Prospects for neutrino decoherence measurements at KM3NeT

João Coelho

for the KM3NeT Collaboration

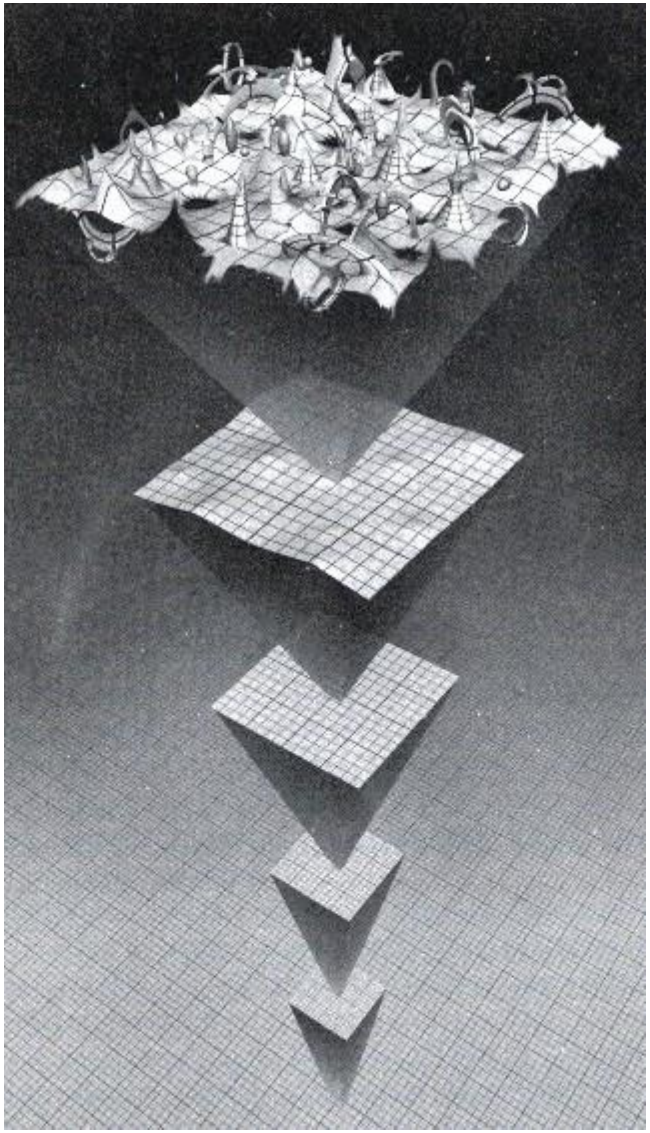
APC Laboratory

15 July 2022

Outline

1. Theoretical context
2. Experimental signatures
3. KM3NeT results
4. Epilogue: Open questions on phenomenological model

QG and Decoherence



- At Planck scales spacetime may be permeated with short-lived horizons
- Could such horizons act as a quantum bath, generating non-unitary quantum evolution?

Unitary **Non-Unitary**

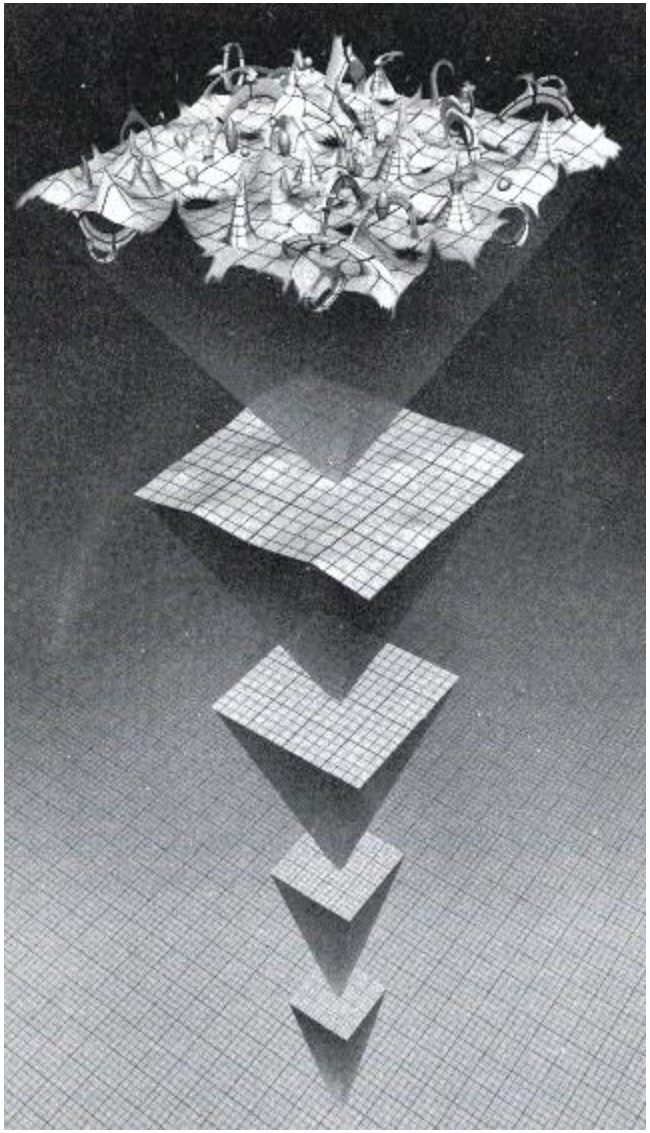
$$\partial_t \rho = -i[H, \rho] + \not{H}(\rho)$$

