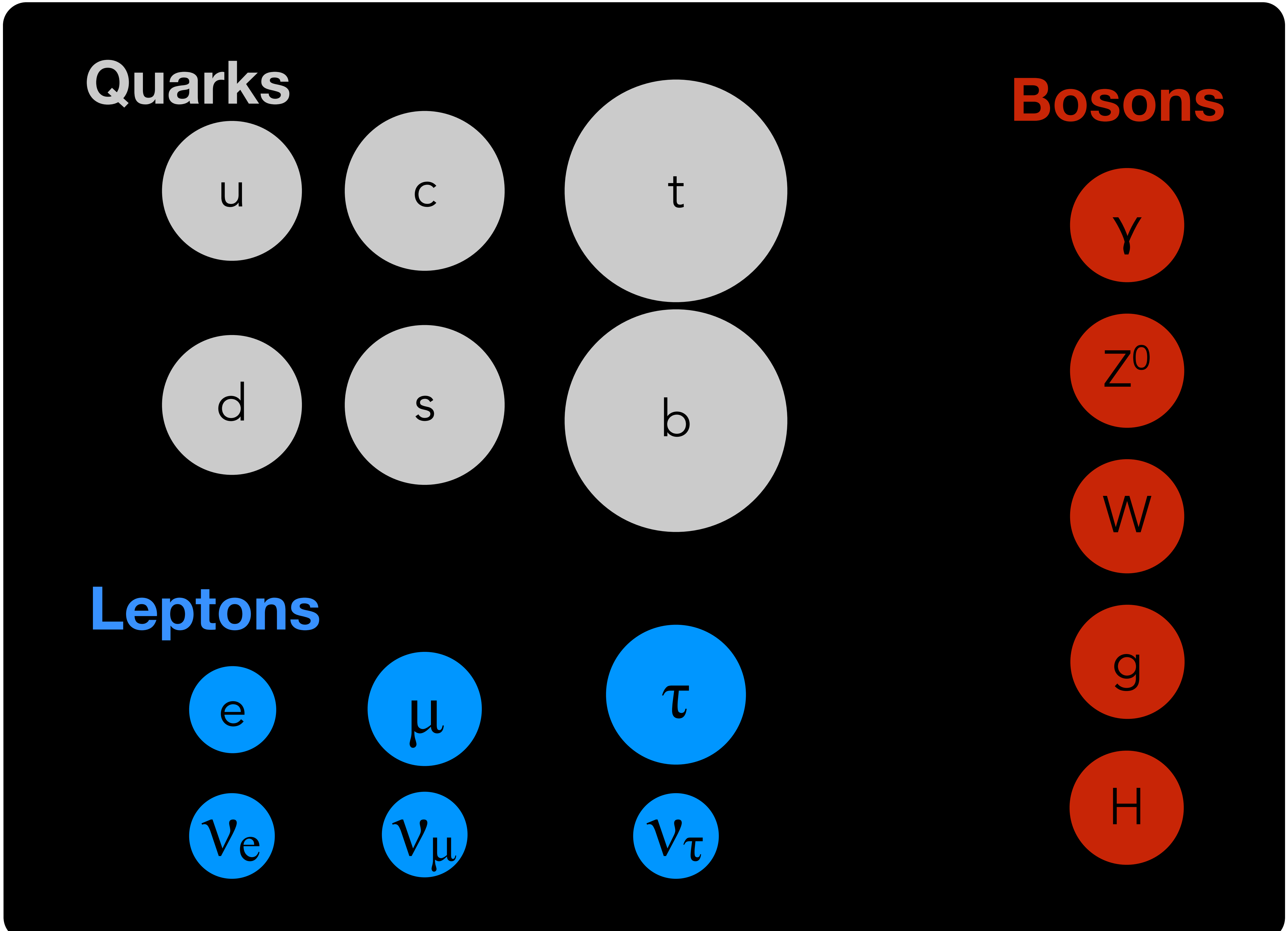
Neutrino Oscillation and Resolving the Neutrino Mass Ordering

D. Jason Koskinen

August 29, 2015
4th International Conference on New Frontiers in Physics

Standard Model & Neutrinos



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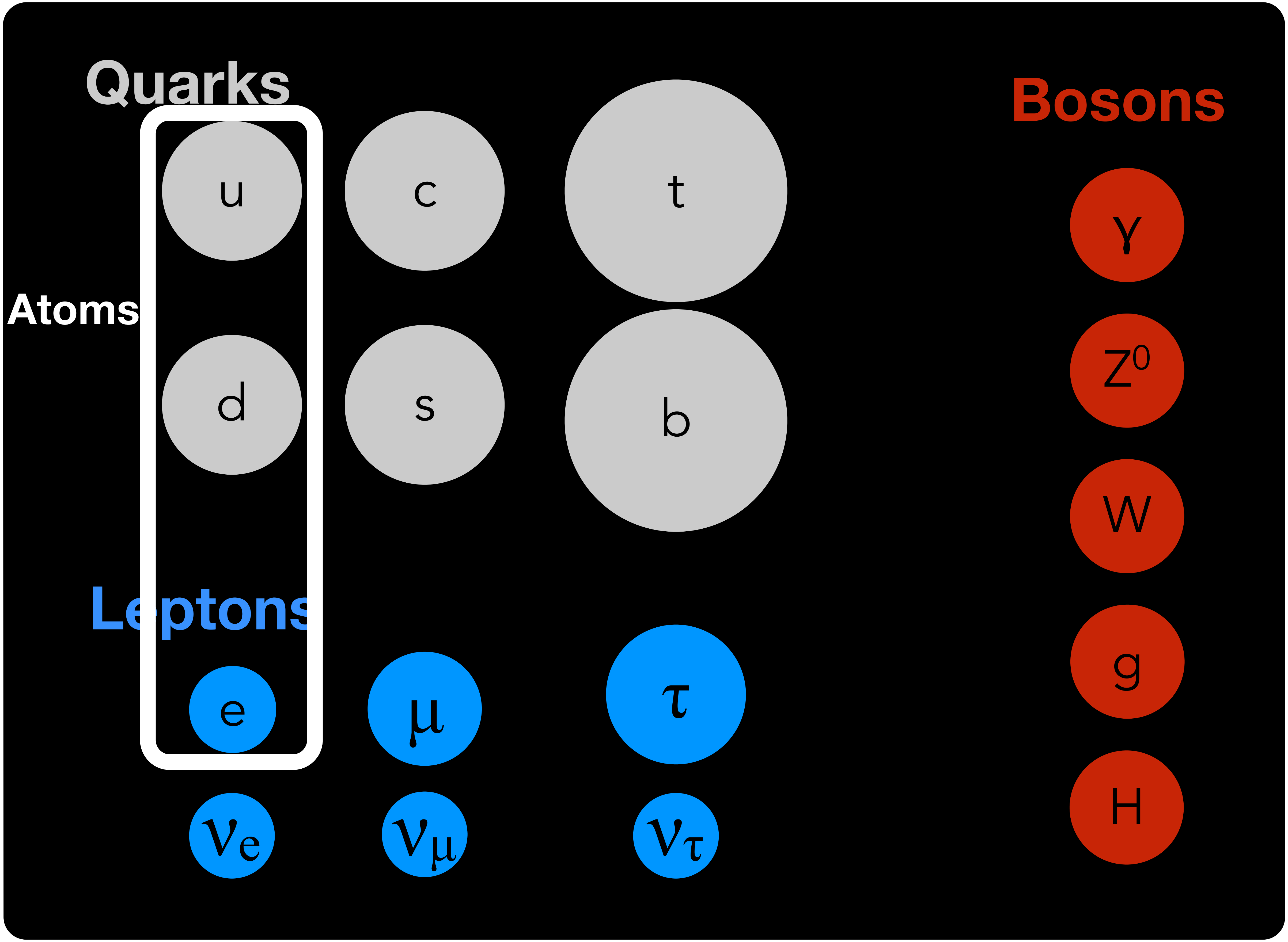

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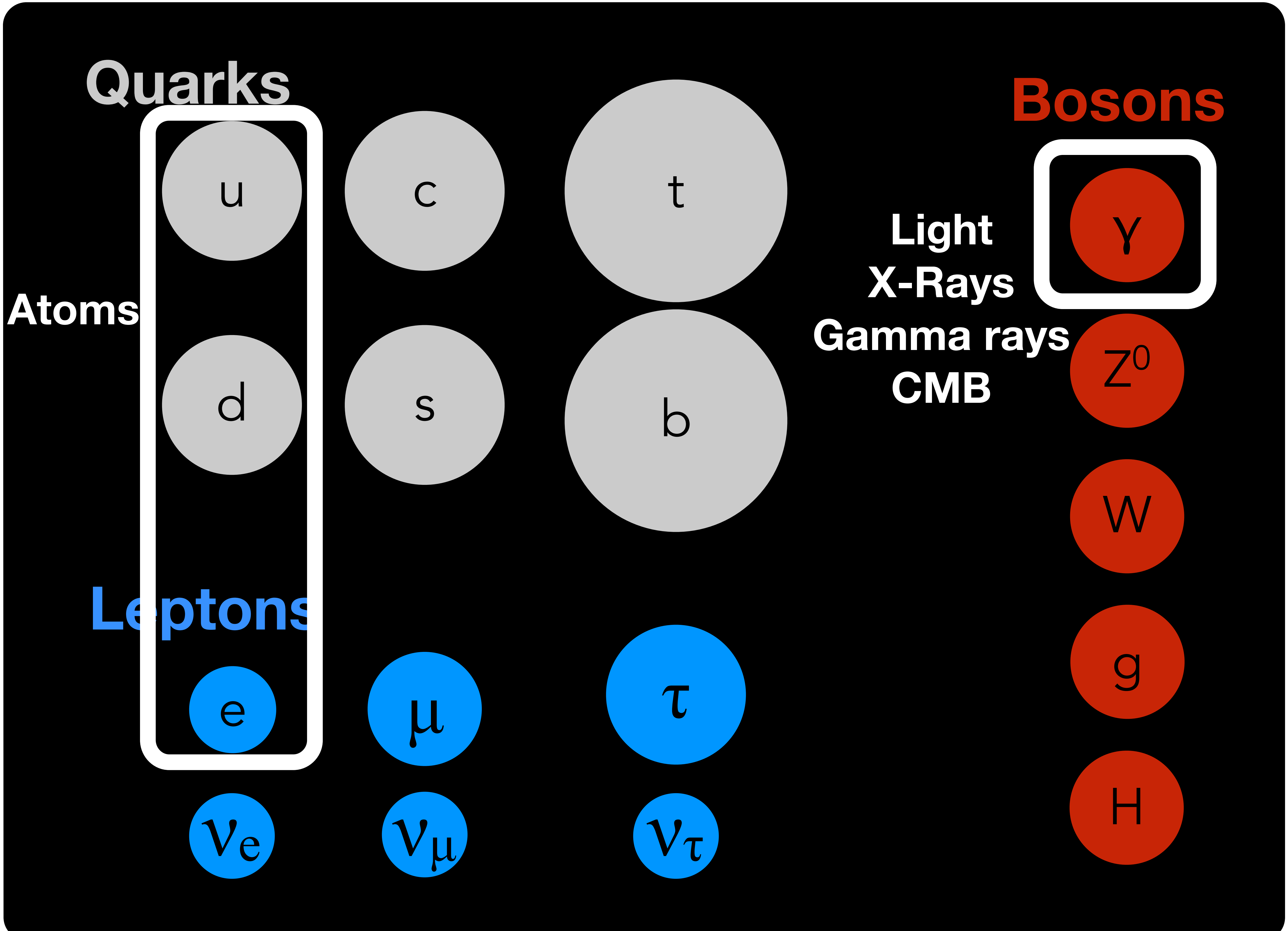

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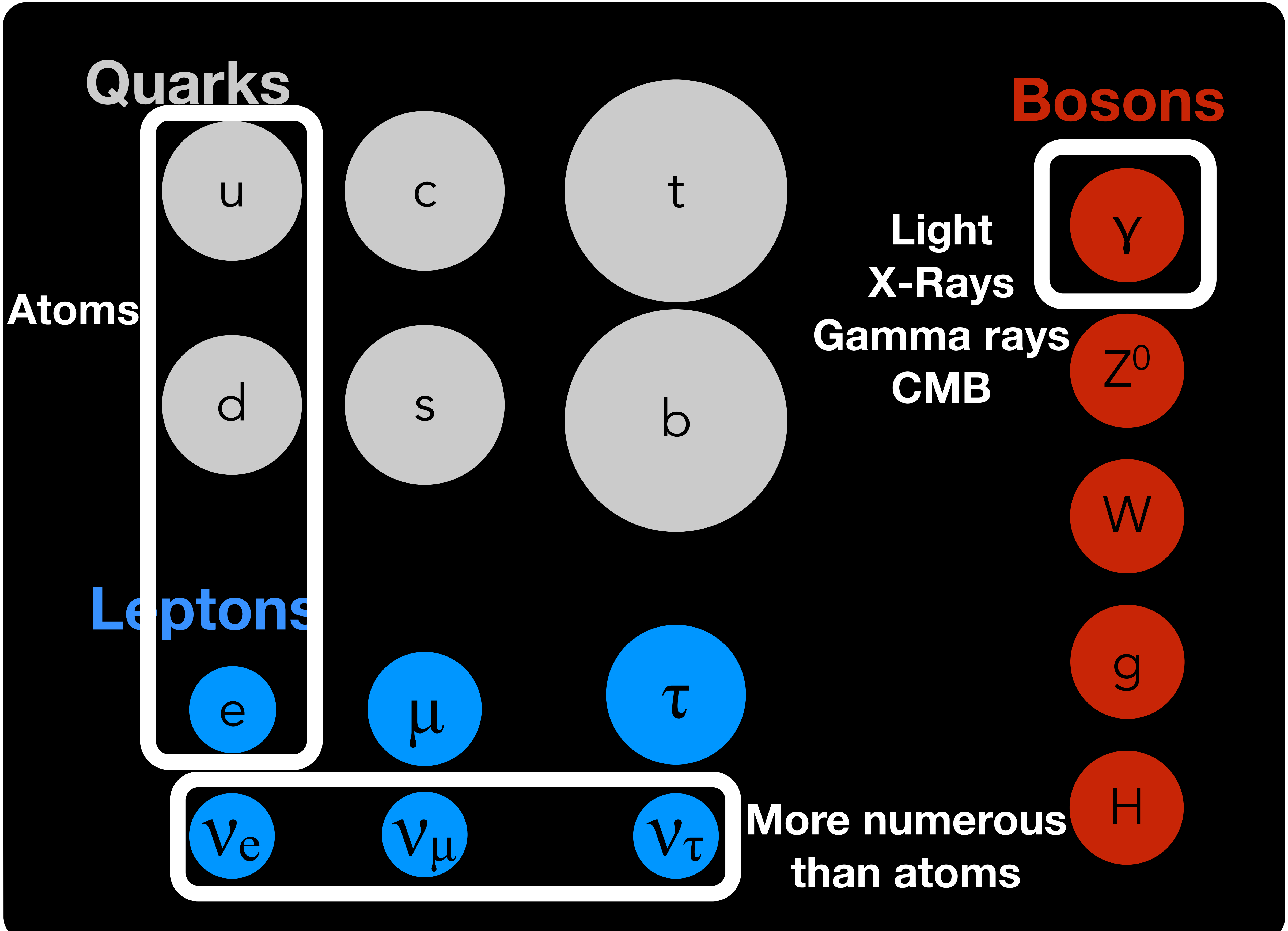

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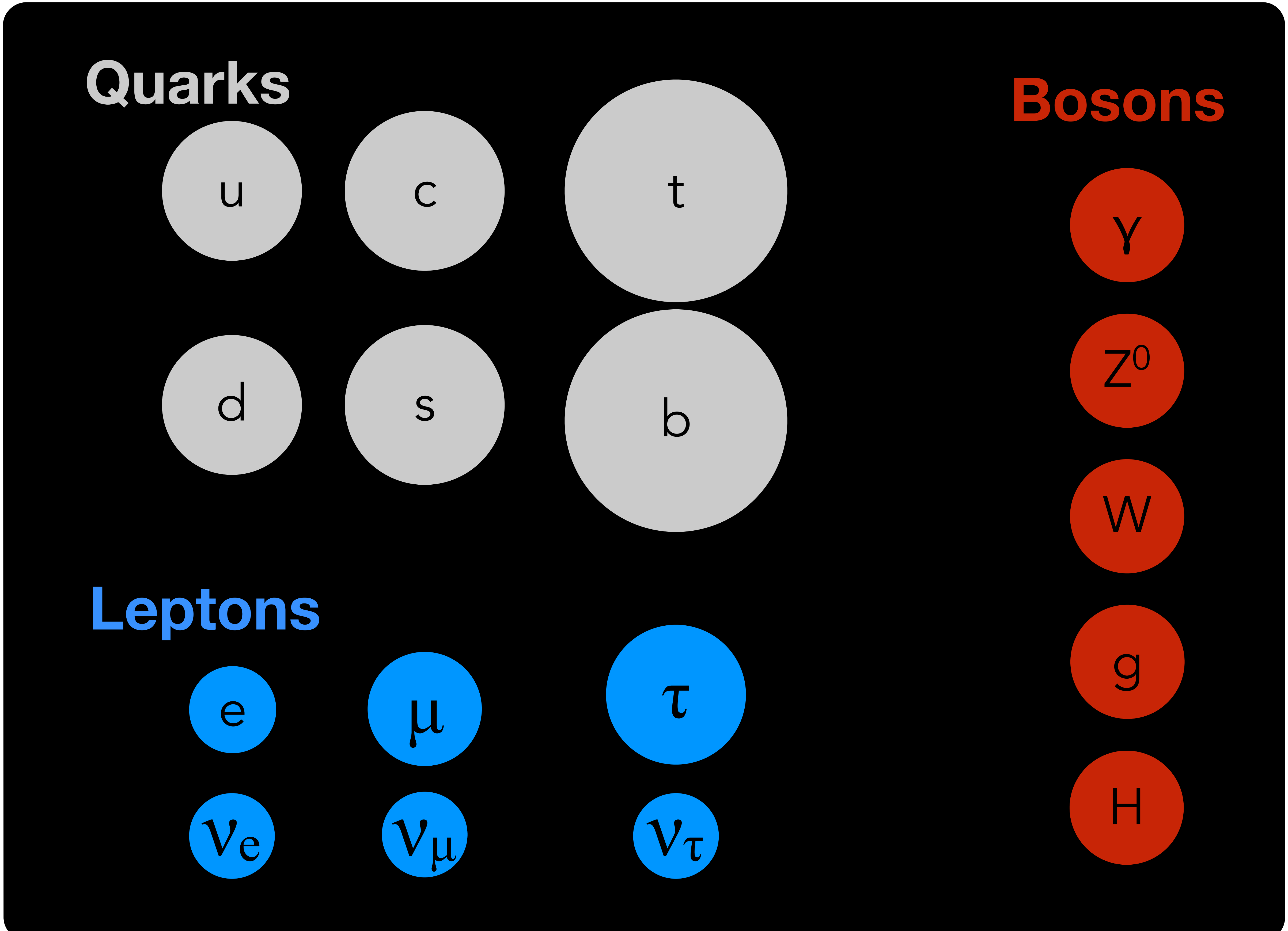

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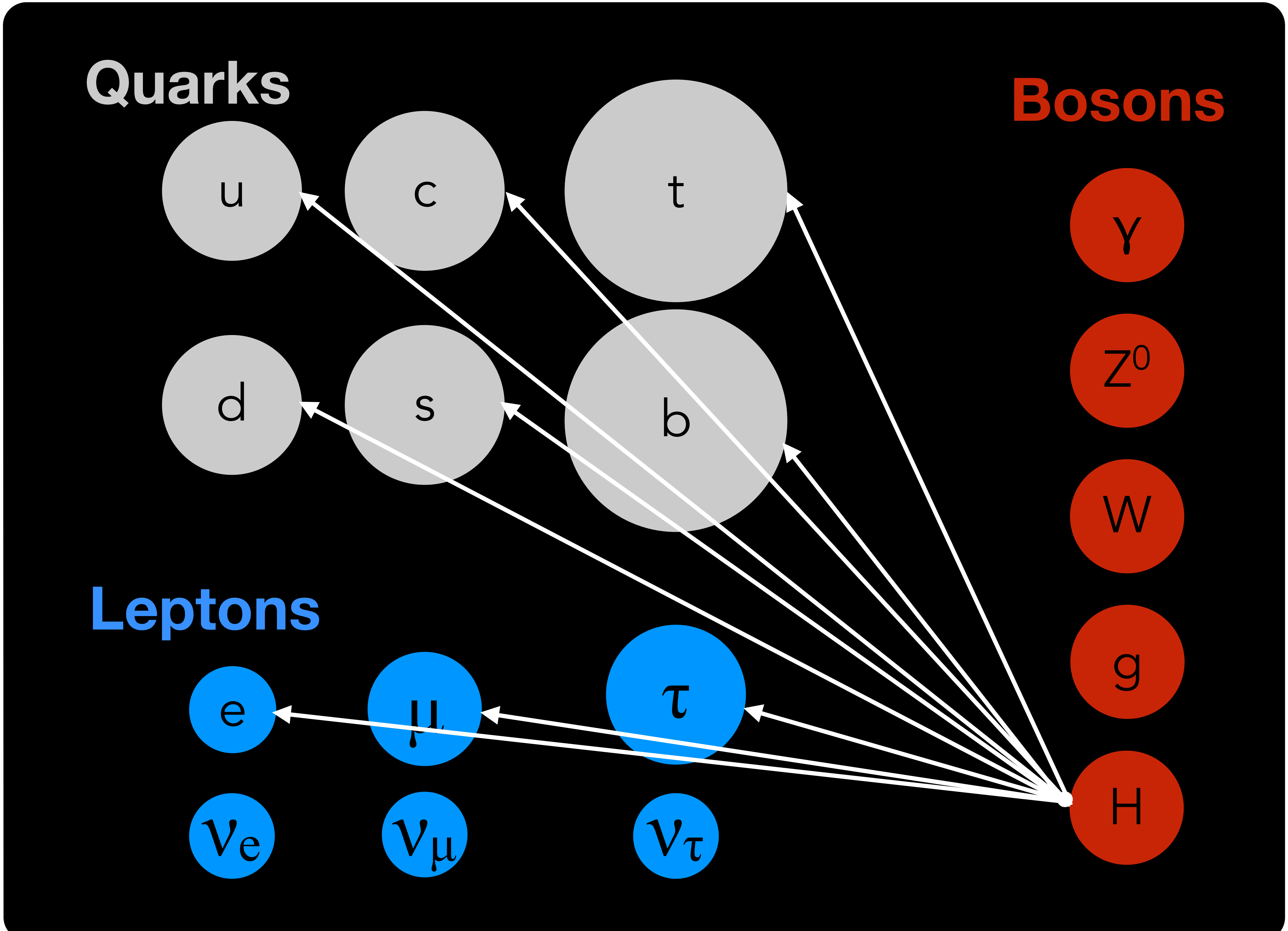

