}^L\sin\theta_{23}^D + \sin^2\theta_{23}^D) + M_1(\sin\theta_{23}^L - \sin\theta_{23}^D) + M_2\cos\delta_{CP} = 0$

IceCube Neutrino Observatory





Source: Prog.Part.Nucl.Phys. 102 (2018) 73-88



- Detection of atmospheric, astrophysical ν
- Searches for sterile neutrino
- Determination of oscillation parameters

Analysis of Flavour Ratio (R)

Category	Events (E>60 TeV)
Cascade	41
Track	17
Double Cascade	2
Total	60

Category	Cascade	Track	Double Cascade
Total	72.7% (Pc)	23.4% (Pt)	3.9% (Pdc)
Nu_e	56.7%	9.8%	21.1%
Nu_mu	15.7%	72.8%	14.2%
Nu_tau	27.6%	10.5%	64.7%
Muon	0.0%	6.9%	0.0%

$$R_{exp} = \frac{track}{shower} = \frac{17-1}{41+2} = 0.372$$

$$R = \frac{P_t \sum_\alpha p_t^\alpha \phi_\alpha}{P_c \sum_\alpha p_c^\alpha \phi_\alpha + P_{dc} \sum_\alpha p_{dc}^\alpha \phi_\alpha}$$

$$\chi^2 = \frac{[R_{exp} - R(\theta_{ij}, \delta_{CP})]^2}{\sigma_{exp}^2}$$

$$\sigma_{exp} = \sqrt{\frac{(1-R_{exp})R_{exp}}{N}}$$

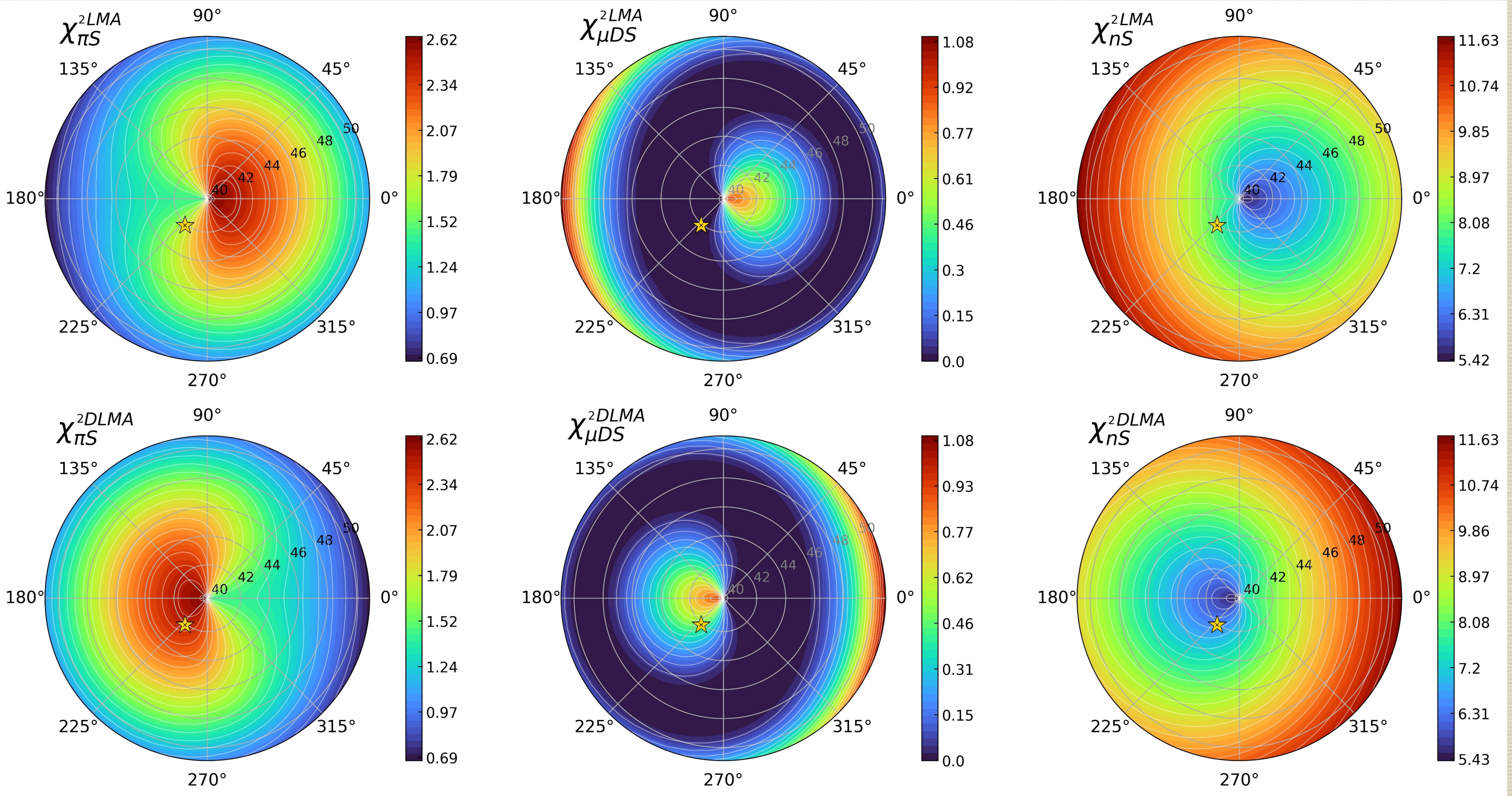
N: Total no of events

Sensitivity to LMA/DLMA Solutions

- π Source: Lowest χ^2 at upper octant of θ_{23}, best fit excluded at $\chi^2 = 1.7(2.4)$ for LMA(DLMA).

- μ Source: $\chi^2 = 0$ region, best fit prefers LMA.

- n Source: Least favoured, prefers lower octant, best fit excluded for LMA (DLMA) at $\chi^2 = 7.9(6.5)$.



Remarks

- Degeneracy of θ_{12} is with θ_{23} and δ_{CP}
- IceCube Data cannot break this degeneracy alone
- Knowing the θ_{23}, δ_{CP} from other experiments will help in removing the degeneracies between LMA and DLMA solutions
- Can be looked into using new high energy neutrino data and also add atmospheric neutrinos in the analysis

Thank You