Dimensional Analysis

$$\not{H} \sim \mu^2 / M_P$$

$$\mu \sim E? \qquad \mu \sim \Delta E?$$

QG and Decoherence



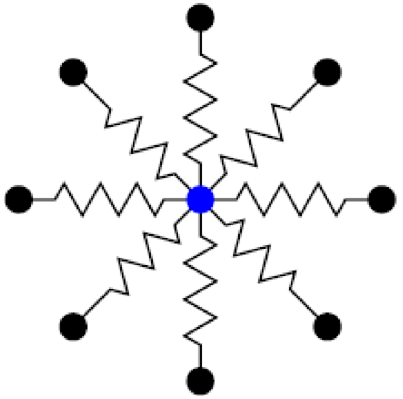
- At Planck scales spacetime may be permeated with short-lived horizons
- Could such horizons act as a quantum bath, generating non-unitary quantum evolution?

Unitary **Non-Unitary**

$$\partial_t \rho = -i[H,\rho] + \frac{1}{2}\sum_j 2A_j\rho A_j^\dagger - \{A_j^\dagger A_j, \rho\}$$

Lindblad Equation:

Most general Markovian evolution that preserves probabilities even in the environment system



Neutrino Oscillations

- Neutrinos are created in a superposition of mass states
- Time evolution generates flavour oscillations

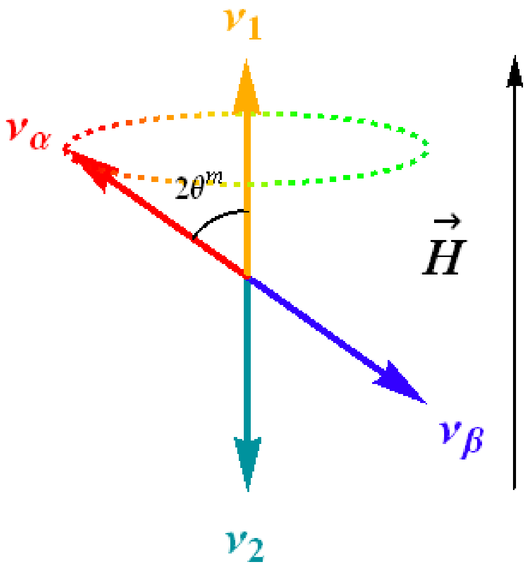
$$P_{\alpha\beta} = \frac{1}{2}\sin^2 2\theta[1 - \cos\Delta t]$$

Unitary QM

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left|\langle\nu_\beta|e^{-iHt}|\nu_\alpha\rangle\right|^2$$

$$< H > .t \sim \Delta E.L \sim \frac{\Delta m^2 L}{2E}$$



Neutrino Decoherence

- Interaction with some environment → Mixed states
- Time evolution given by Lindblad equation

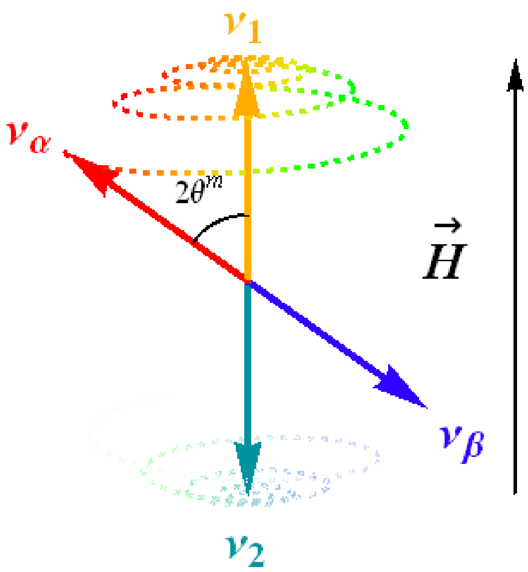
$$P_{\alpha\beta} = \frac{1}{2}\sin^2 2\theta[1 - e^{-\Gamma t}\cos\Delta t]$$