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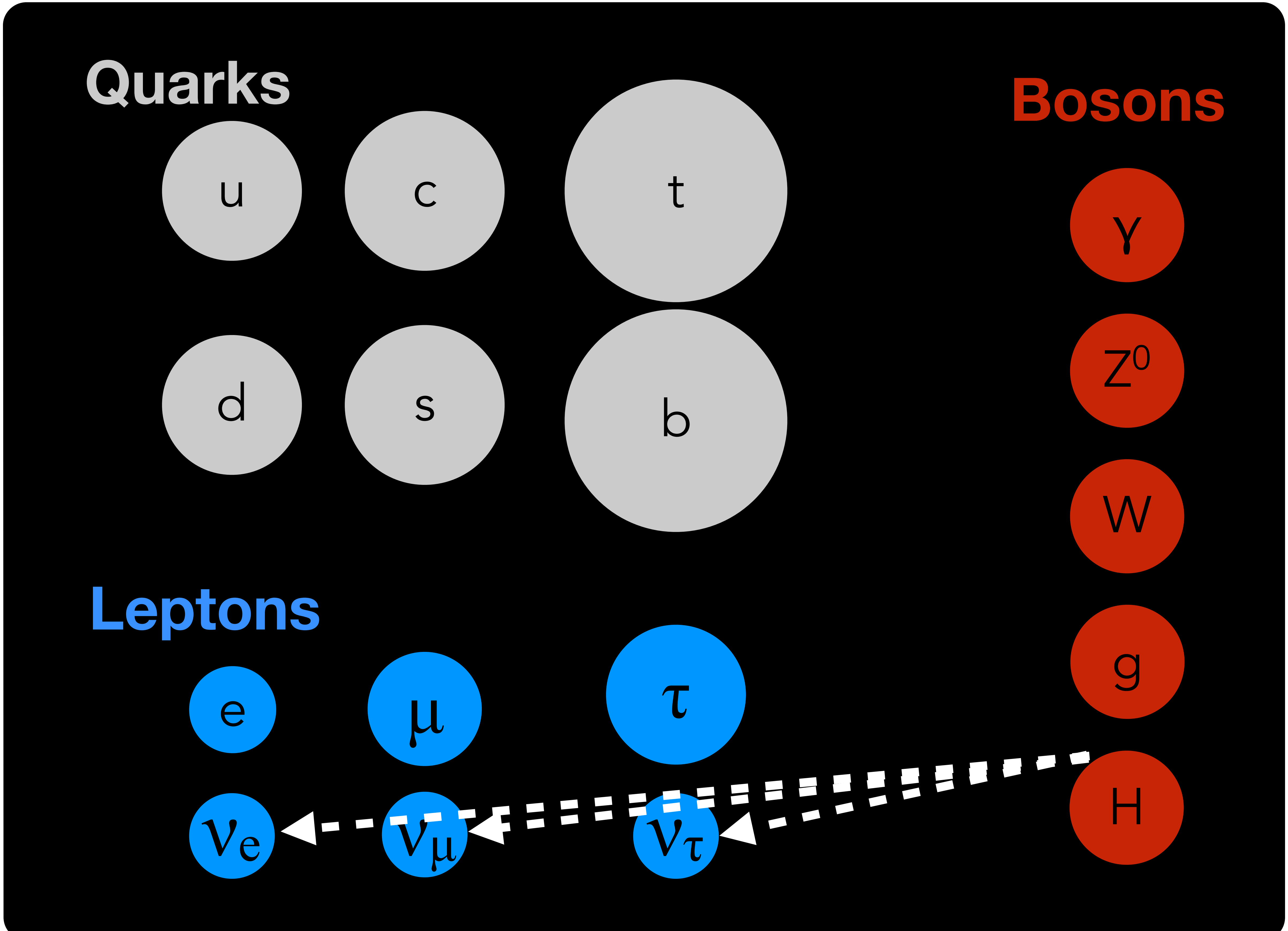

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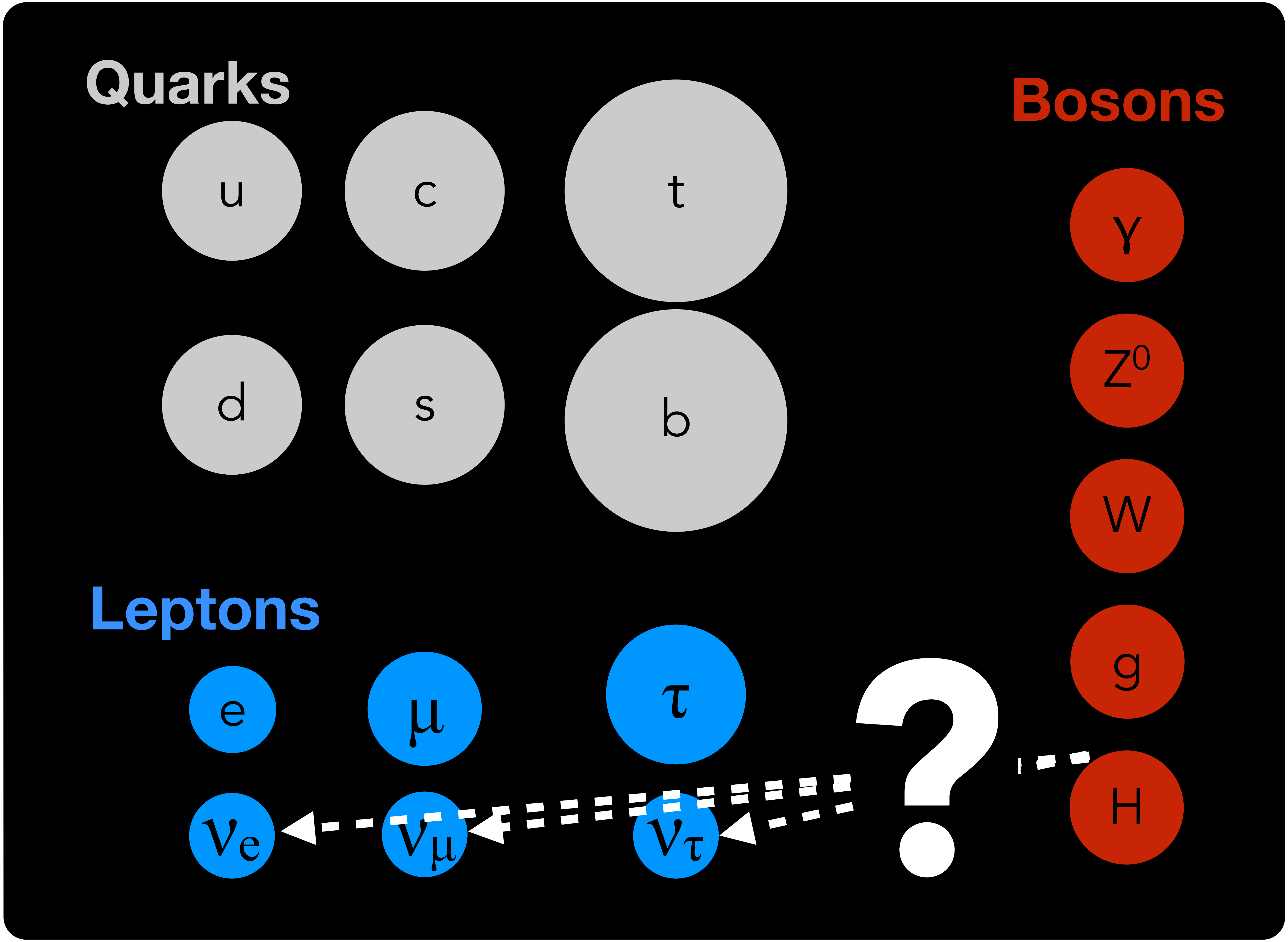


Neutrino Admixture

Flavor Eigenstate

Mass Eigenstate

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \mathcal{U}_{\mathrm{PMNS}} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

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

- Neutrinos are produced/detected in 'flavor' states but move through space as a composition of 'mass' states

Measuring Parameters

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

underlying nature of weak mixing

$C_{12} = \cos\theta_{12}$ $S_{12} = \sin\theta_{12}$

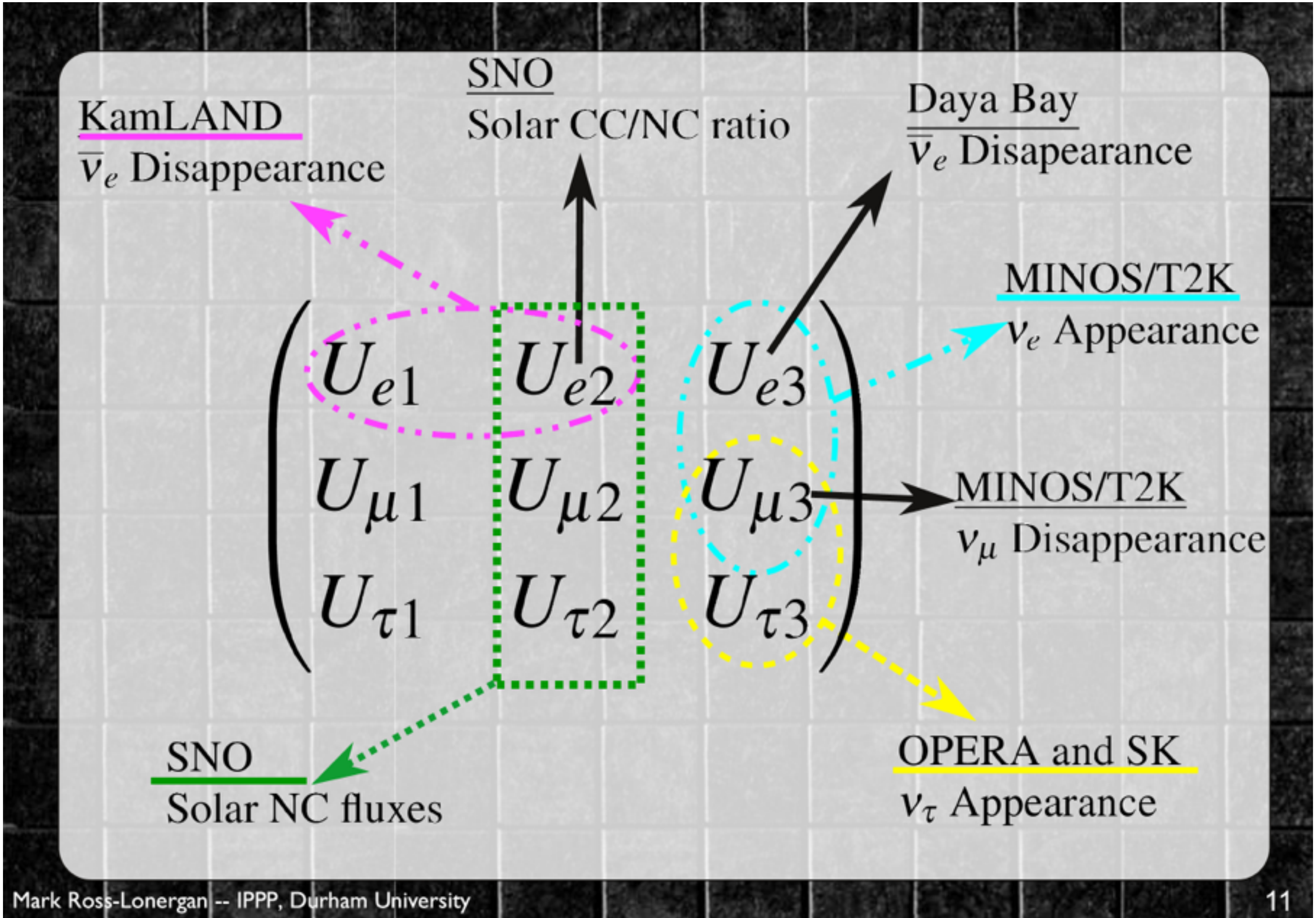
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Experimentally measured values

Three angles and one Charge-Parity phase

What Is Being Measured?

*NOW2014



Fundamental Mixing

Quarks (CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Confirms Unitarity

Leptons (PMNS)

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

Currently Assumes Unitarity

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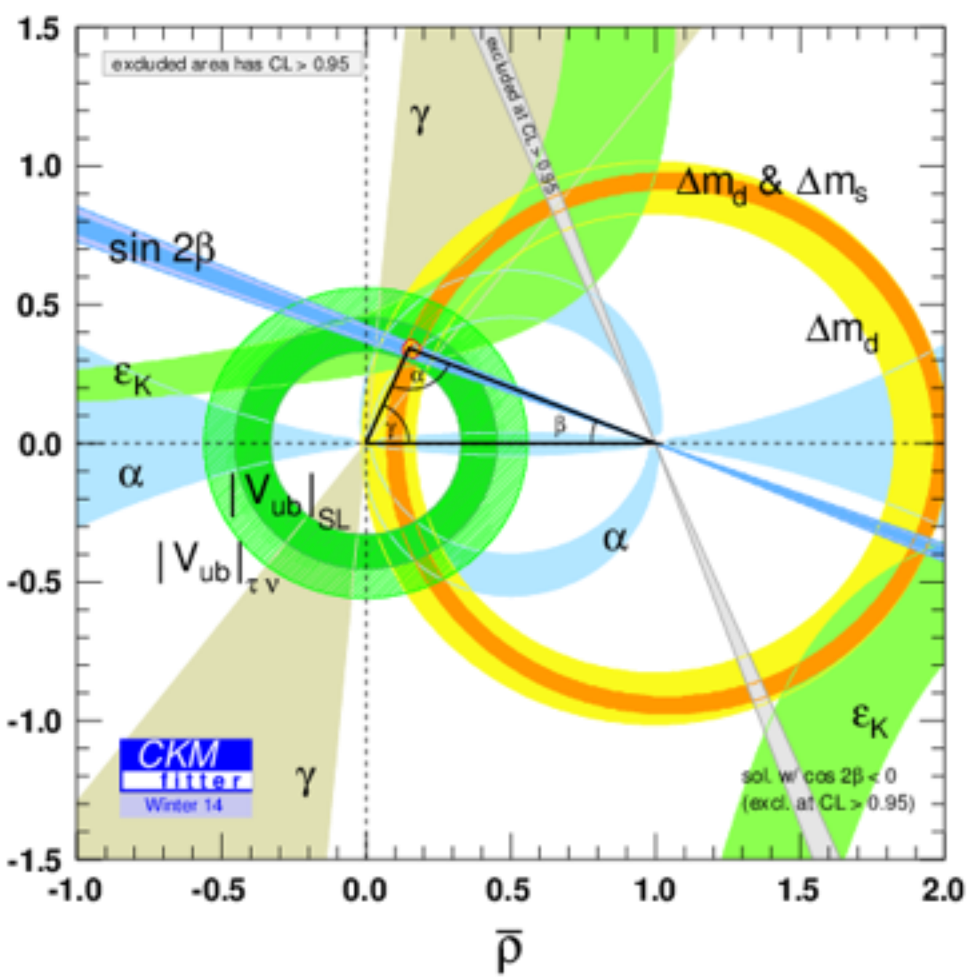

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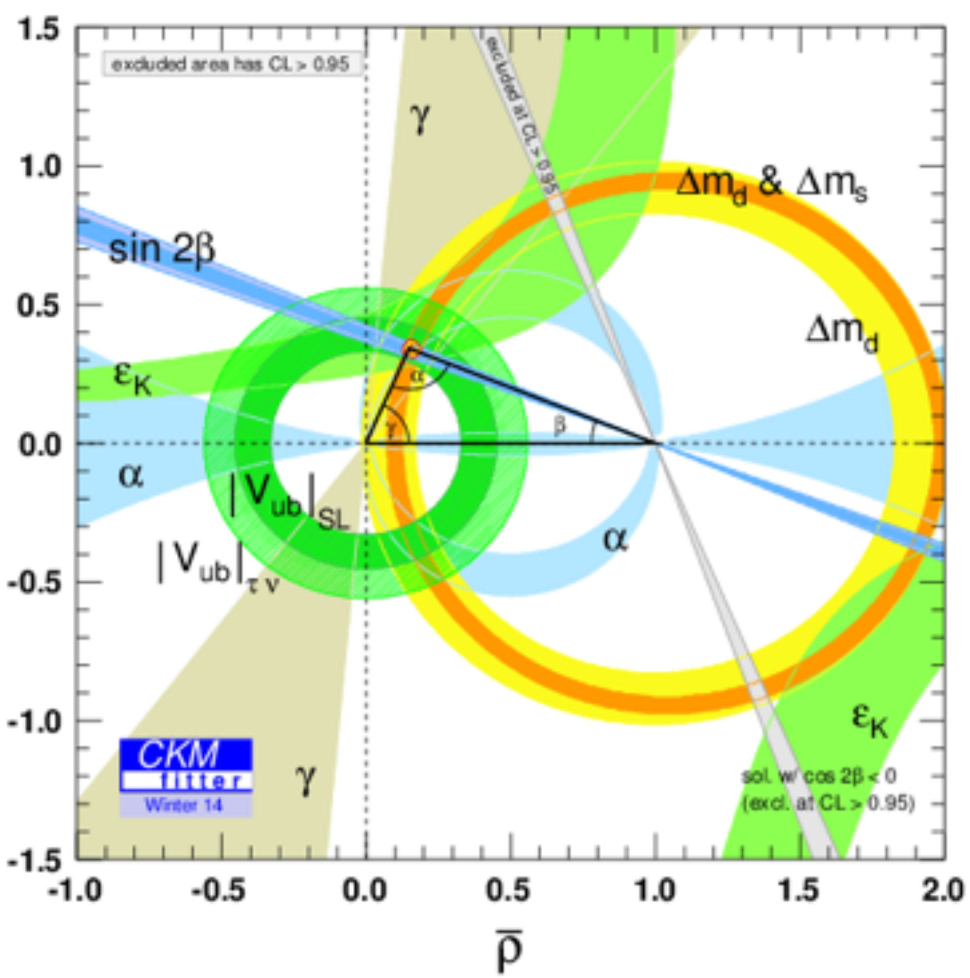

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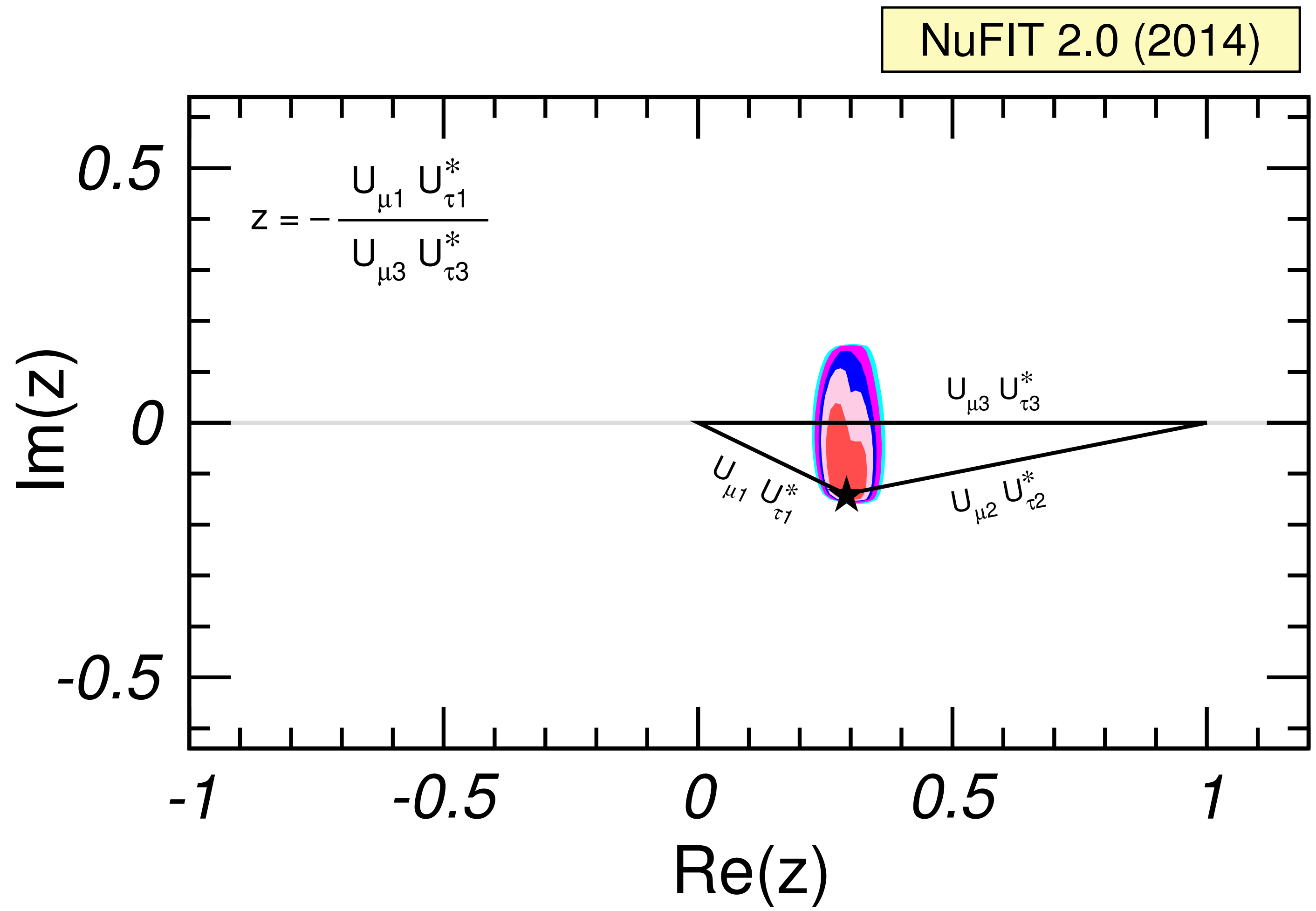


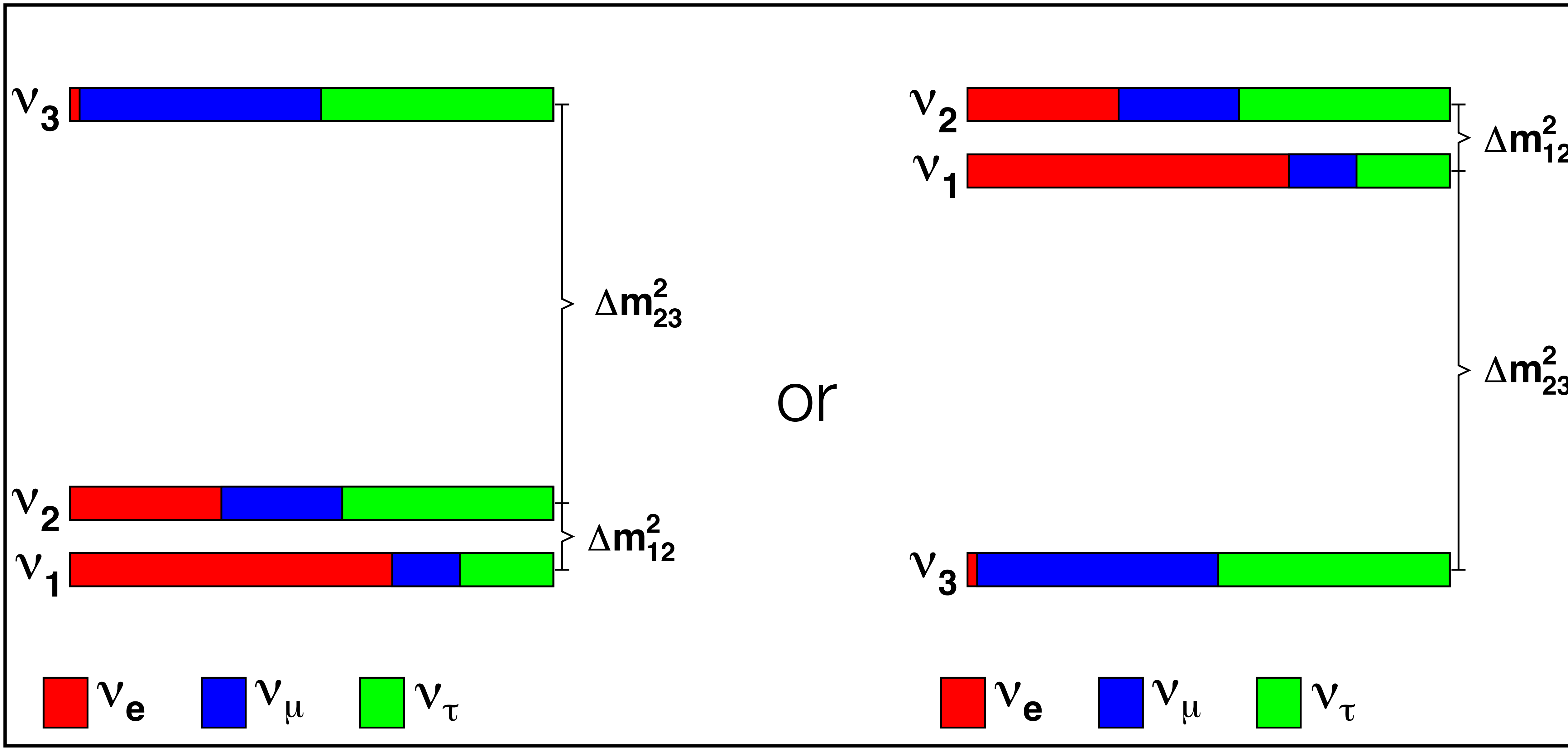
Currently Assumes Unitarity

Neutrino Oscillation

- The three conventional neutrino angles have been measured, but NOT all the 9 individual PMNS elements

- More data and more oscillation channels are necessary to complete even a minimally constraining PMNS 'unitary' triangle

Mass Ordering



Why? (Models)

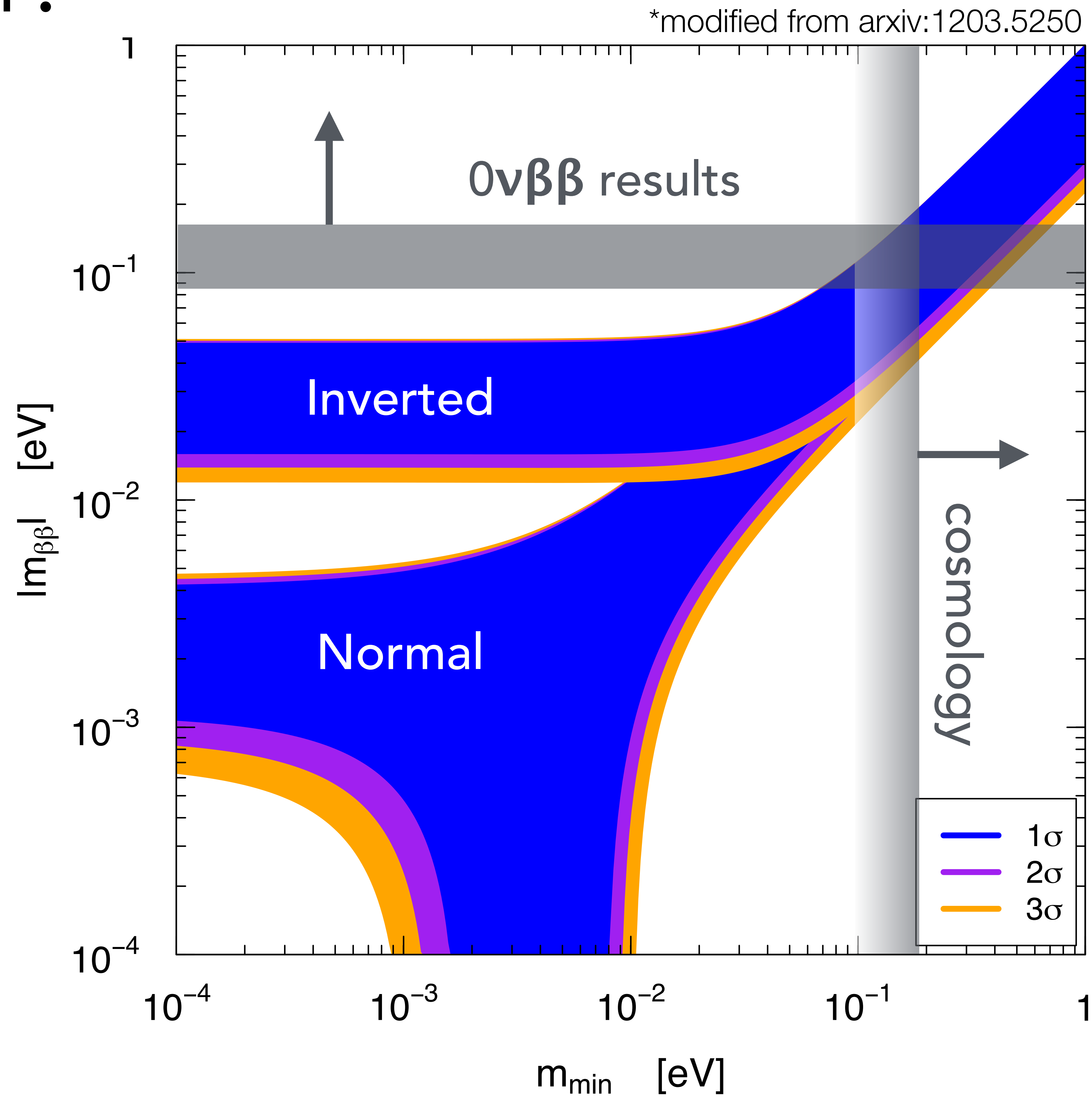
*hep-ph/0608137

- 86 models were identified in 2006* for lepton flavor symmetries
  - 55 are now disfavored for predicting θ_{13} > 3 sigma from measured
  - A prime remaining discriminator is the predicted order **Inverted**/ **Normal**

TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

Reference	Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:				
dGM [18]	Either			≥ 0.011 @ 2σ
$\mathbf{L_e - L_\mu - L_\tau}$ **Models:**				
BM [35]	Inverted			0.00029
BCM [36]	Inverted			0.00063
GMN1 [37]	Inverted		≥ 0.52	≤ 0.01
GL [38]	Inverted			0
PR [39]	Inverted		≤ 0.58	≥ 0.007
$\mathbf{S_3}$ **and** $\mathbf{S_4}$ **Models:**				
CFM [40]	Normal			0.00006 - 0.001
HLM [41]	Normal	1.0	0.43	0.0044
	Normal	1.0	0.44	0.0034
KMM [42]	Inverted	1.0		0.000012
MN [43]	Normal			0.0024
MNY [44]	Normal			0.000004 - 0.000036
MPR [45]	Normal			0.006 - 0.01
RS [46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
	Normal	$\theta_{23} \leq 45°$		0
TY [47]	Inverted	0.93	0.43	0.0025
T [48]	Normal			0.0016 - 0.0036
$\mathbf{A_4}$ **Tetrahedral Models:**				
ABGMP [49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL [50]	Normal			0.006 - 0.04
Ma [51]	Normal	1.0	0.45	0
SO(3) Models:				
M [52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:				
CPP [53]	Normal			0.007 - 0.008
	Inverted			≥ 0.00005
	Inverted			≥ 0.032
WY [54]	Either			0.0006 - 0.003
	Either			0.002 - 0.02
	Either			0.02 - 0.15

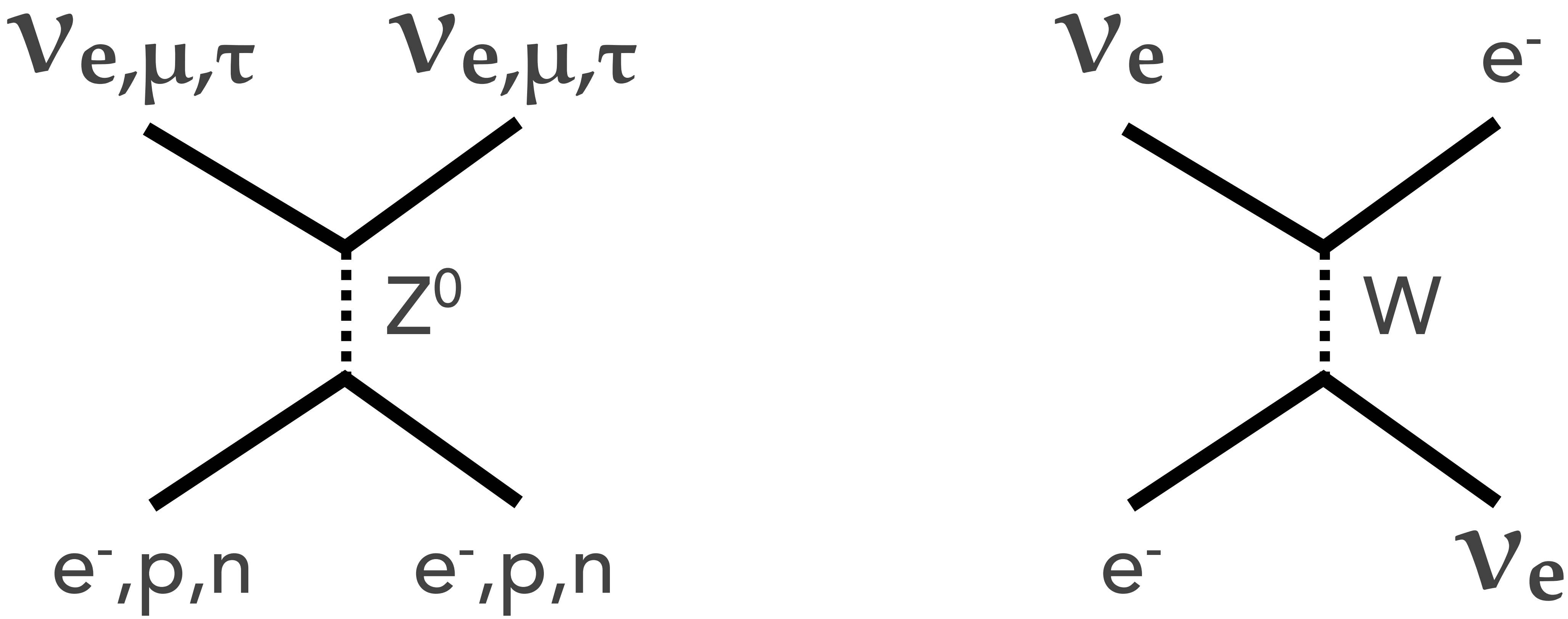
Pay-Off?



- If the neutrino is a majorana particle **and** the mass ordering is inverted, then current 0νββ experiments are in good shape, but if not…

Resolving the Neutrino Mass Ordering via Oscillation

Oscillations in Matter



- Electron (anti)neutrinos pick up an `effective' mass, which modifies the vacuum oscillation probability

Matter

Vacuum Oscillations $P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$

Matter Oscillations $P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$

$$\boxed{\Delta \tilde{m}^2 \; = \; \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},}$$

$$\xi \; \equiv \; \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

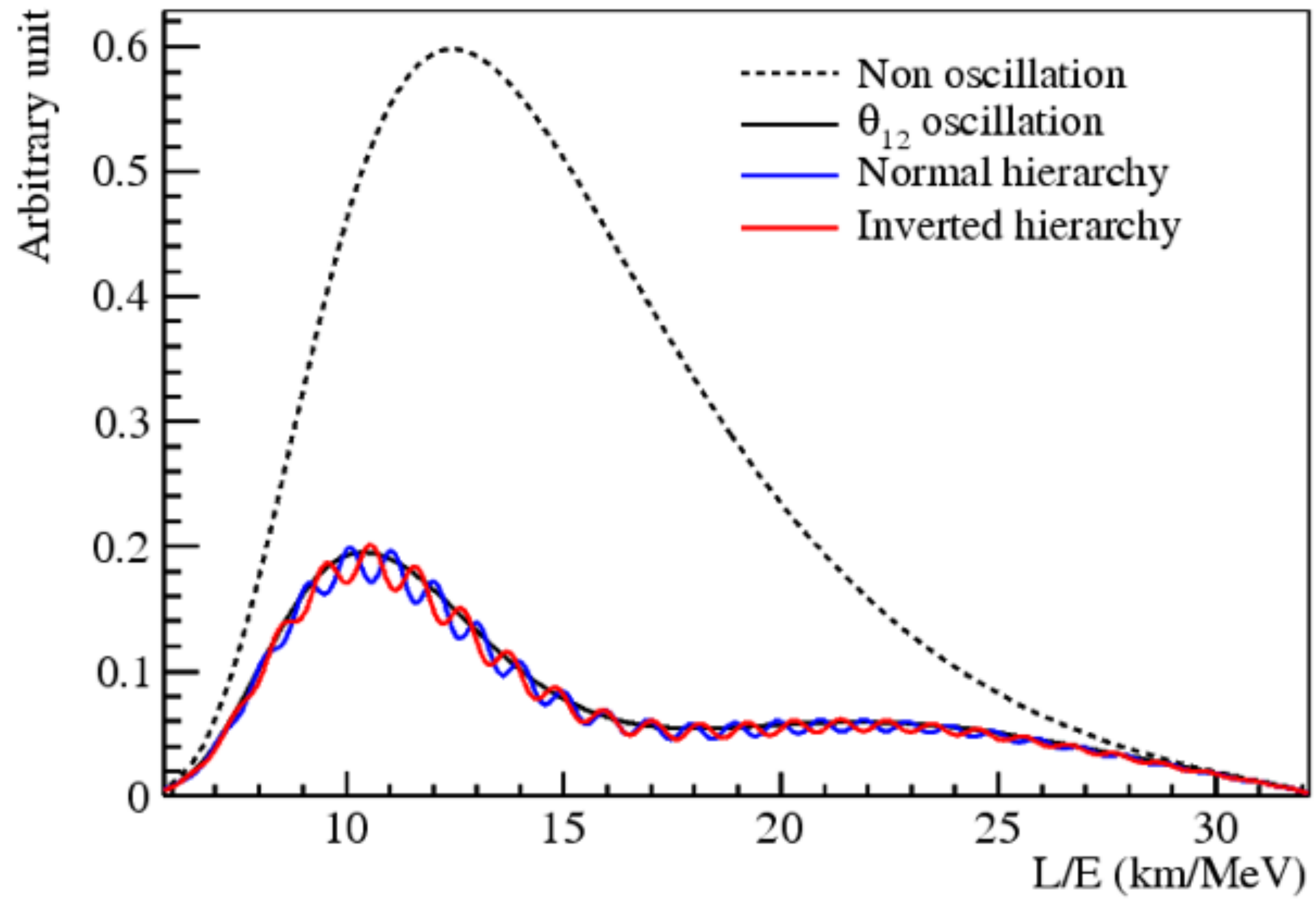
$$\hat{A} \; = \; \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E \, G_F \, n_e}{\Delta m^2}$$

*W. Winter, Neutrino 2014

Reactor Experiment Possibilities

Jiangmen Underground Neutrino Observatory

RENO-50

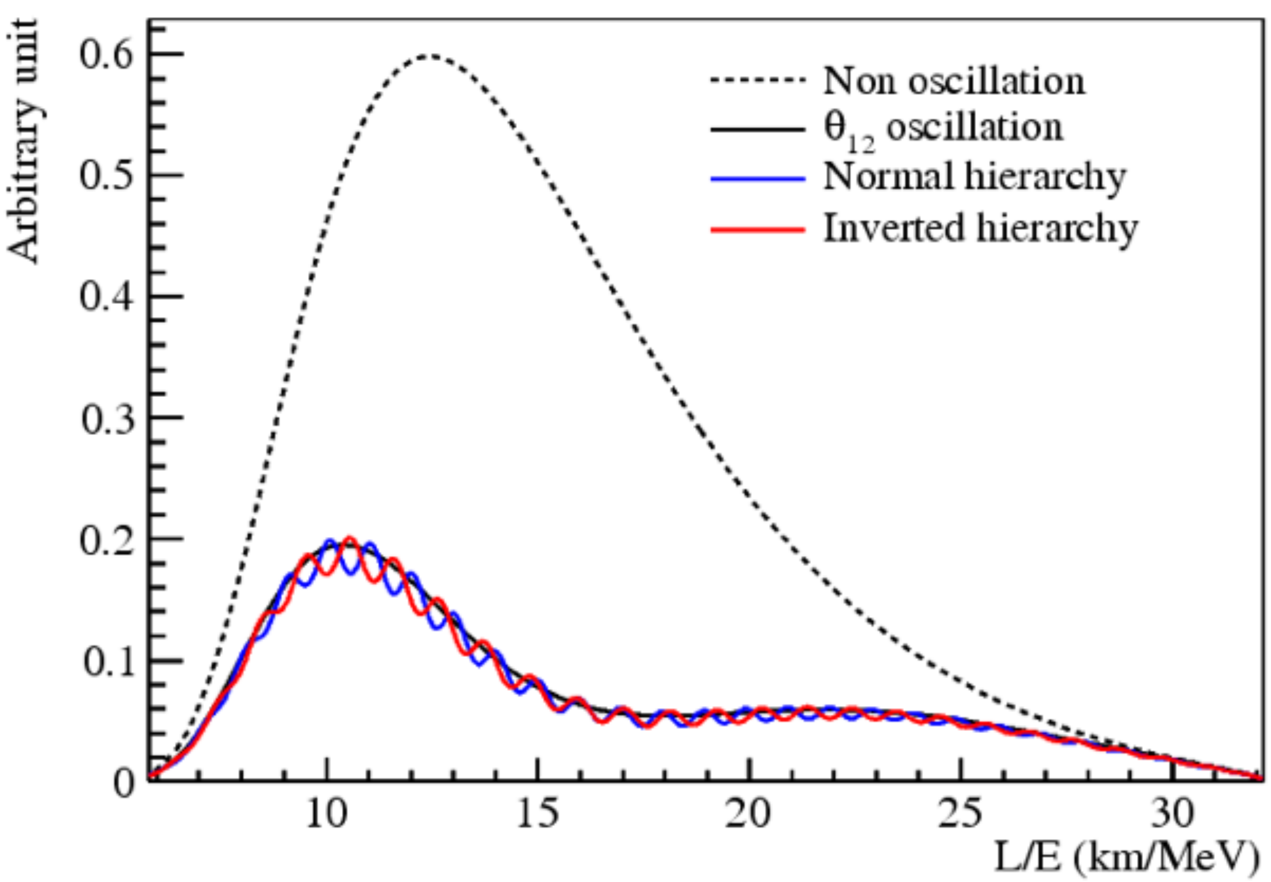


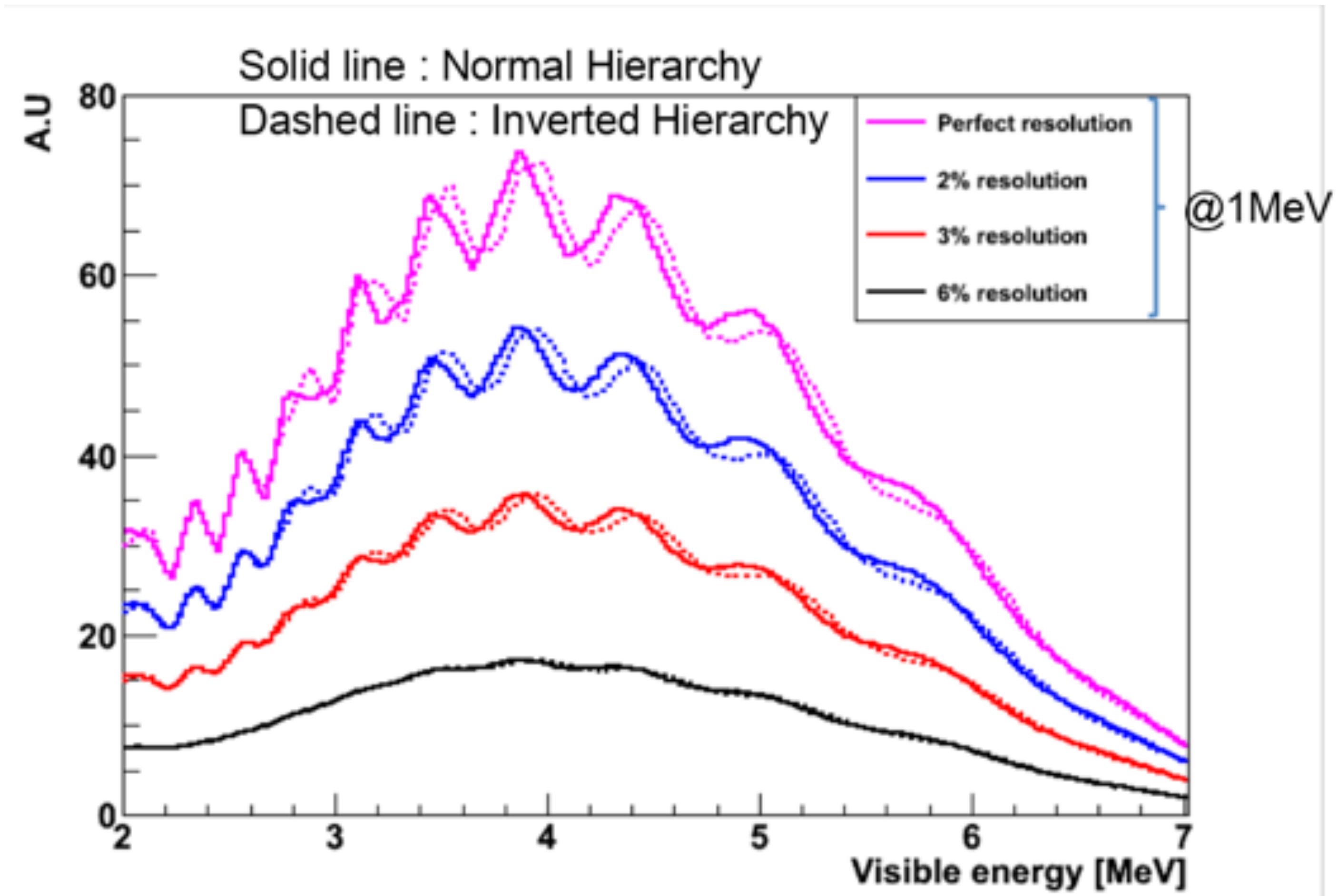
- Long baseline reactor experiments with O(10) KTons of liquid scintillator requiring very good energy resolution