Open QM

$$\partial_t \rho = -i[H,\rho] + \frac{1}{2}\sum_j 2A_j\rho A_j^\dagger - \{A_j^\dagger A_j, \rho\}$$

- Complete Positivity
- Trace Preserving
- Increasing Entropy
- Energy Conservation

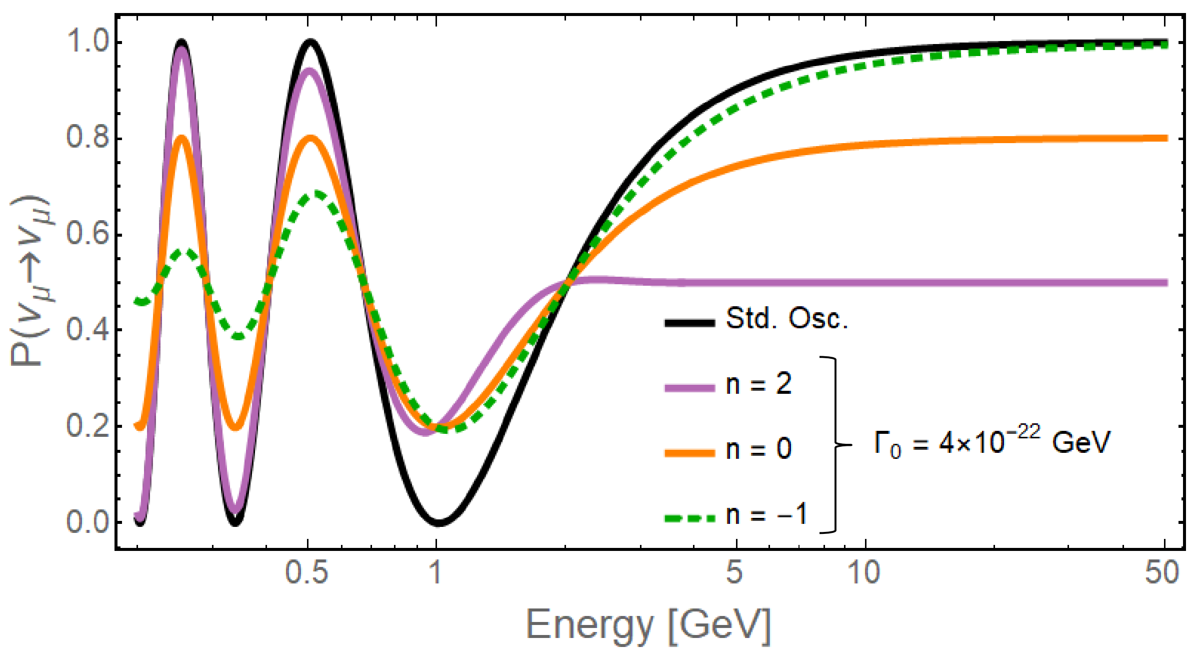
$$\rho(t) = \begin{bmatrix} \rho_{11} & \rho_{12}\ e^{i\Delta t - \Gamma t} \\ \rho_{21}\ e^{-i\Delta t - \Gamma t} & \rho_{22} \end{bmatrix}$$



Energy Dependence

- Little is known about how Γ depends on energy
- Γ has dimension of energy
- Dimensional analysis guesses:
  - $\Gamma(E) \sim E^2/M_P \sim 10^{-19}$ GeV * E^2 ?
  - $\Gamma(E) \sim \Delta m^2/M_P \sim 10^{-40}$ GeV ?
  - $\Gamma(E) \sim \Delta E^2/M_P = (\Delta m^2)^2 / (E\, M_P) \sim 10^{-61}$ GeV * E^{-1} ?