*X. Li, Windows on the Universe 2013

Reactor Neutrinos

- Proposed reactor + liquid scintillator experiments
- Neutrino ordering gives a modulation of solar oscillation parameters in reactor long-baselines

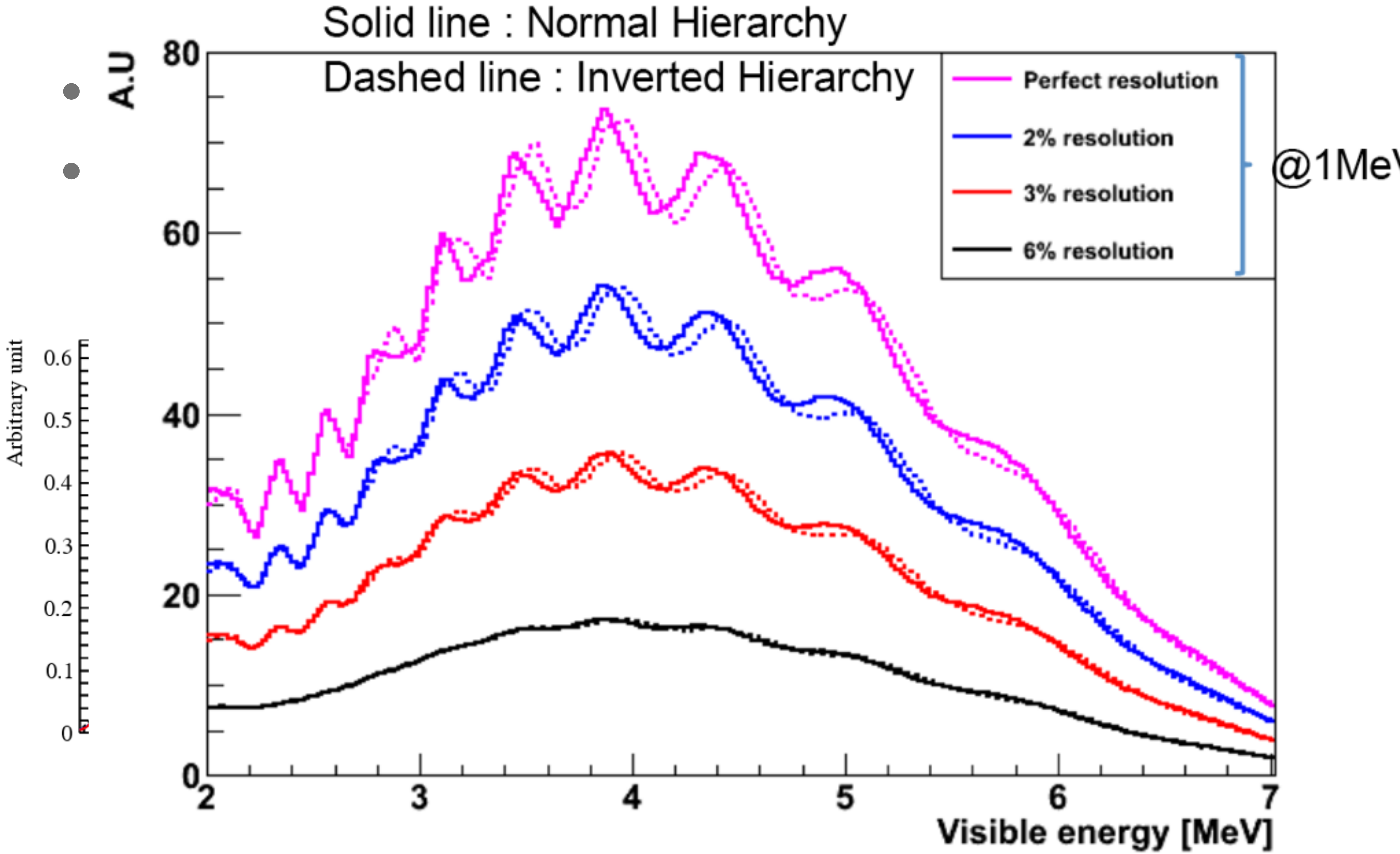




*X. Li, Windows on the Universe 2013

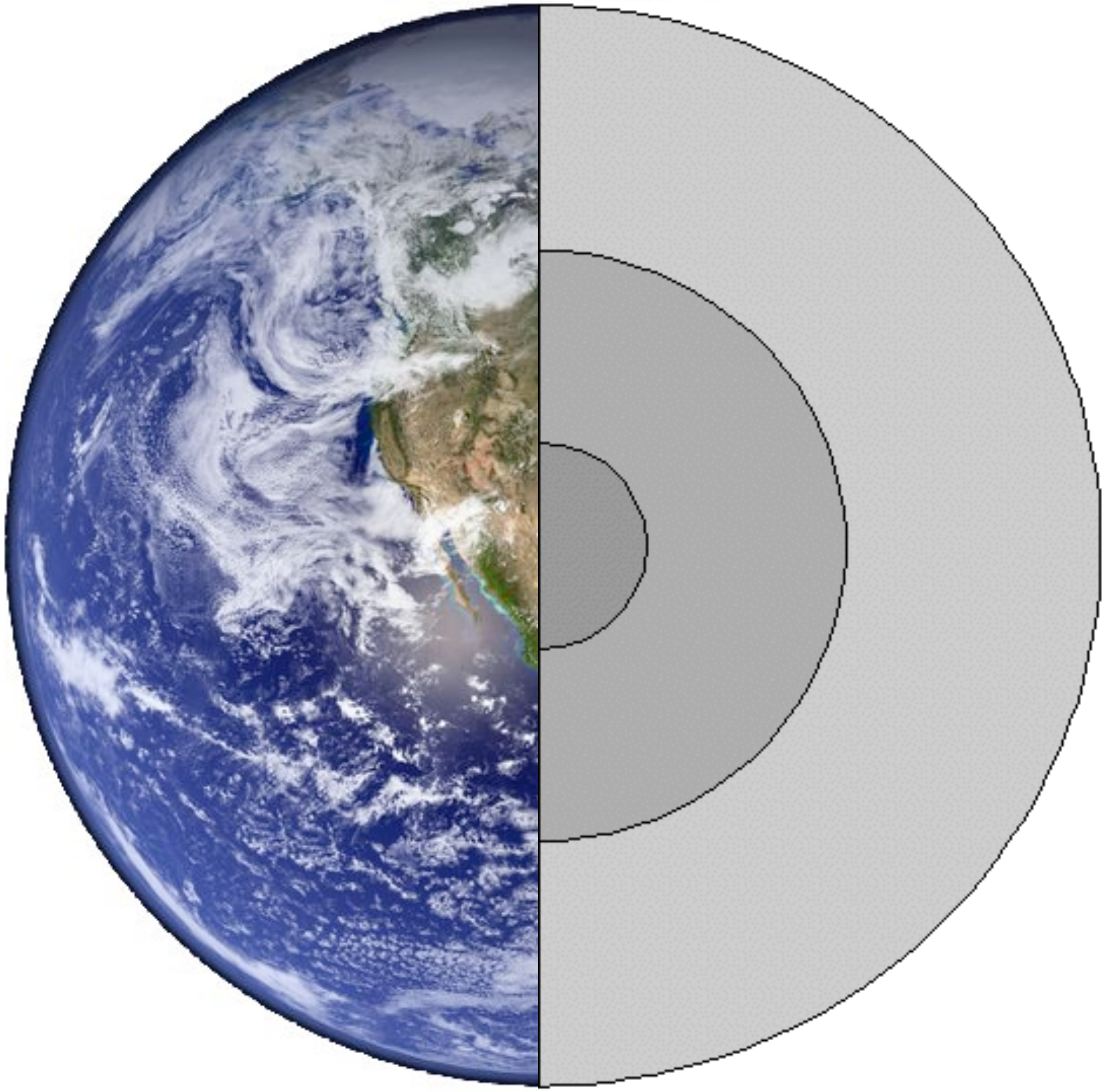
**J.S. Park, International Workshop on "RENO-50" 2013

Reactor Neutrinos



**J.S. Park, International Workshop on "RENO-50" 2013

Neutrino Mass Ordering



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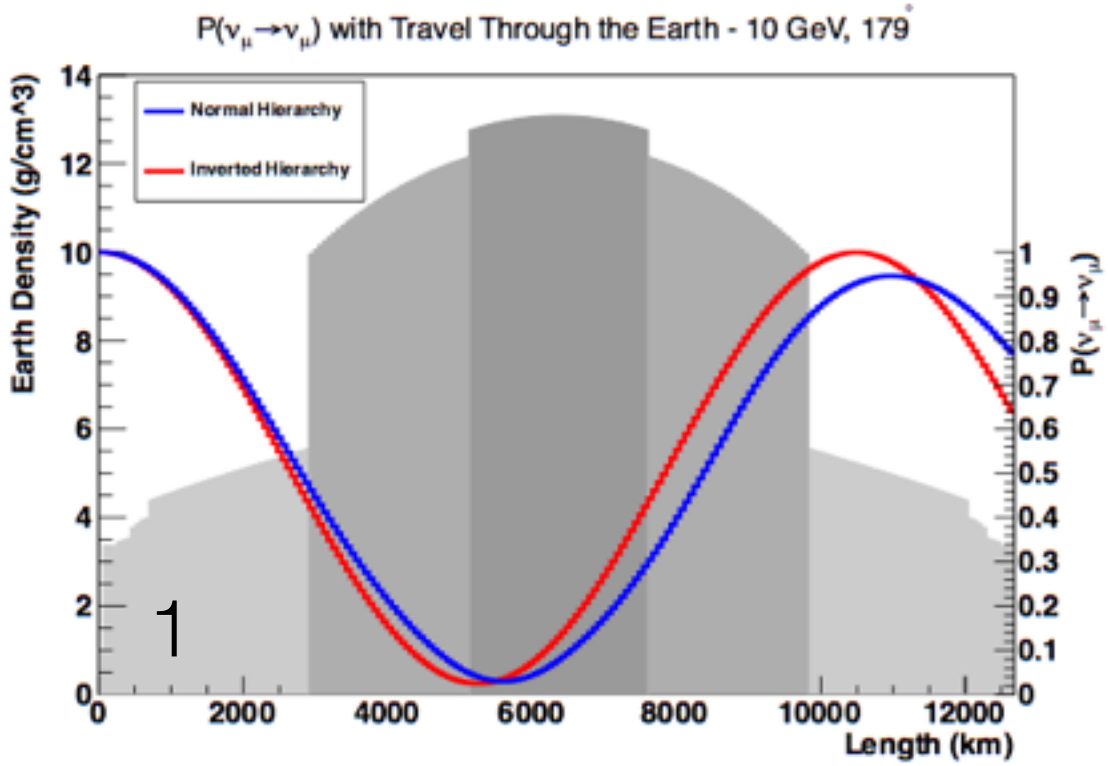

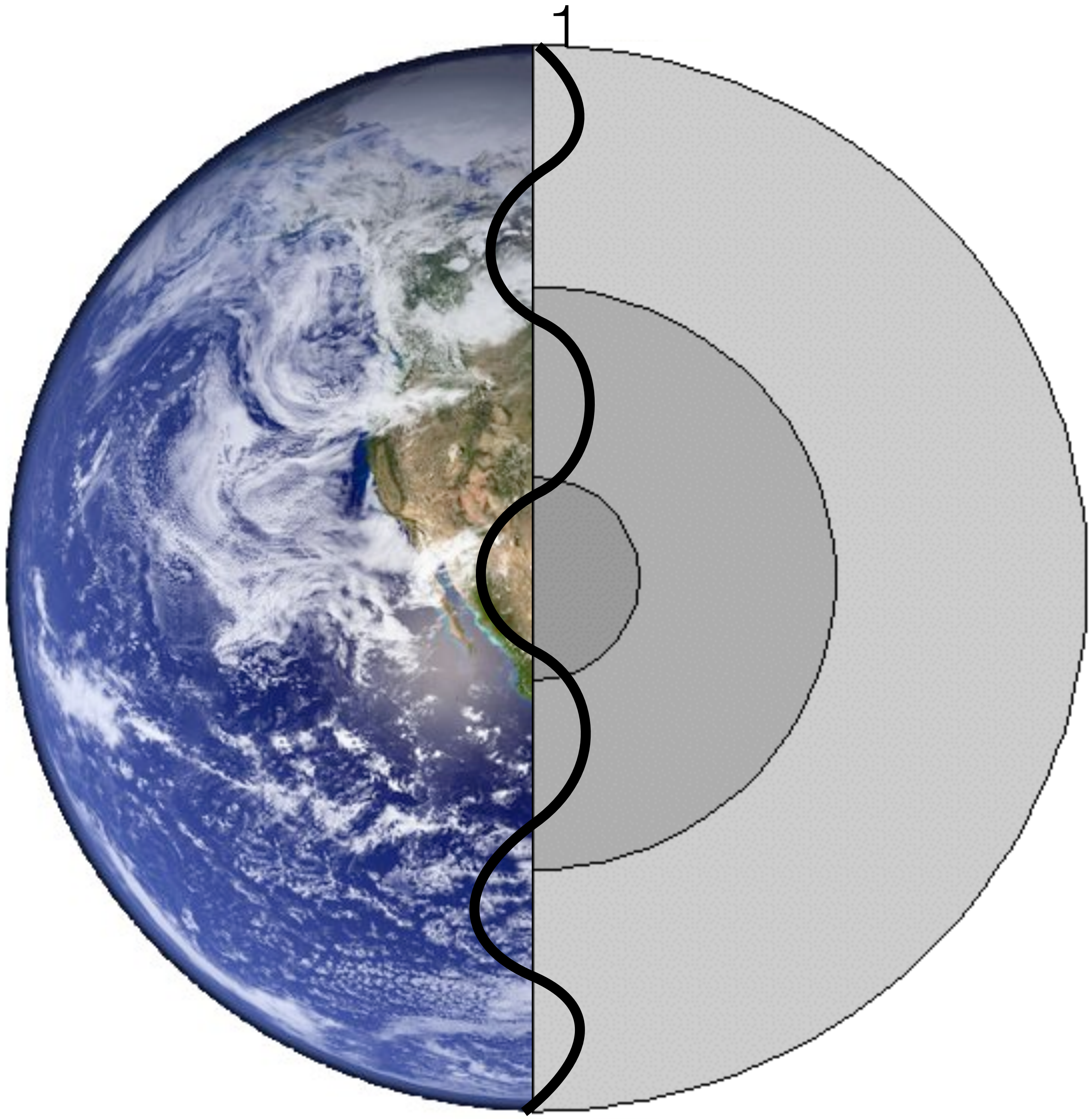

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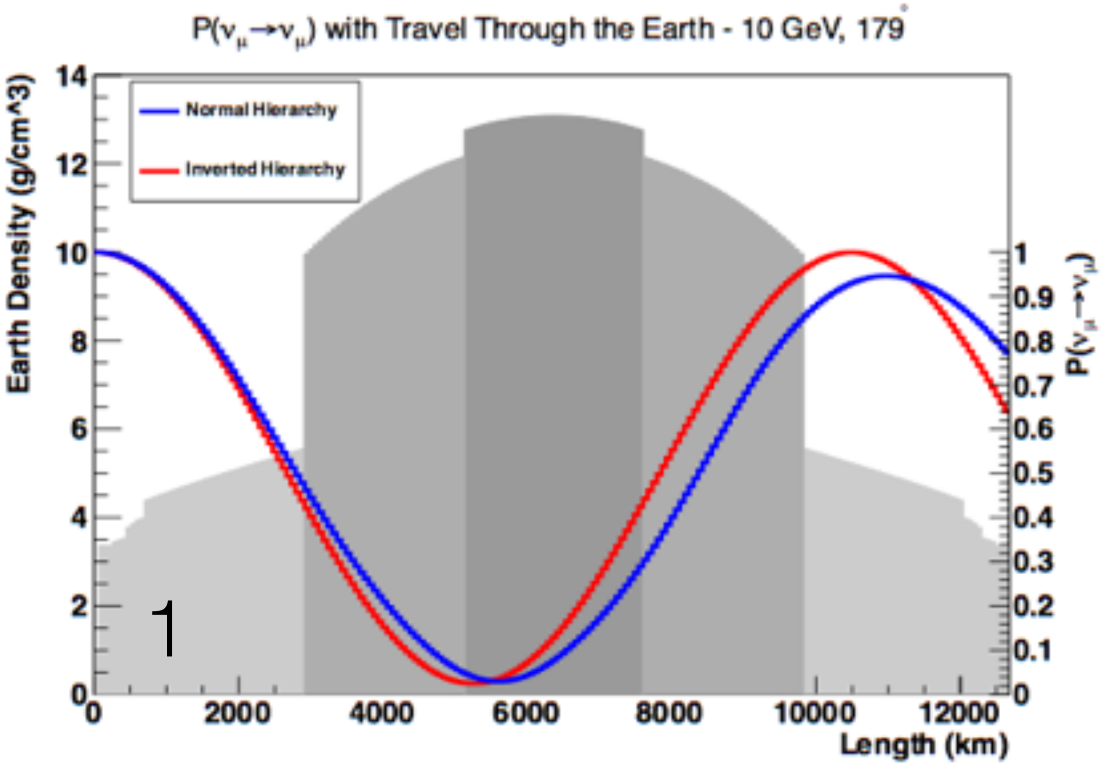

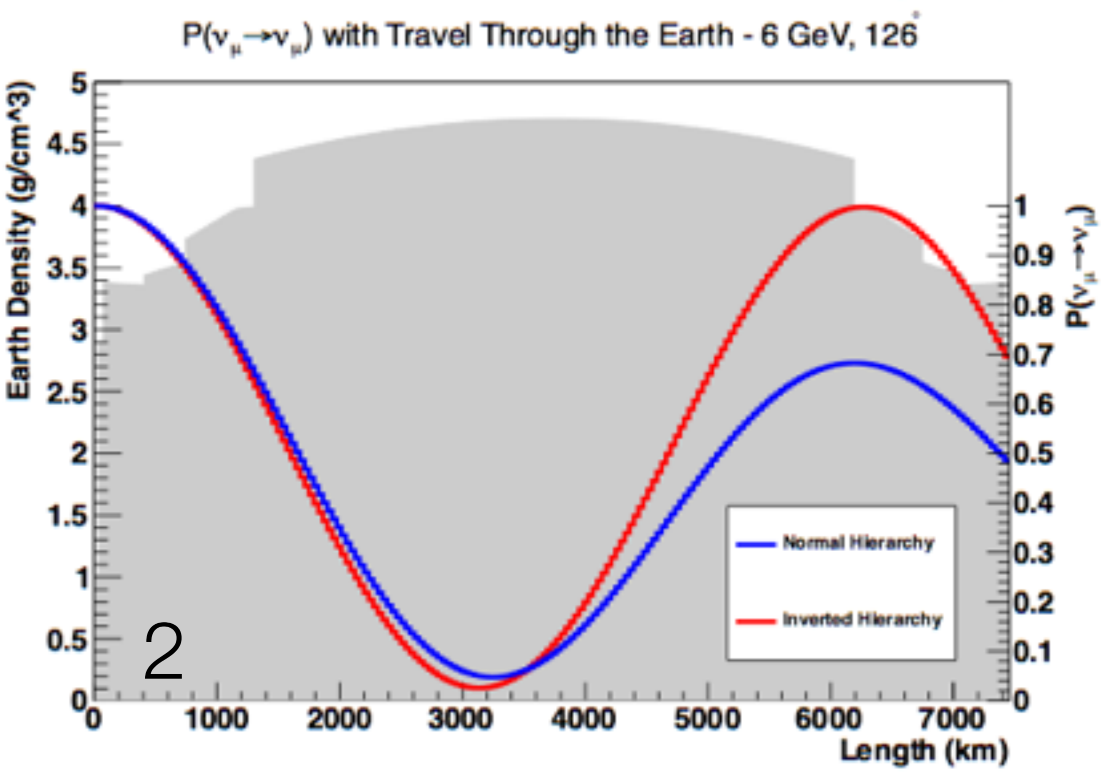

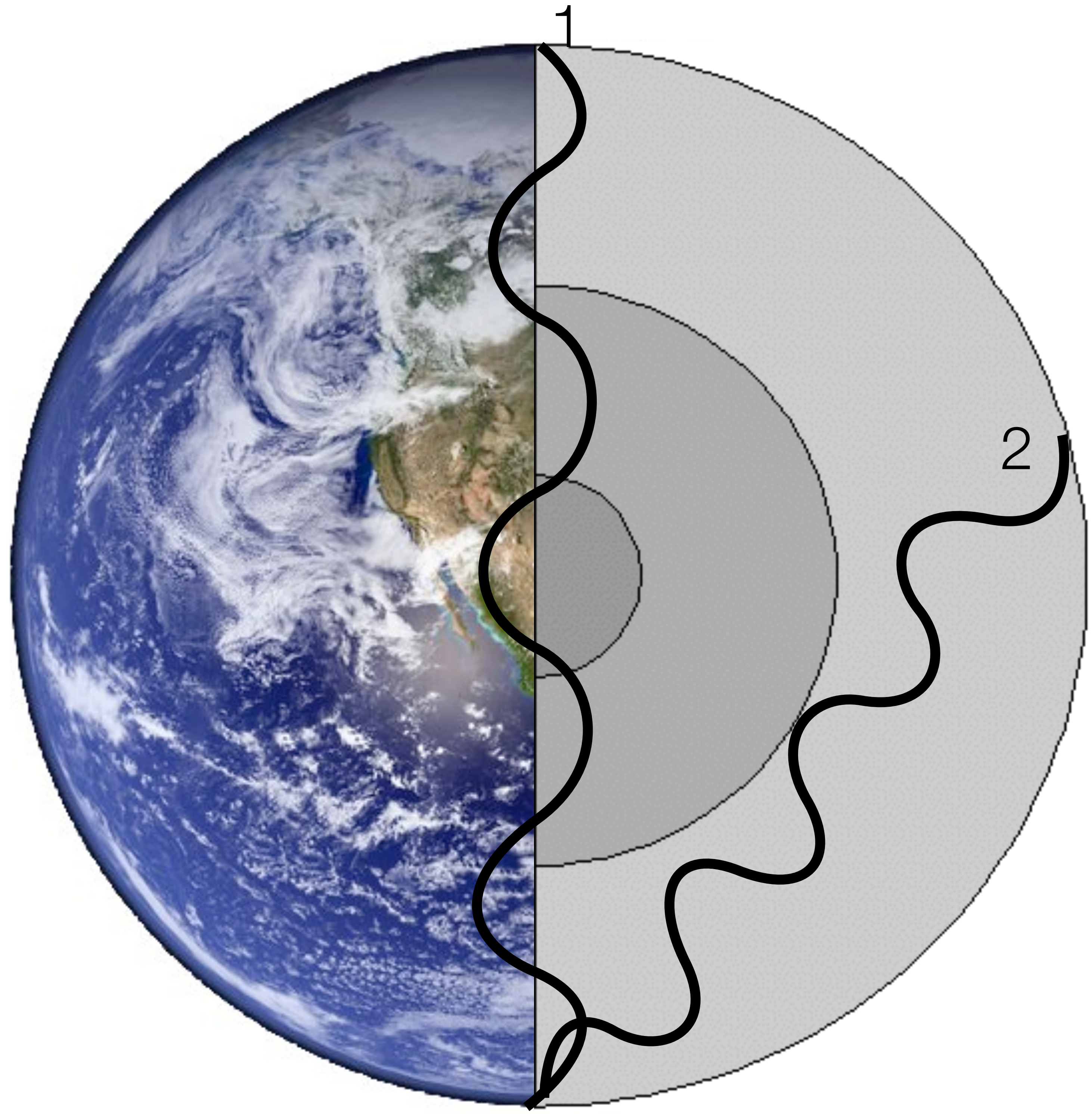

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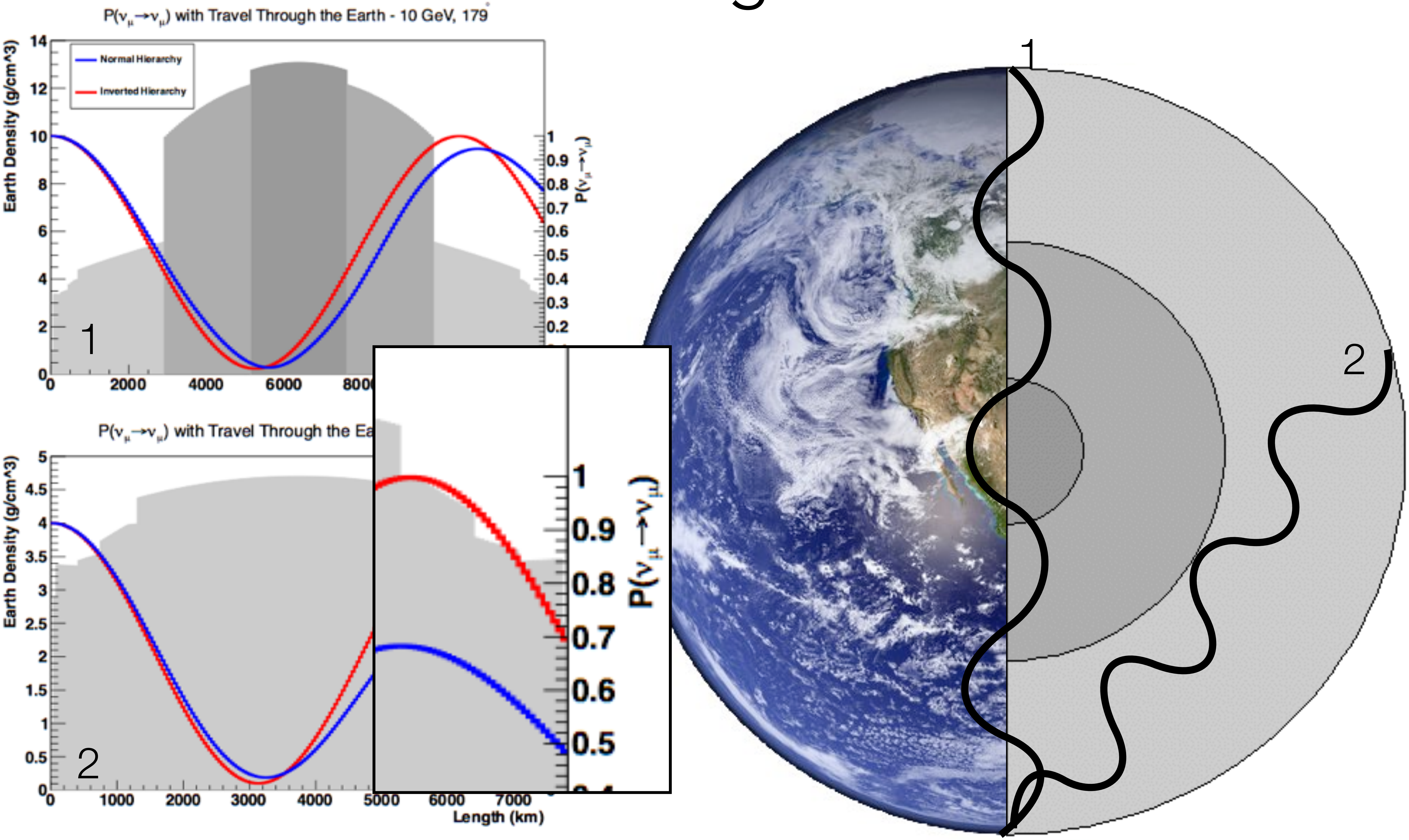
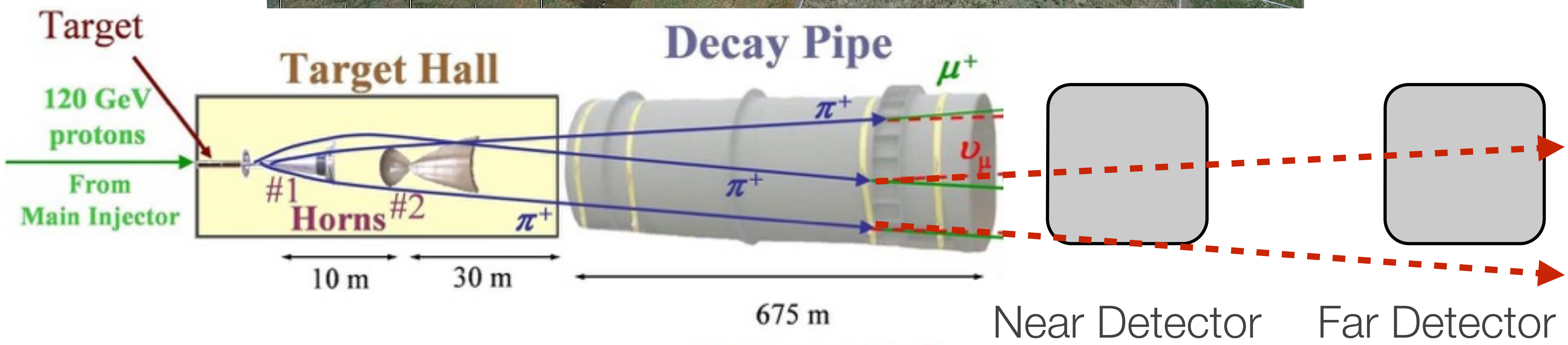


- Inverted/Normal ordering has up to a 20% difference in oscillation probability for specific energies and zenith angles (baselines)

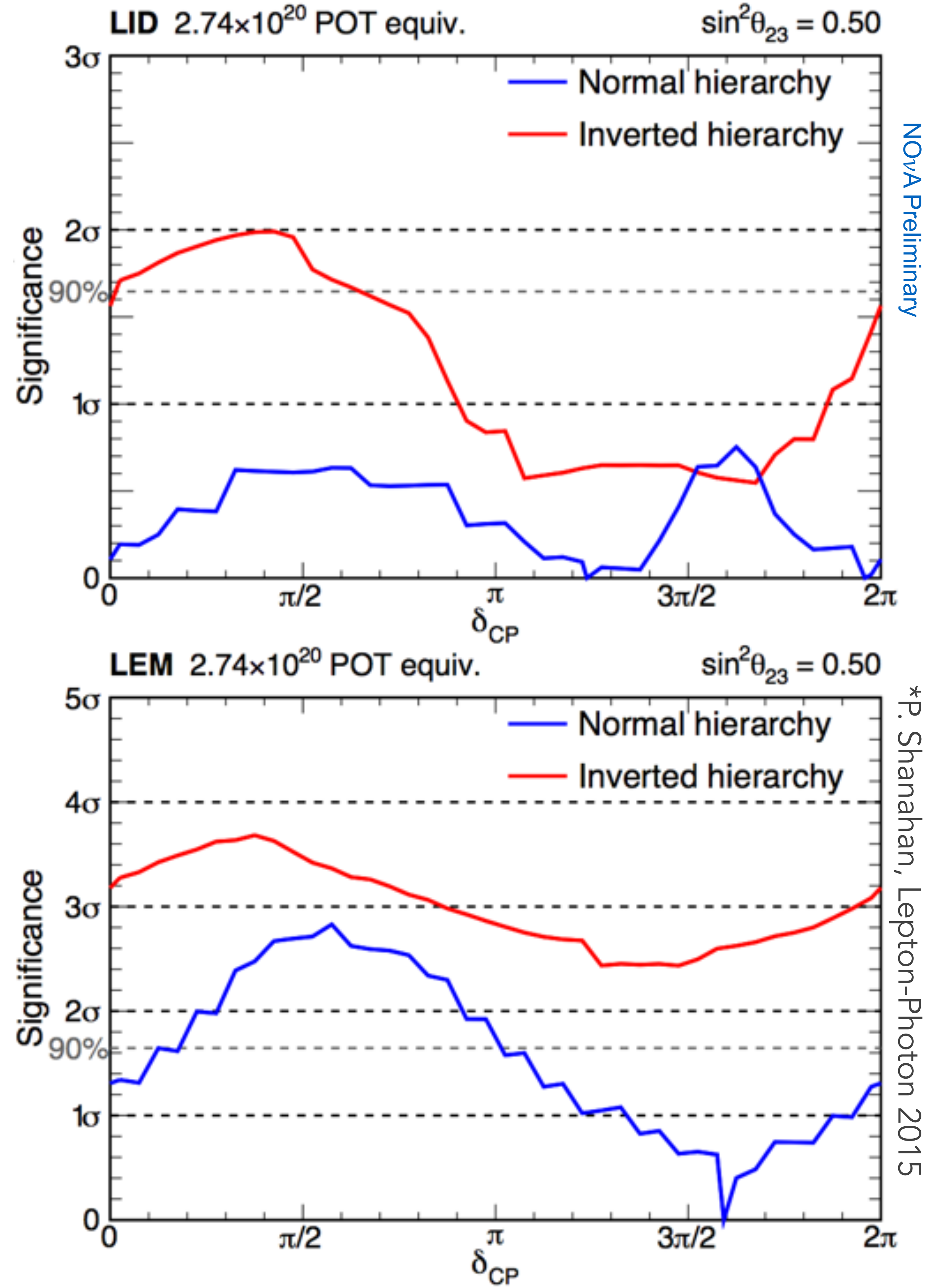
Accelerator Neutrinos for Neutrino Ordering

Others
T2K
Hyper-K
ESSnuSB
DUNE



NOνA

- First results released in early August
- Two multivariate ν_e selectors - LID & LEM
  - LID selects 6 events while LEM selects 11 (includes the 6 LID selected events)
- Ordering(hierarchy) and CP-value are intrinsically coupled for long baseline experiments



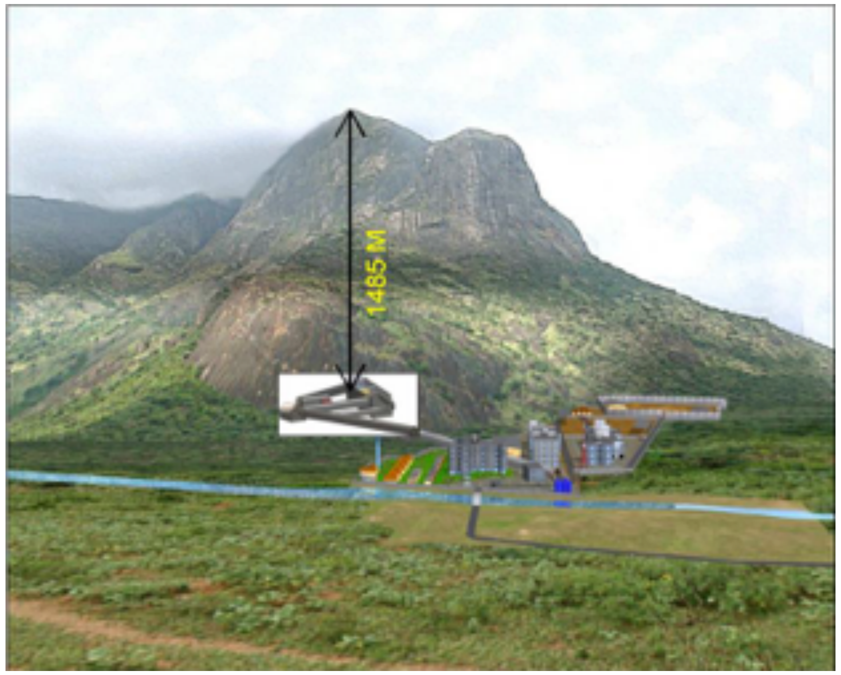
*P. Shanahan, Lepton-Photon 2015

Future Atmospheric Experiments

India-Based Neutrino Observatory (INO)

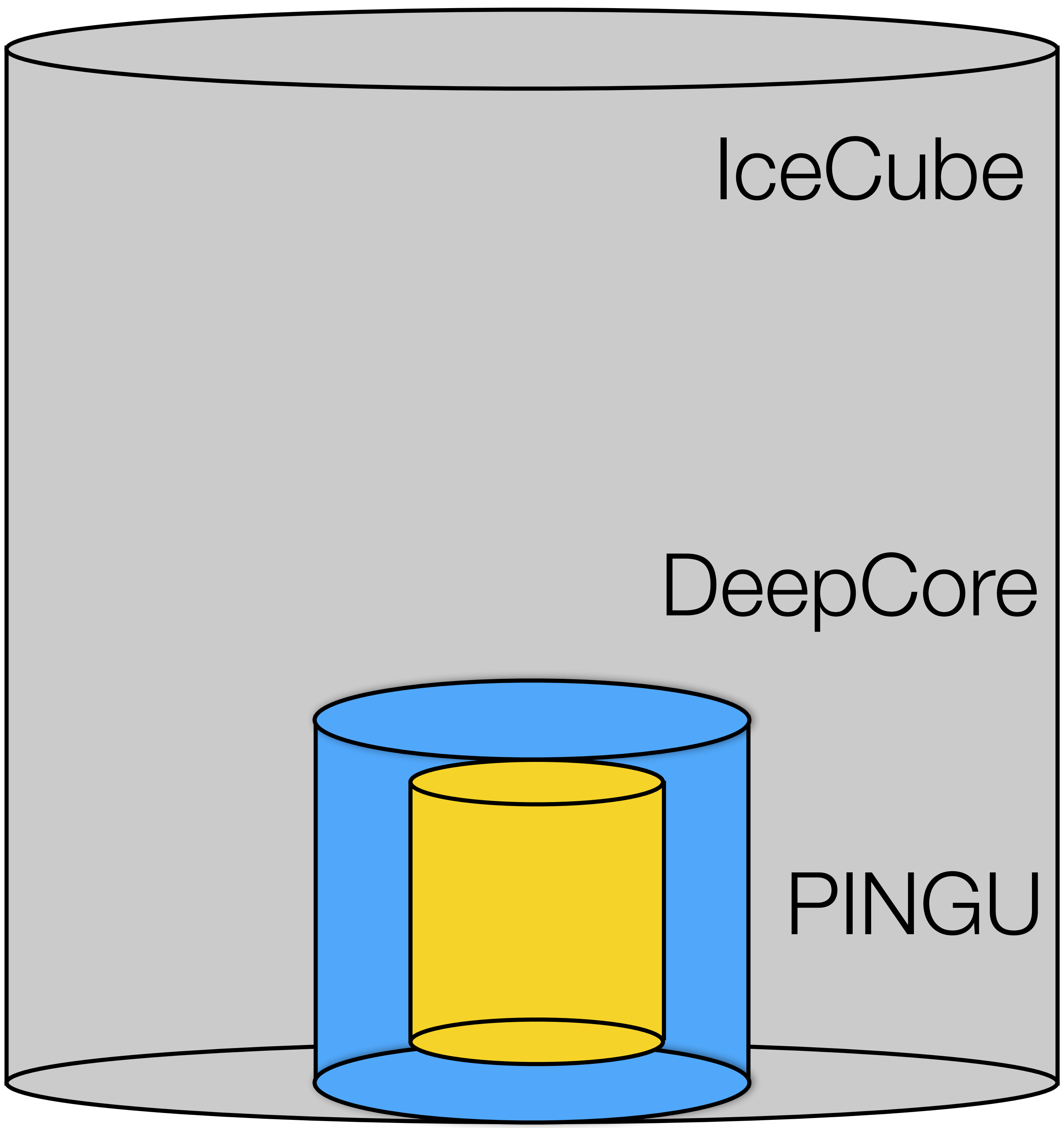
Oscillation Research with Cosmics in the Abyss (ORCA)

Precision IceCube Next Generation Upgrade (PINGU)



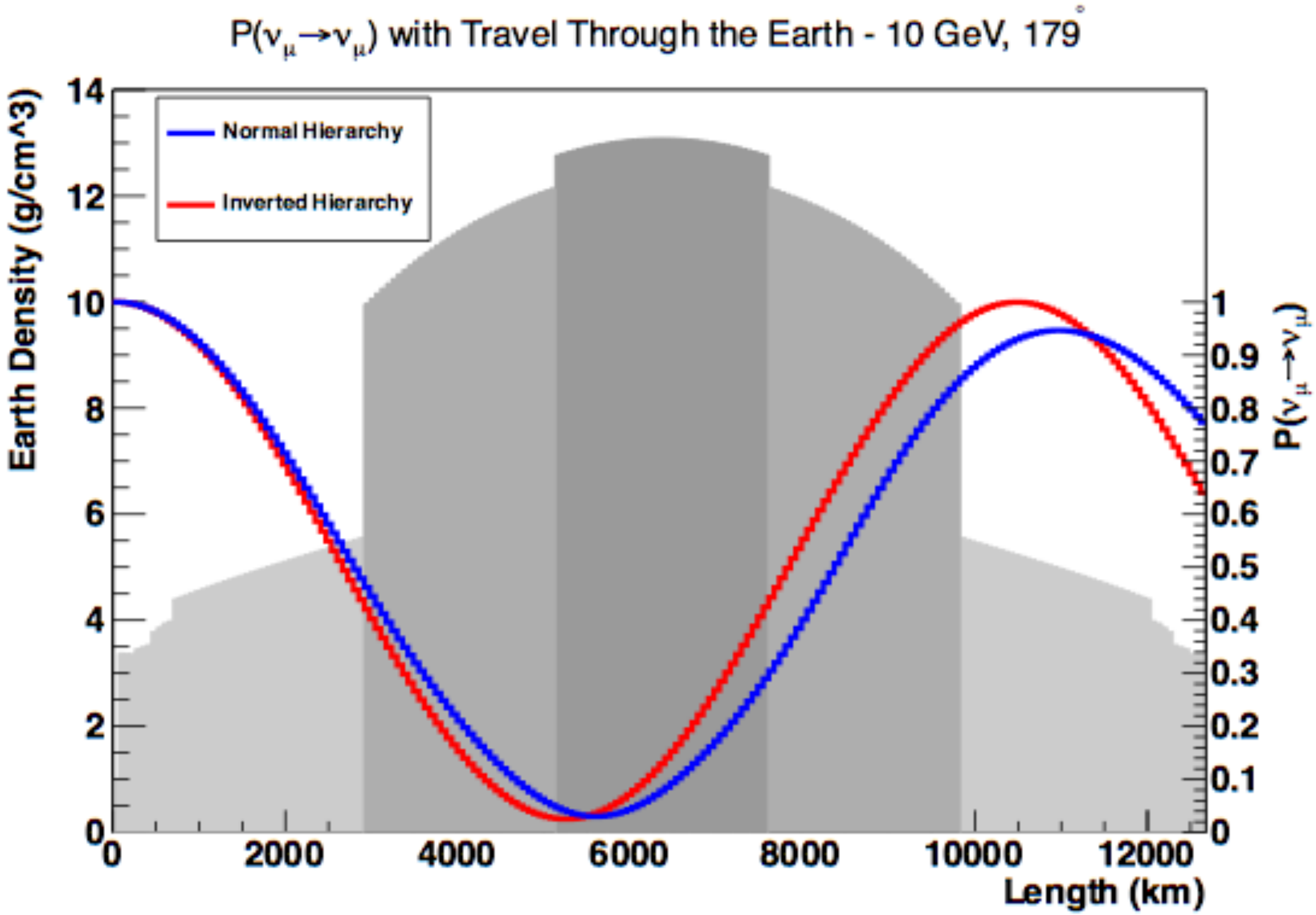
Precision IceCube Next Generation Upgrade (PINGU)

- Use existing and familiar technology to infill IceCube/DeepCore
- Improve rejection of cosmic ray muon background
- ~40 strings deployed over 2-3 years