- Take a phenomenological approach: $\Gamma(E) = \Gamma_0\, (E/E_0)^n$



Energy Dependence

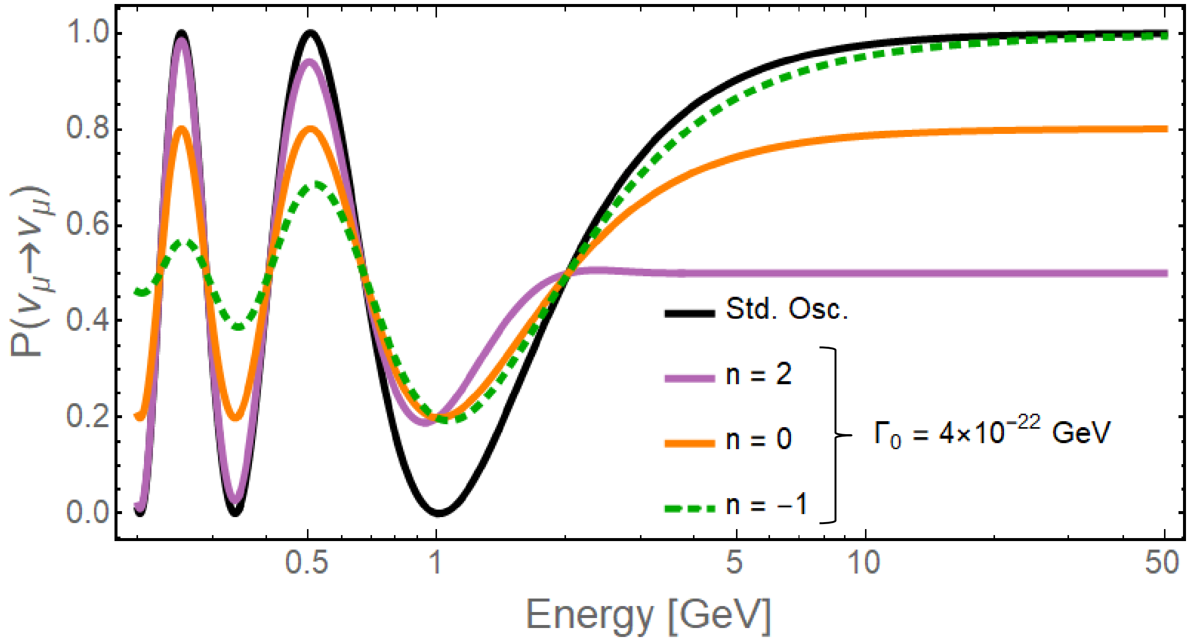
- Little is known about how Γ depends on energy

From the previous equation, the decoherence time can be inferred

Luciano Petruzziello

$$\tau_D = \frac{1}{\sigma\,(\Delta E^2)^2} = \frac{\hbar^6}{16\, m^2\, \ell_p^4\, t_p\, (\Delta E^2)^2}\,.$$

$\Gamma(E) \sim m^2(\Delta m^2)^2/M_P^5 \sim 10^{-156}$ GeV



3x3 Systems

- Neutrinos come in 3 flavours
- Hilbert space can be described by SU(3)
- Expand all operators in generators of SU(3) (Gell-Mann Matrices)

$$[F_j, F_k] = i \sum_l f_{jkl} F_l$$

$$\partial_t \rho = -i[H, \rho]$$

↓

Operators as sum SU(3) of generators

$$\mathscr{O} = \sum_j \mathrm{tr}\left[\mathscr{O} F_j\right] F_j$$

$$\partial_t \vec{\rho} = \widetilde{H}_{vac} \vec{\rho}$$

System of 9 coupled equations

Simple block-diagonal form

$$\widetilde{H}_{vac} = \begin{bmatrix} 0_{3\times 3} & 0 & 0 & 0 \\ 0 & -i\sigma_2 \Delta_{21} & 0 & 0 \\ 0 & 0 & -i\sigma_2 \Delta_{31} & 0 \\ 0 & 0 & 0 & -i\sigma_2 \Delta_{32} \end{bmatrix}$$

3x3 Systems

- Neutrinos come in 3 flavours
- Hilbert space can be described by SU(3)
- Expand all operators in generators of SU(3) (Gell-Mann Matrices)

$$[F_j, F_k] = i \sum_l f_{jkl} F_l$$

$$\partial_t \rho = -i[H, \rho] + \frac{1}{2} \sum_j 2A_j \rho A_j^\dagger - \{A_j^\dagger A_j, \rho\}$$

Operators as sum SU(3) of generators

$$\mathscr{O} = \sum_j \mathrm{tr}\left[\mathscr{O} F_j\right] F_j$$

$$\partial_t \vec{\rho} = \left(\widetilde{H} - \widetilde{L}\right) \vec{\rho}$$

System of 9 coupled equations

In general* 36 parameters!

$$\widetilde{L}_{jk} = \frac{1}{2} \sum_{lmn} (\vec{a}_l \cdot \vec{a}_m) f_{lkn} f_{nmj}$$

Diagonal w/ energy conserv.

$$\widetilde{L} = \begin{bmatrix} 0_{3\times 3} & 0 & 0 & 0 \\ 0 & I_2 \Gamma_{21} & 0 & 0 \\ 0 & 0 & I_2 \Gamma_{31} & 0 \\ 0 & 0 & 0 & I_2 \Gamma_{32} \end{bmatrix}$$