Letter of Intent - arXiv:1401.2046

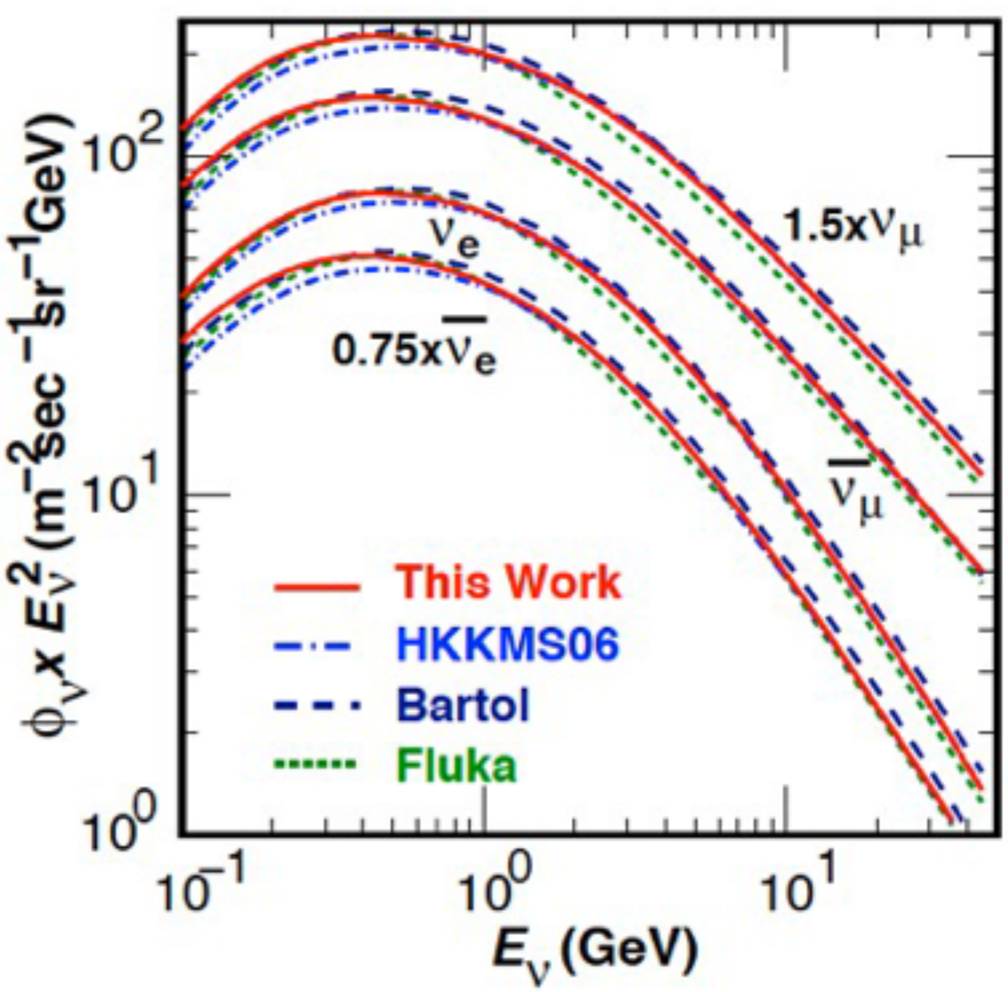
Neutrino Ordering w/ No Magnet



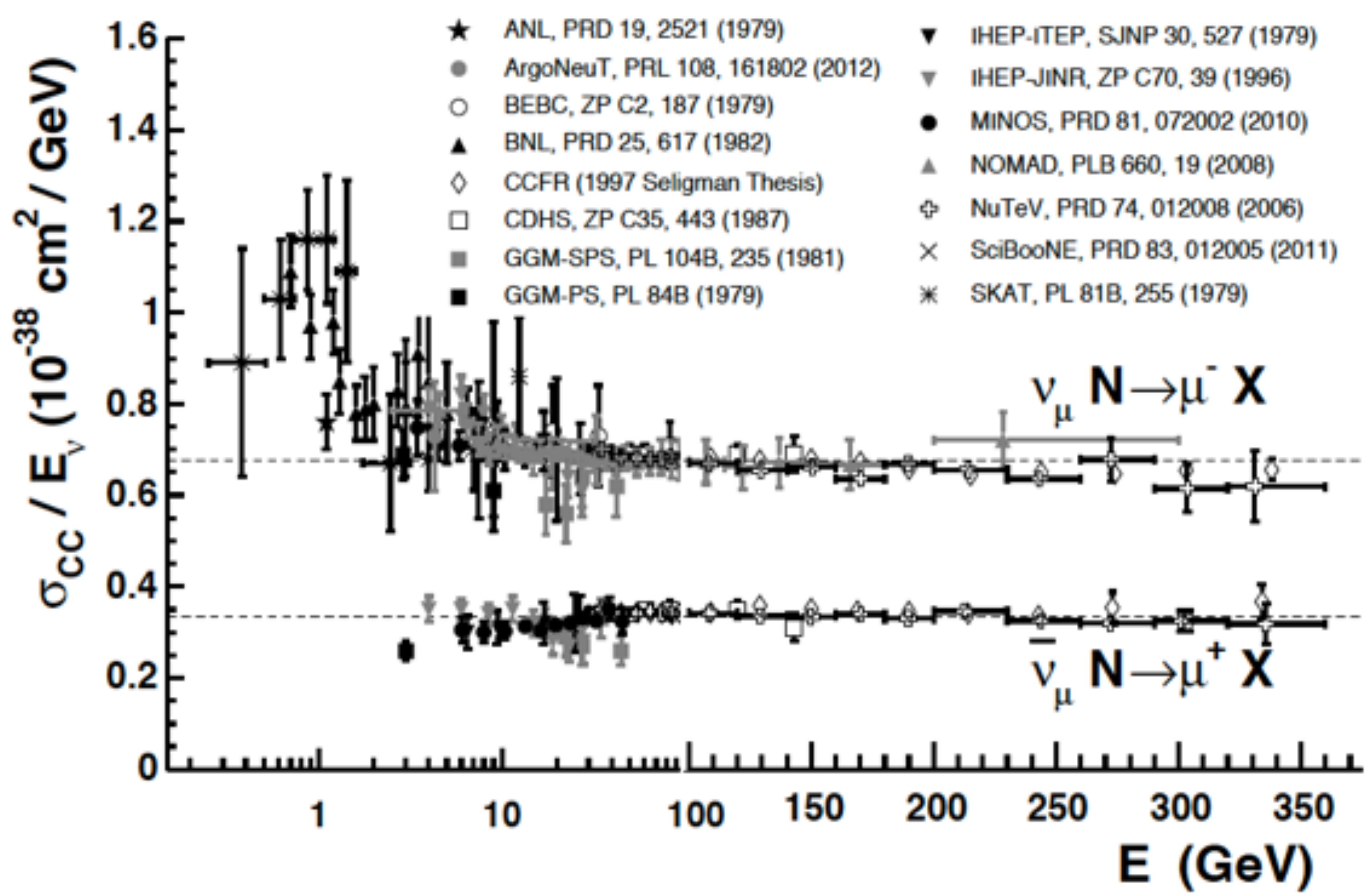
- INO has magnet to separate neutrinos from anti-neutrinos, but PINGA and ORCA do not

Neutrino Ordering w/ No Magnet

arXiv:0203272



*G. Zeller, PDG 2012



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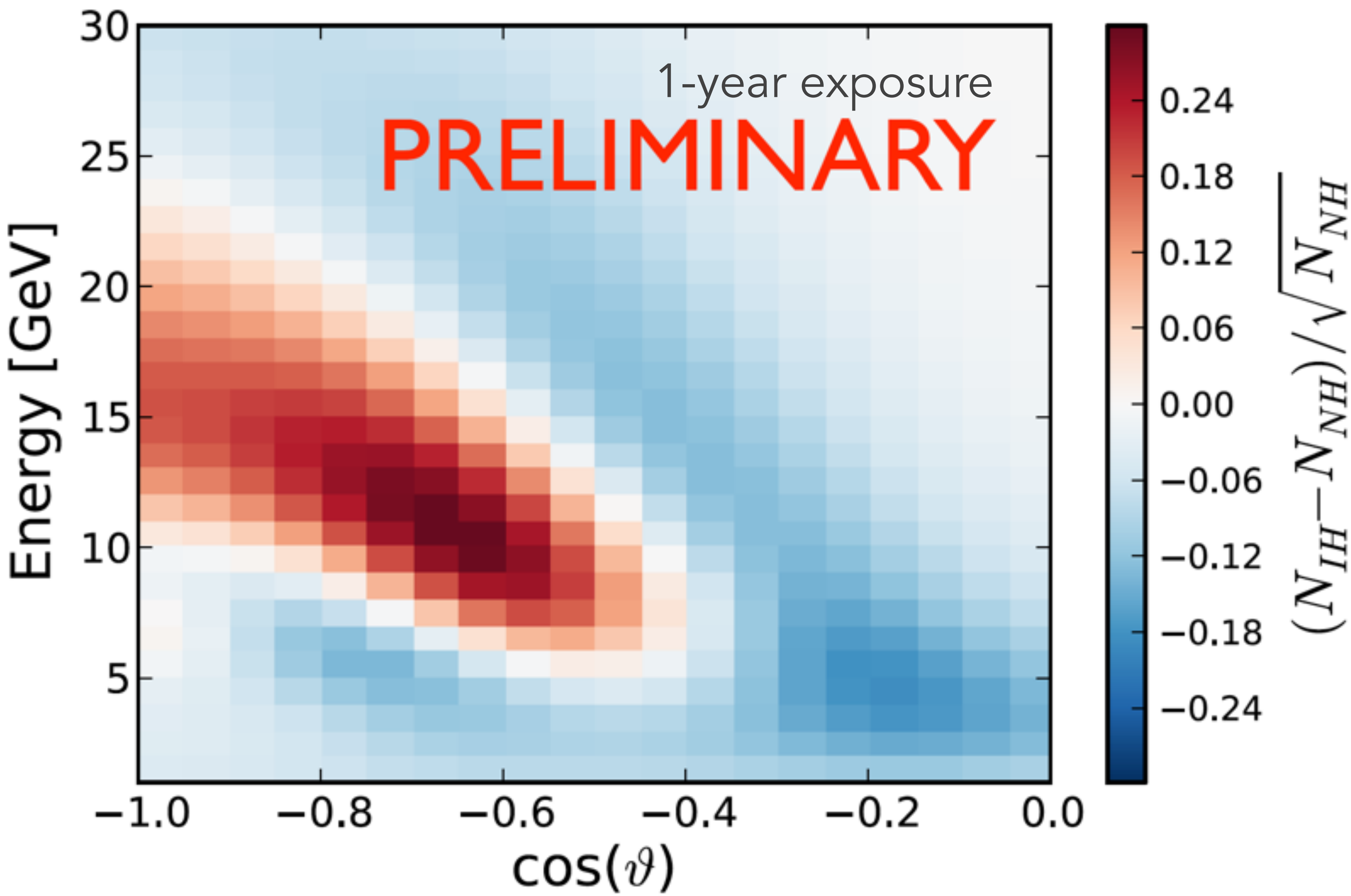
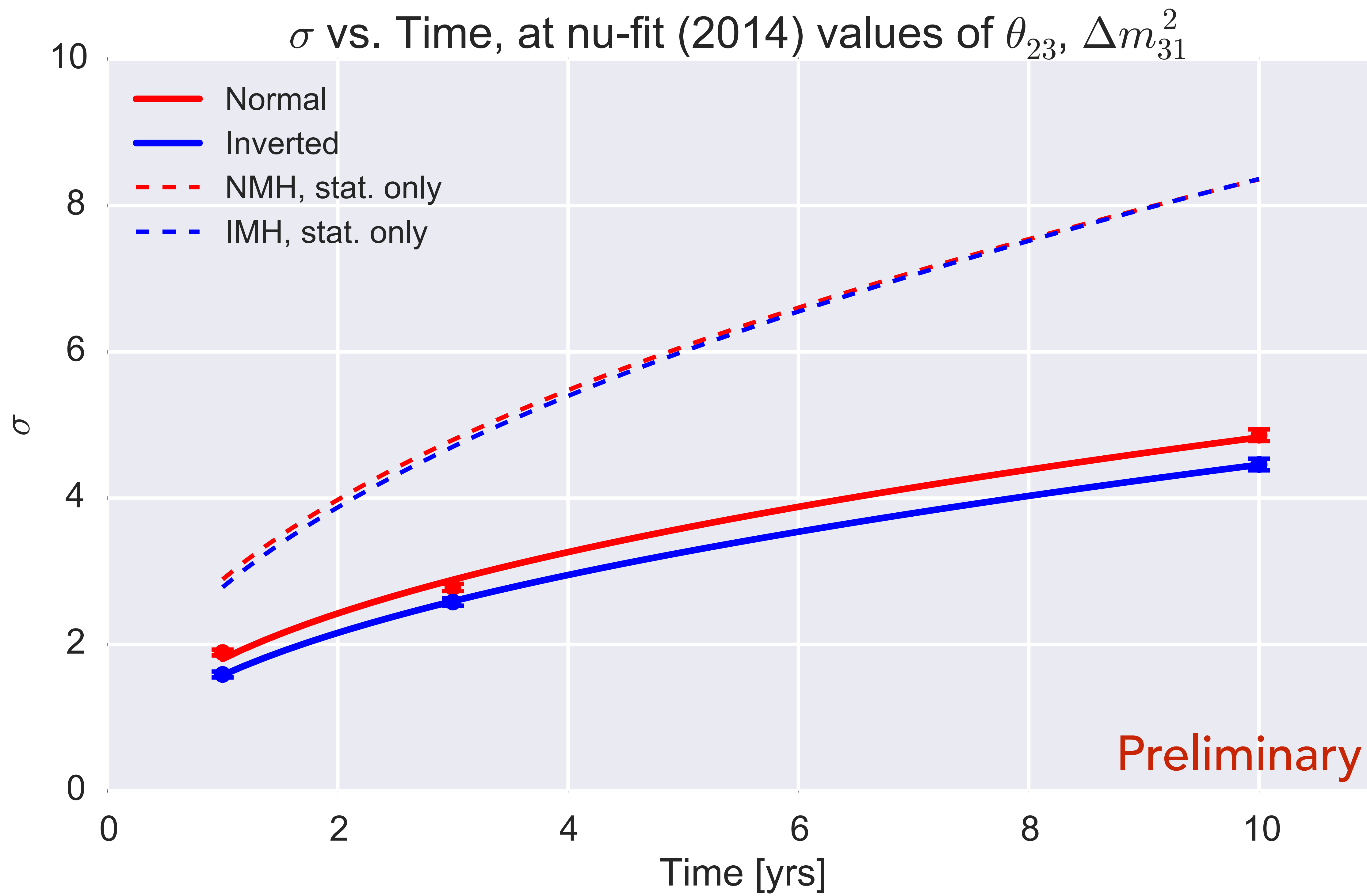
Neutrino Mass Ordering by Eye

Track-Like Events (mainly CC $\nu_\mu+\overline{\nu}_\mu$)



*K. Clark, ICRC2015

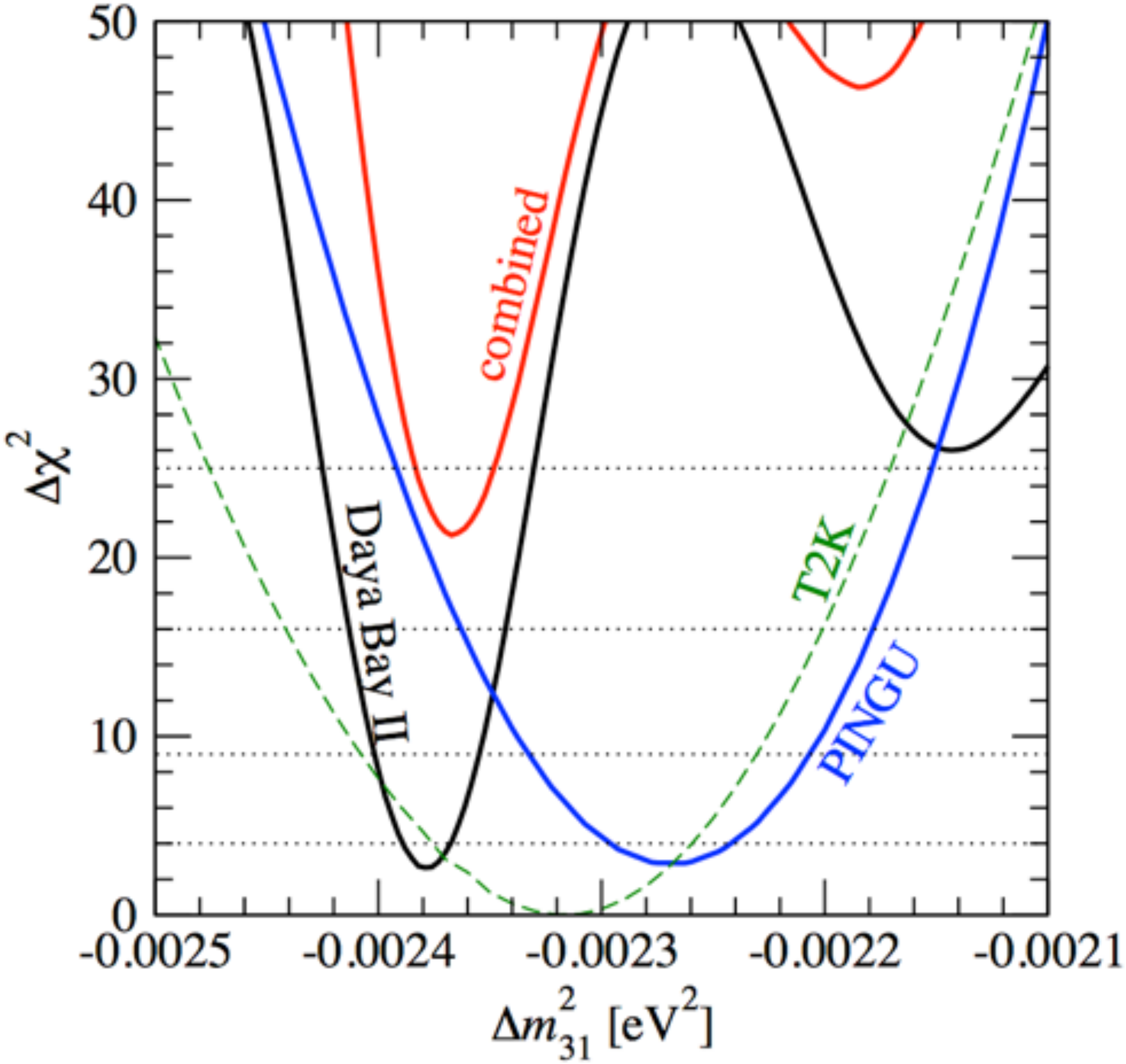
Bottom Line for PINGU

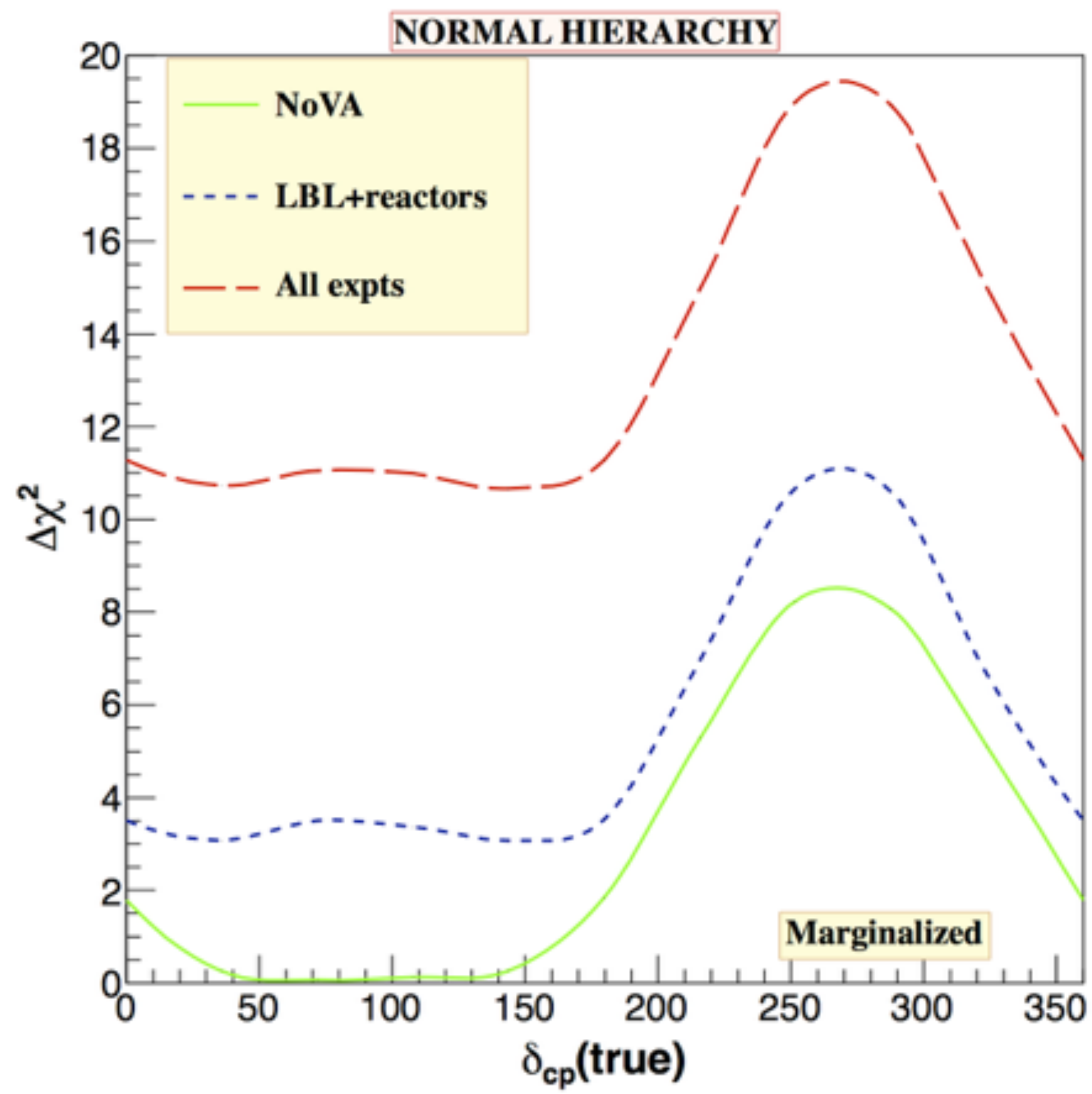


*T. Arlen WIN2015

Global Combination

*Blennow & Schwetz, arXiv:1306.3988





*Ghosh, Thakore & Choubey, arXiv:1212.1305

Conclusion

- Neutrino oscillation is confirmed laboratory signal for Beyond Standard Model physics that requires more investigation than the measurement of only 3 angles and 1 cp-phase

- Neutrino mass ordering is a major remaining target with an active current and future experimental program

Thank You

Backup

ν_τ Appearance in PINGU

*J.P.A.M. de André, NuFact 2014

ν_τ Appearance in PINGU

- Direct measure of $U_{\tau 3}$

*J.P.A.M. de André, NuFact 2014

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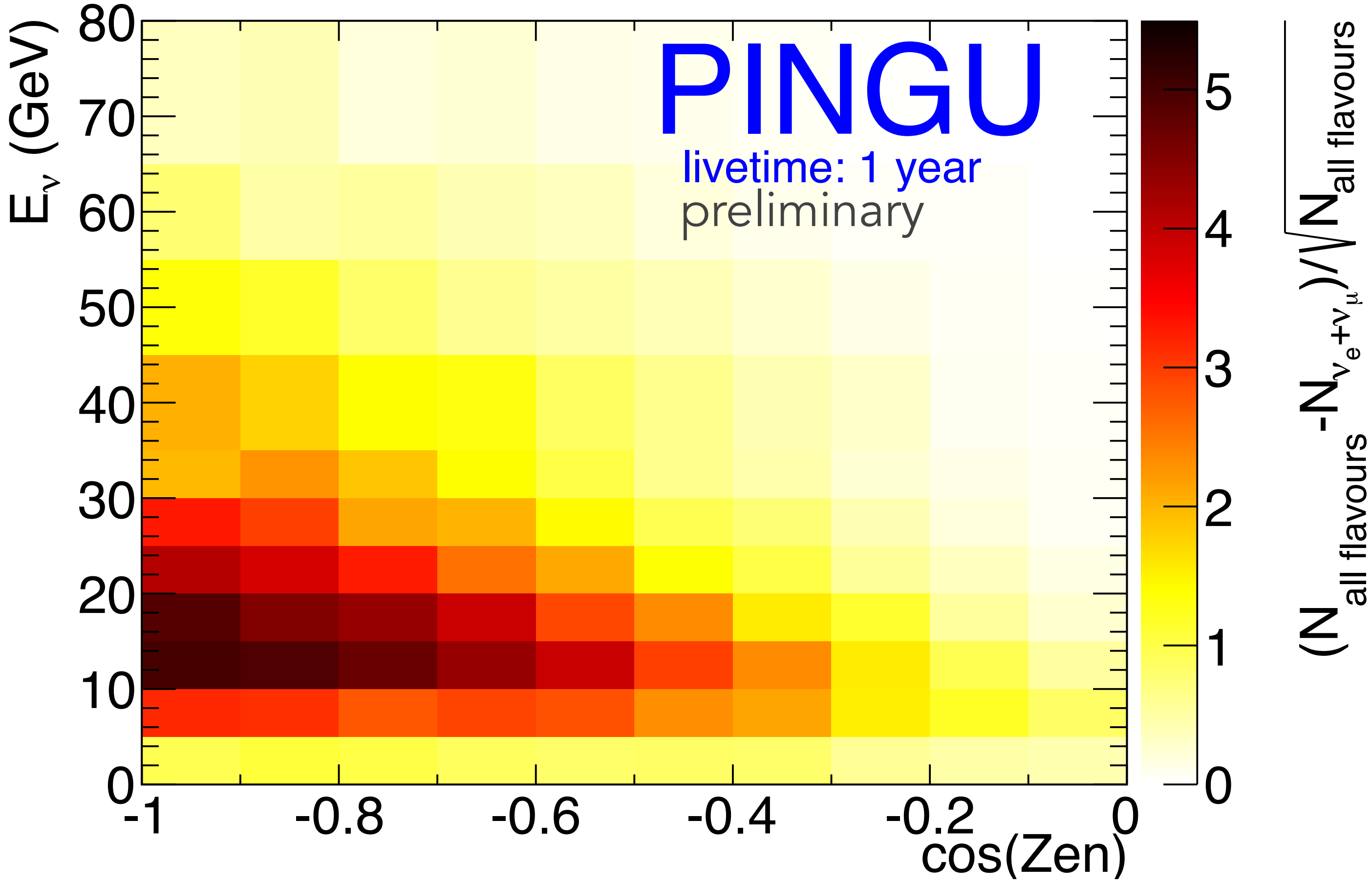
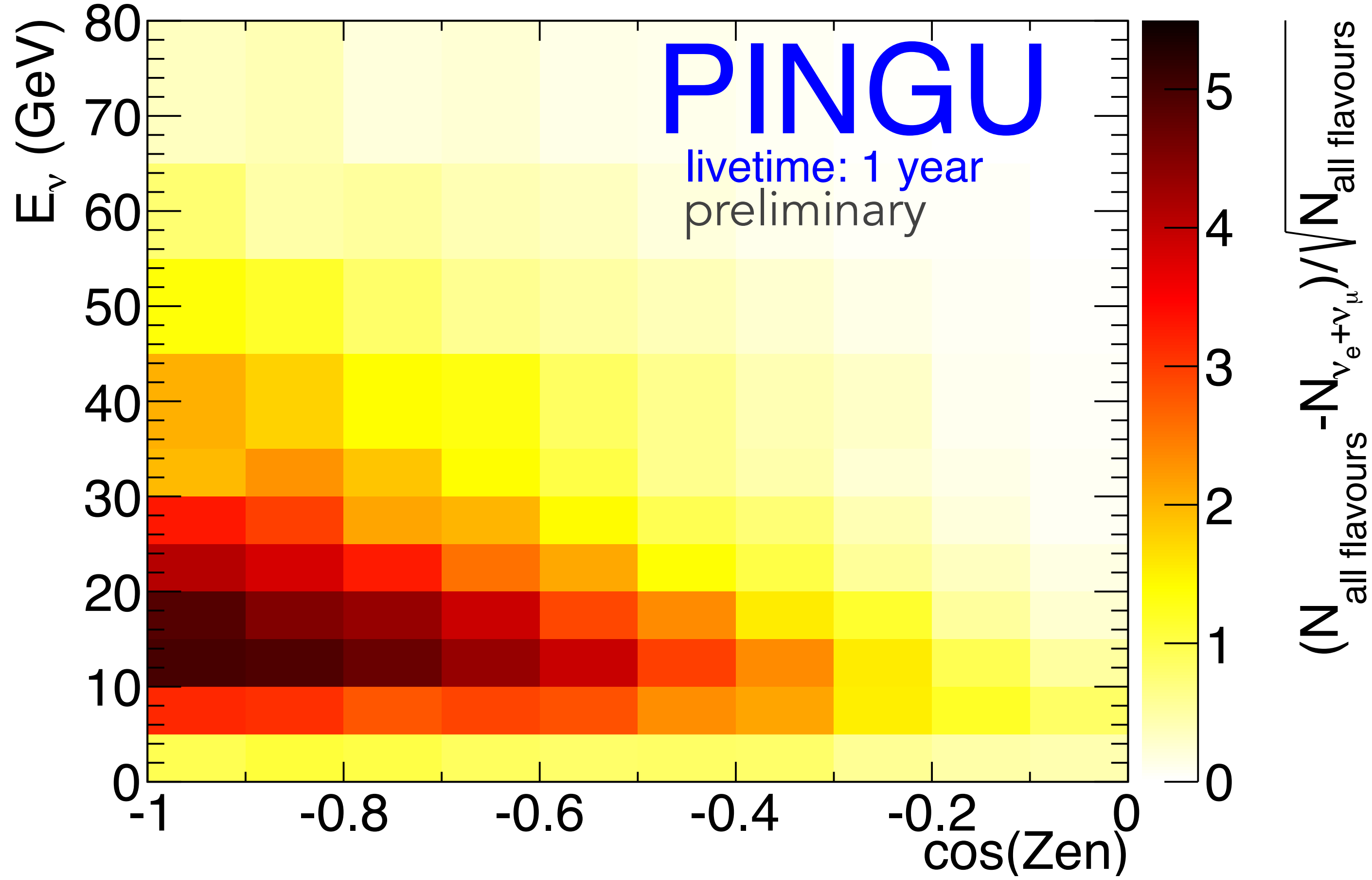


*J.P.A.M. de André, NuFact 2014

ν_τ Appearance in PINGU

- Direct measure of $U_{\tau 3}$
- Energy and zenith angle excess in cascade channel
- PINGU plots currently use same initial Boosted Decision Tree as NMH, but secondary selection for `cascades'



*J.P.A.M. de André, NuFact 2014

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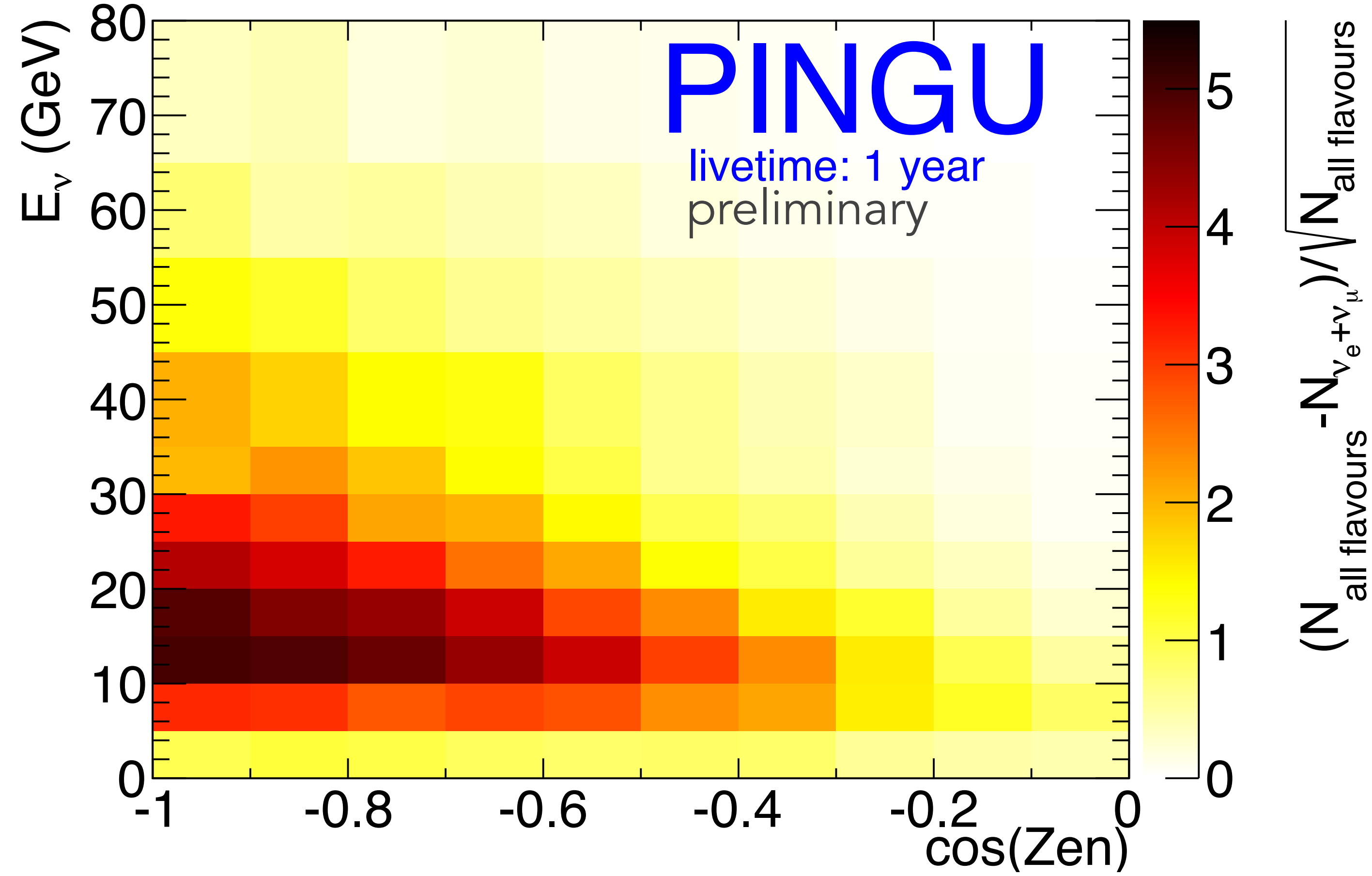

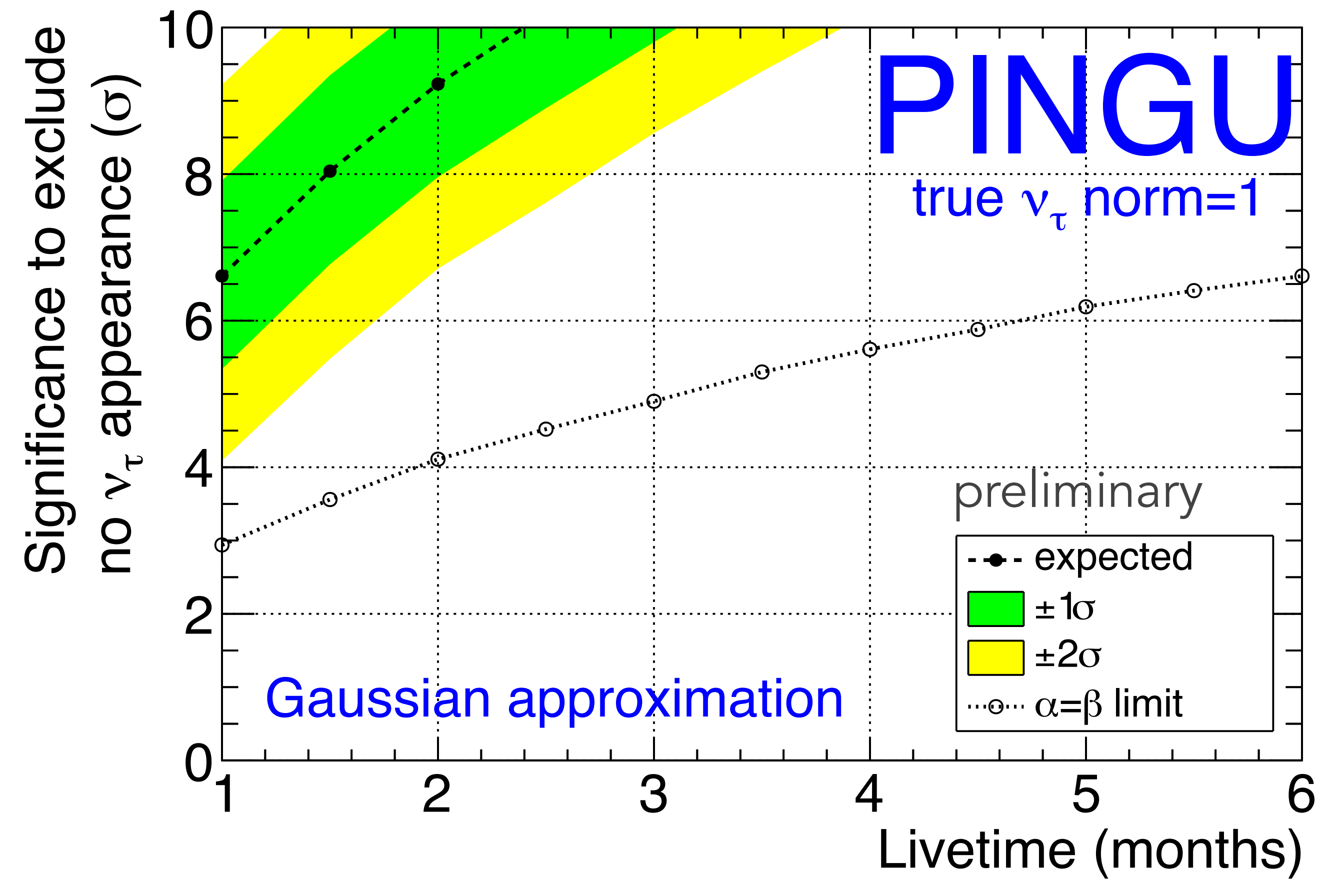

*J.P.A.M. de André, NuFact 2014

Measuring ν_τ Appearance

- High statistics allow possibility to measure

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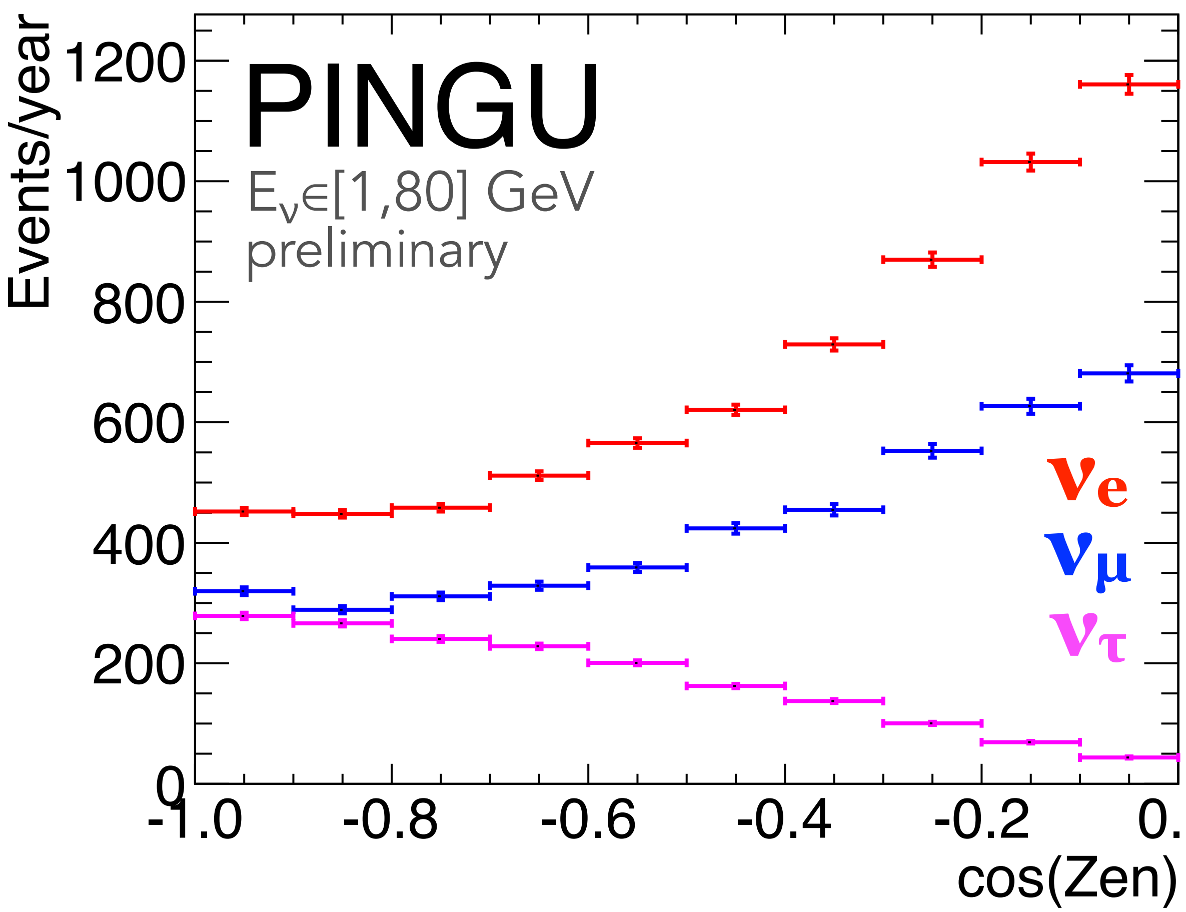

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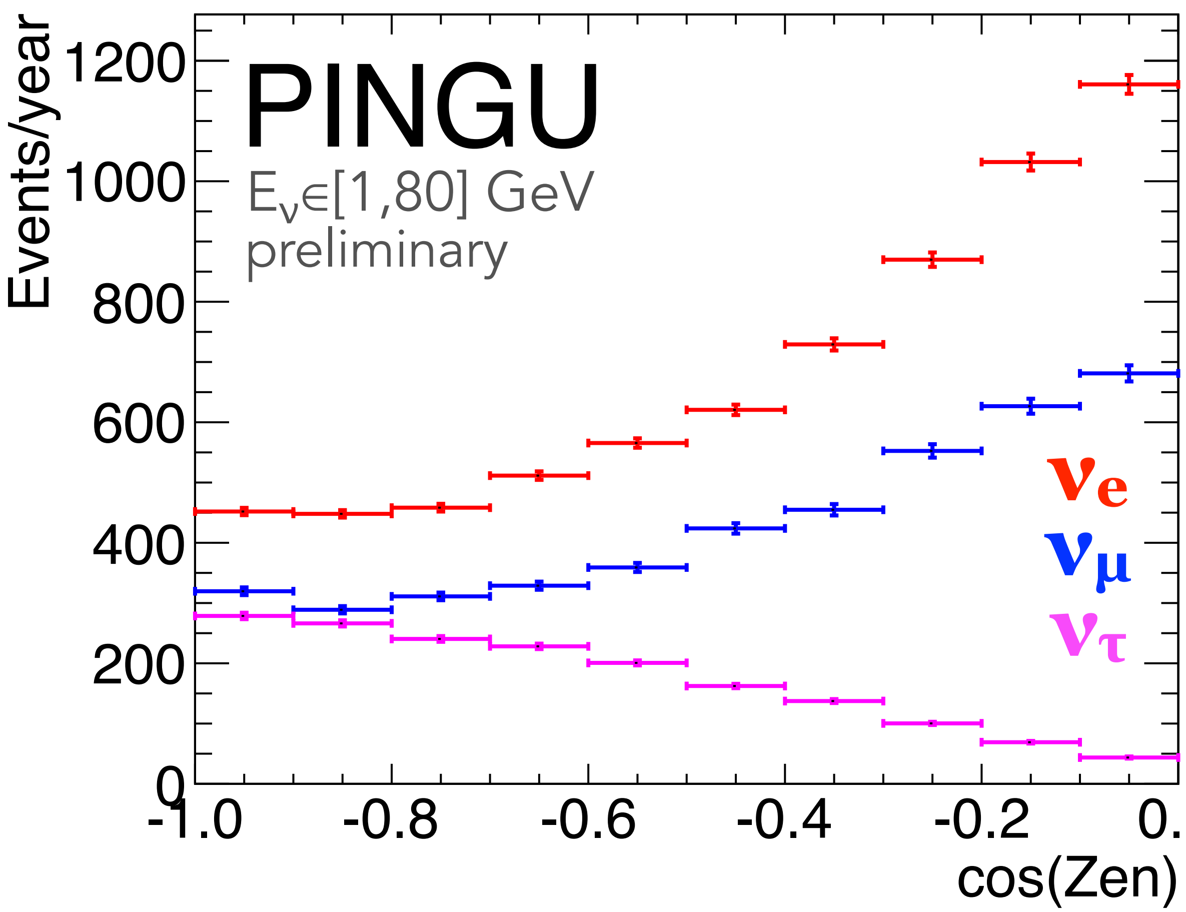
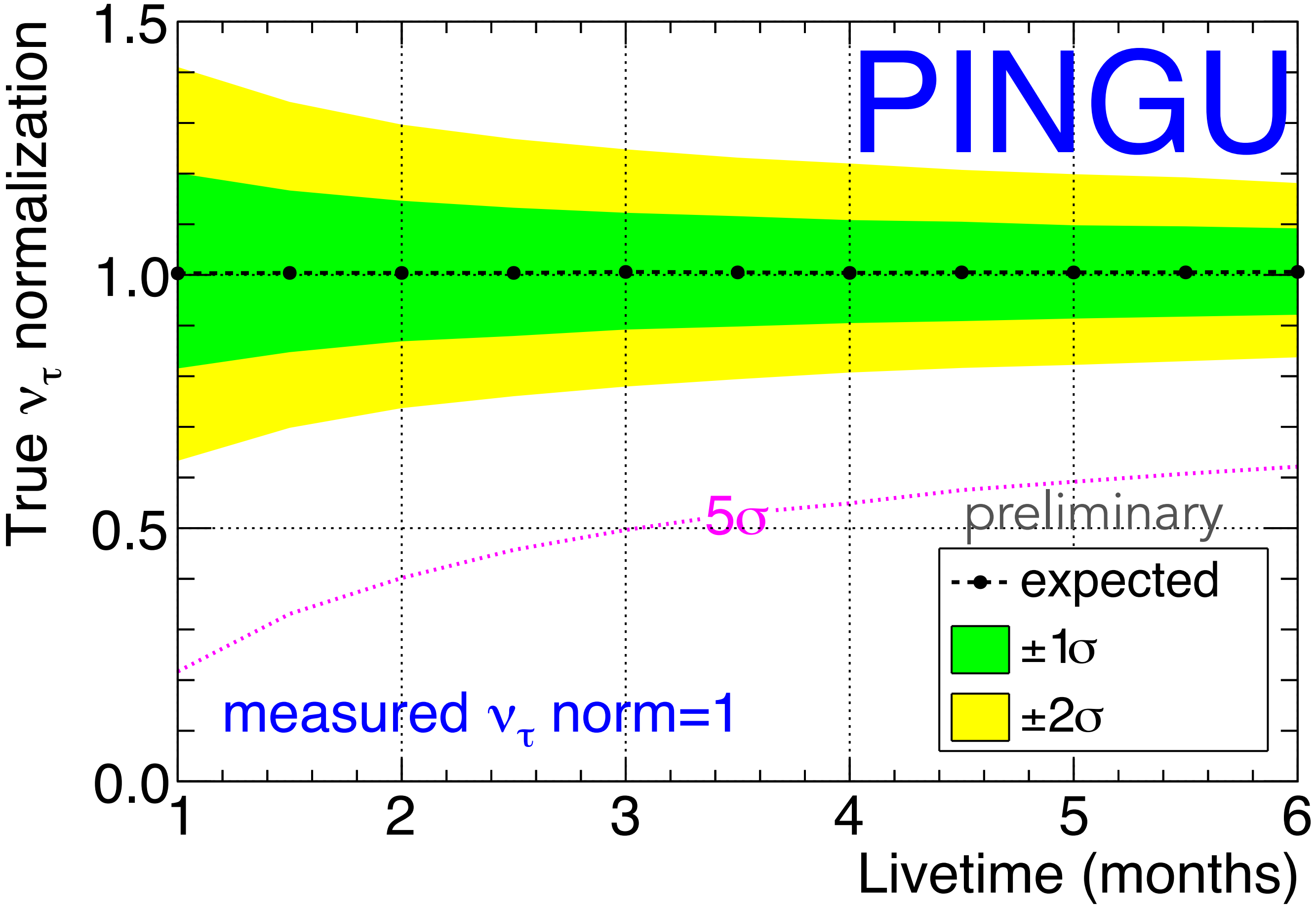
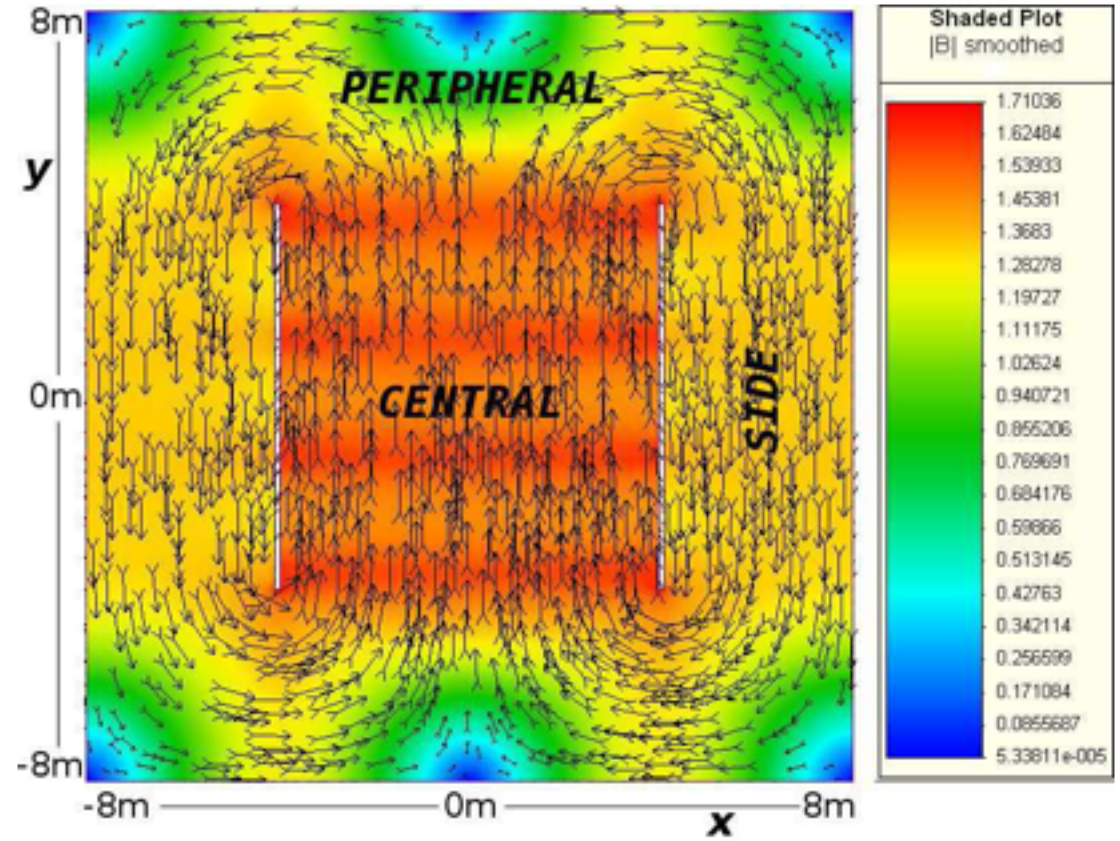
- High statistics allow possibility to measure



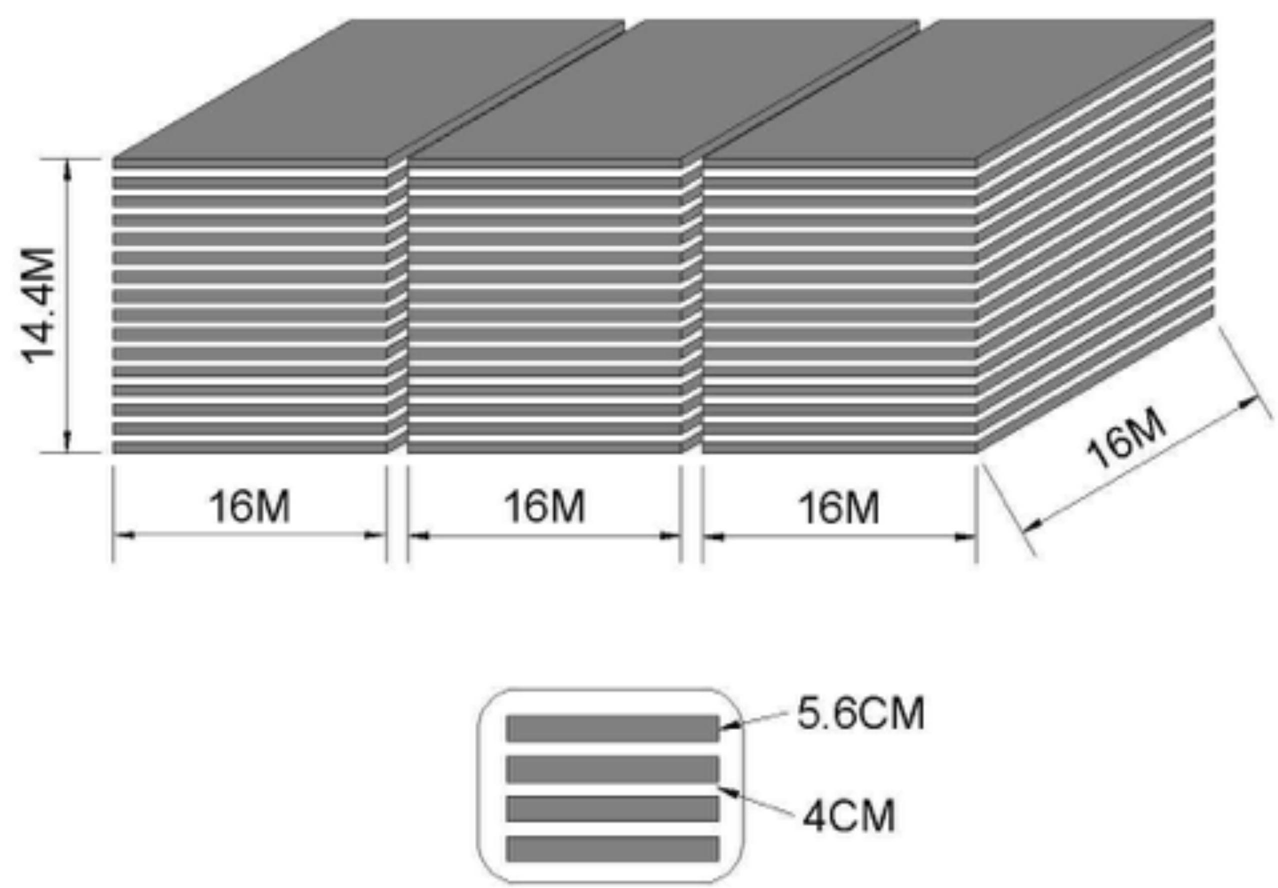


*J.P.A.M. de André, NuFact 2014

INO-ICAL

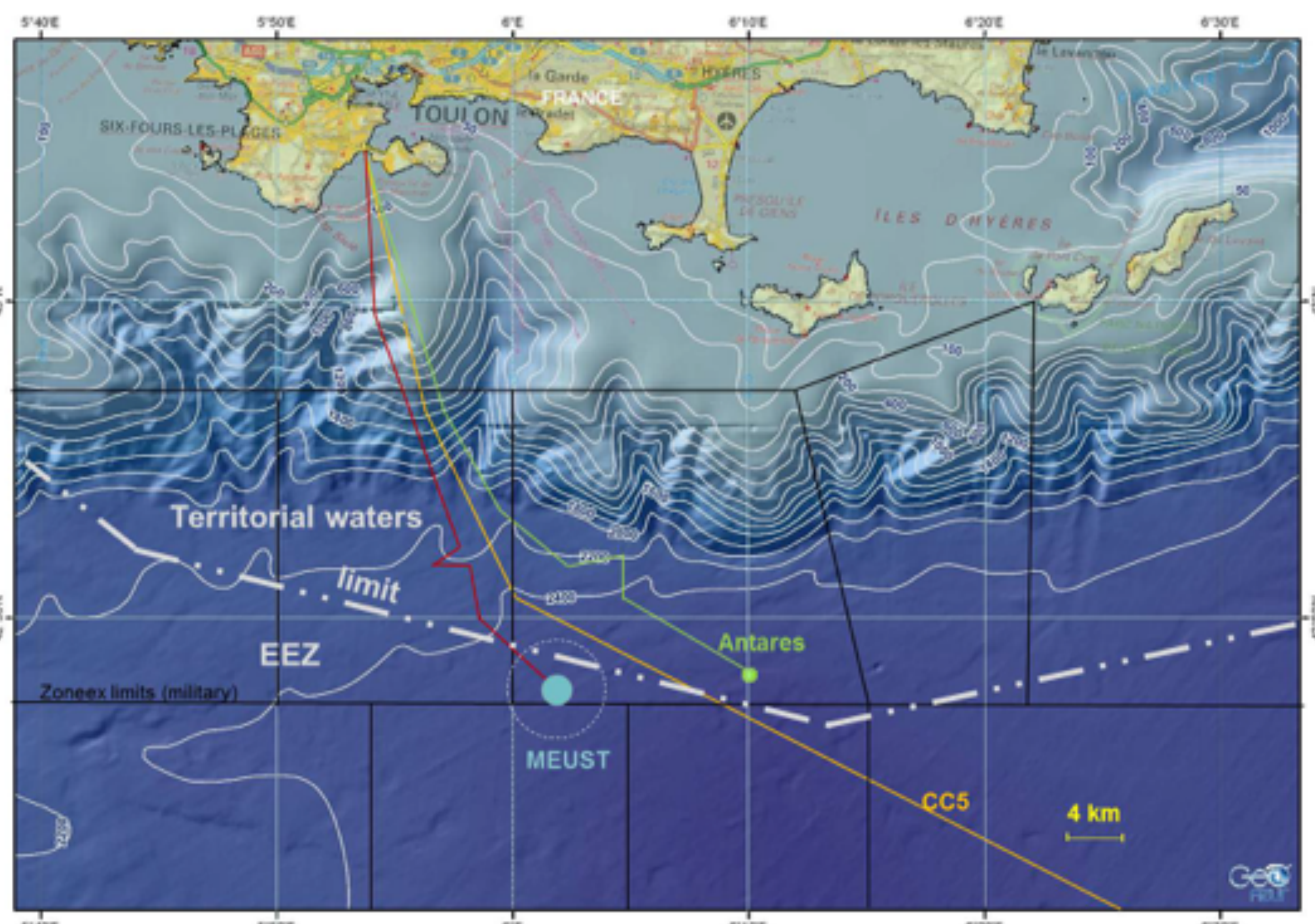


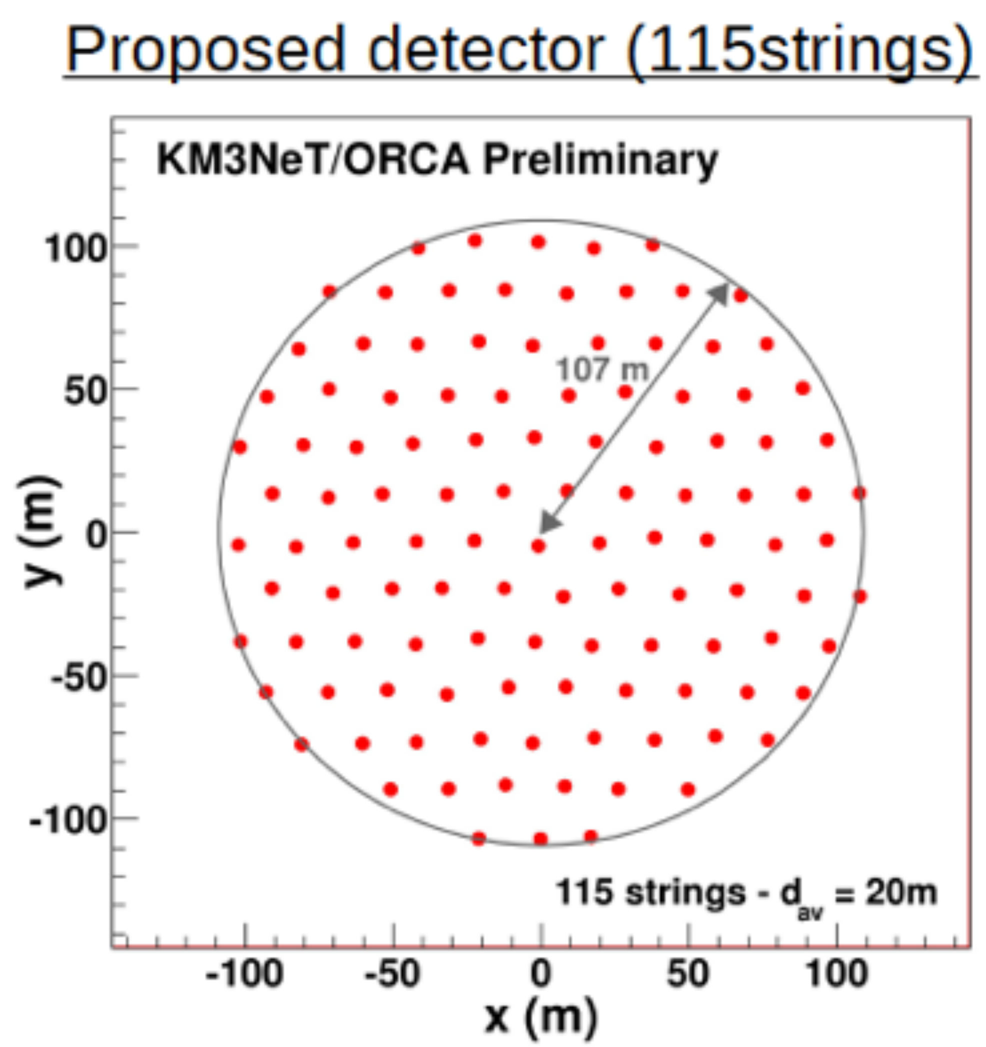
- Magnetized Iron Calorimeter (ICAL)
- Underground lab in the Theni district
- 3 modular 17 kton pieces
  - 14.4m in height x 16m length x 16m width
  - 1.5 Telsa in central region
  - 5.6cm steel w/ gap for RPC
- Resistive plate chambers
- 52 kton



ORCA

- 115 vertical lines at KM3NeT-Fr site in Mediterranean
- 6-7 strings in ORCA configuration are funded as Phase 1
- Pursuing phase 1.5 with 115 lines at French KM3NeT site which would be deployed by 2019

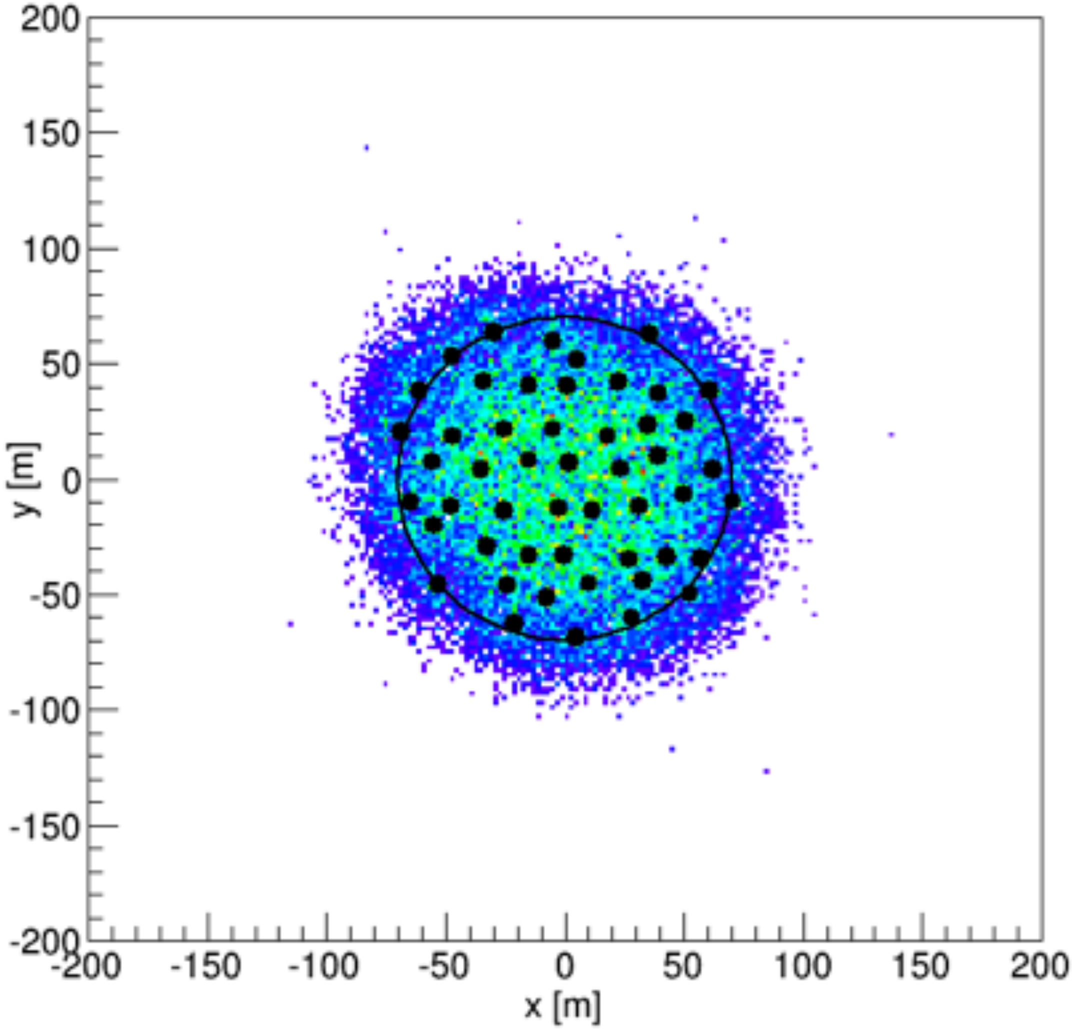




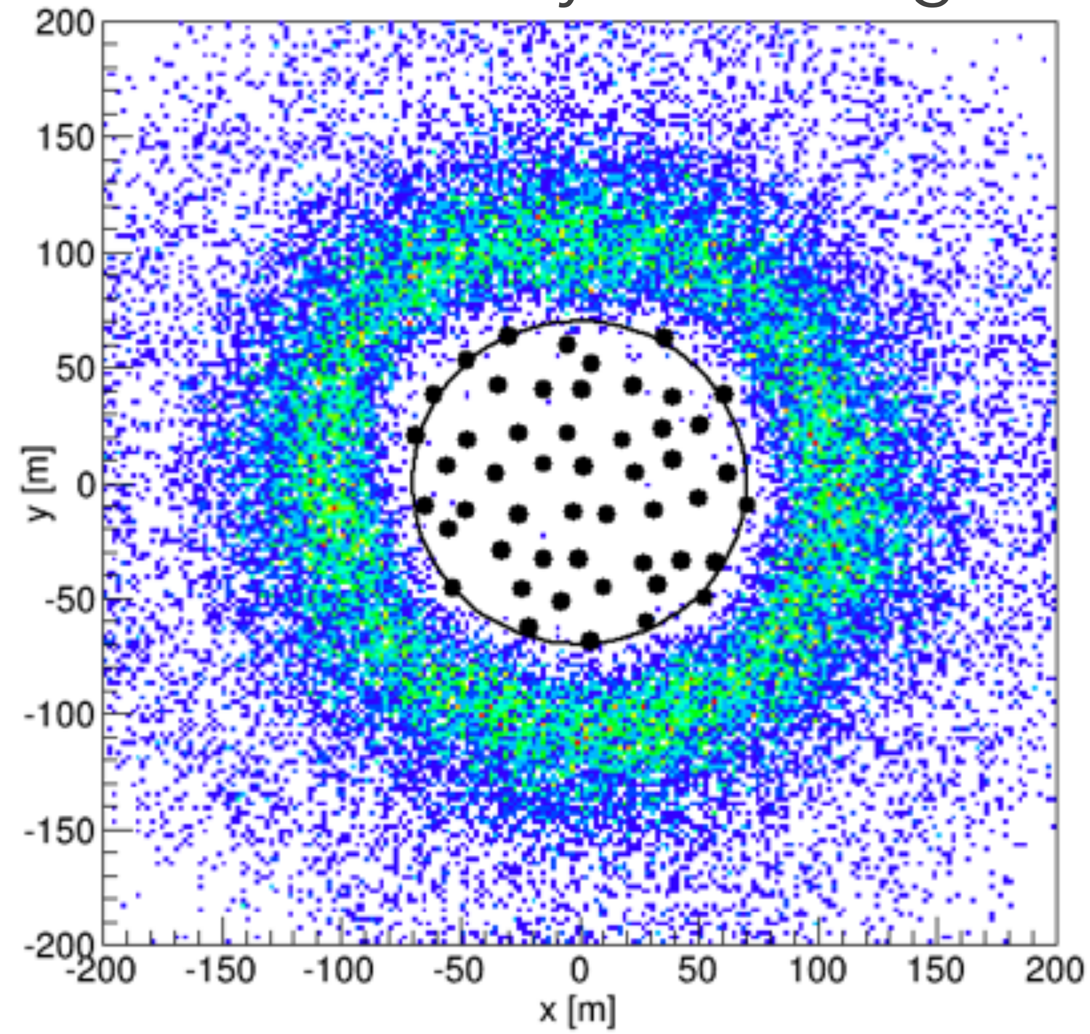
ORCA Cosmic Ray Muon Background

- ORCA has no current plans for an instrumented veto
- Use topological and reconstruction cuts for removal

Neutrinos < 20 GeV



Cosmic Ray Muon Bkg



*U. Katz, 1402.1022

ORCA Preliminary Sensitivity

- Early estimate of significance

- On-going work to include more realistic Monte Carlo physics, systematics assessment, include background, geometry optimization, etc.