*But already assuming increasing entropy ($A_j^\dagger = A_j$)

Cauchy-Schwarz

- Γ_{ij} are not independent
- Related by Cauchy-Schwarz inequalities

$$\widetilde{L}_{jk} = \frac{1}{2} \sum_{lmn} (\vec{a}_l \cdot \vec{a}_m)\, f_{lkn} f_{nmj}$$

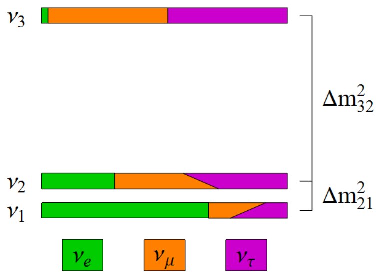
$$\Gamma_{21} = |\vec{a}_3|^2,\ \Gamma_{31} = \frac{1}{4}|\vec{a}_3 + \sqrt{3}\vec{a}_8|^2,\ \Gamma_{32} = \frac{1}{4}|\vec{a}_3 - \sqrt{3}\vec{a}_8|^2$$

$$x \geq \left(\sqrt{y} - \sqrt{z}\right)^2$$

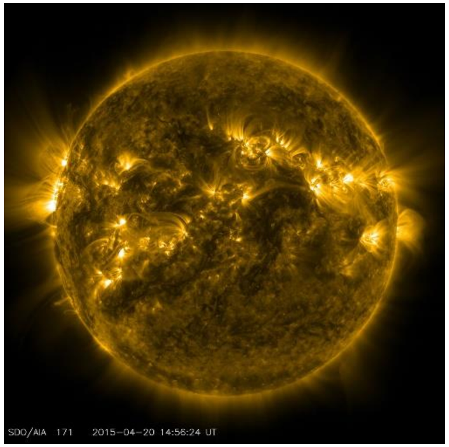
$\{x, y, z\}$ = Any permutation of $\{\Gamma_{21}, \Gamma_{31}, \Gamma_{32}\}$

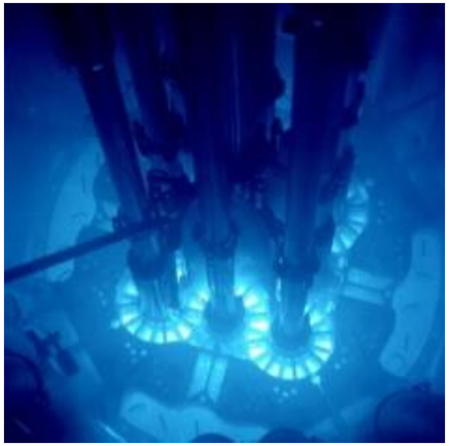
e.g.: $\Gamma_{21} = 0 \Rightarrow \Gamma_{31} = \Gamma_{32}$

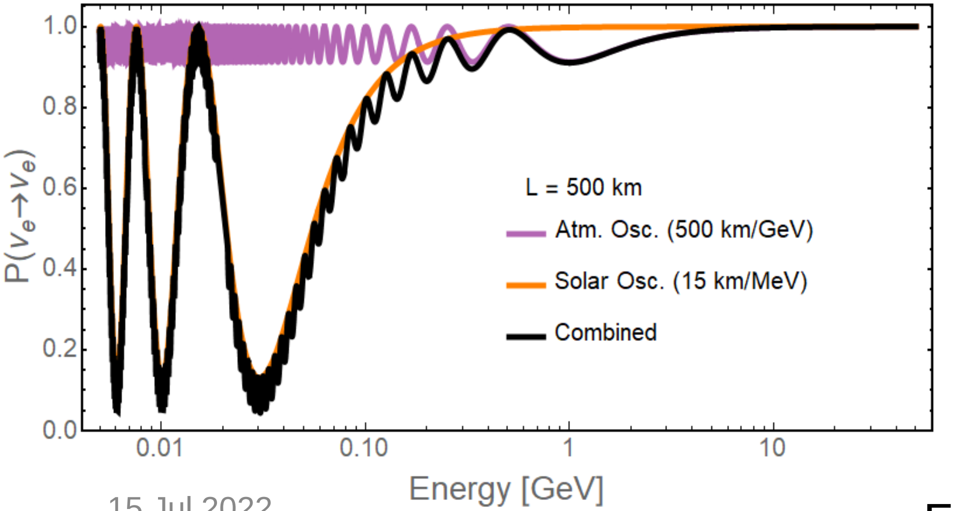
Solar Neutrino Constraints

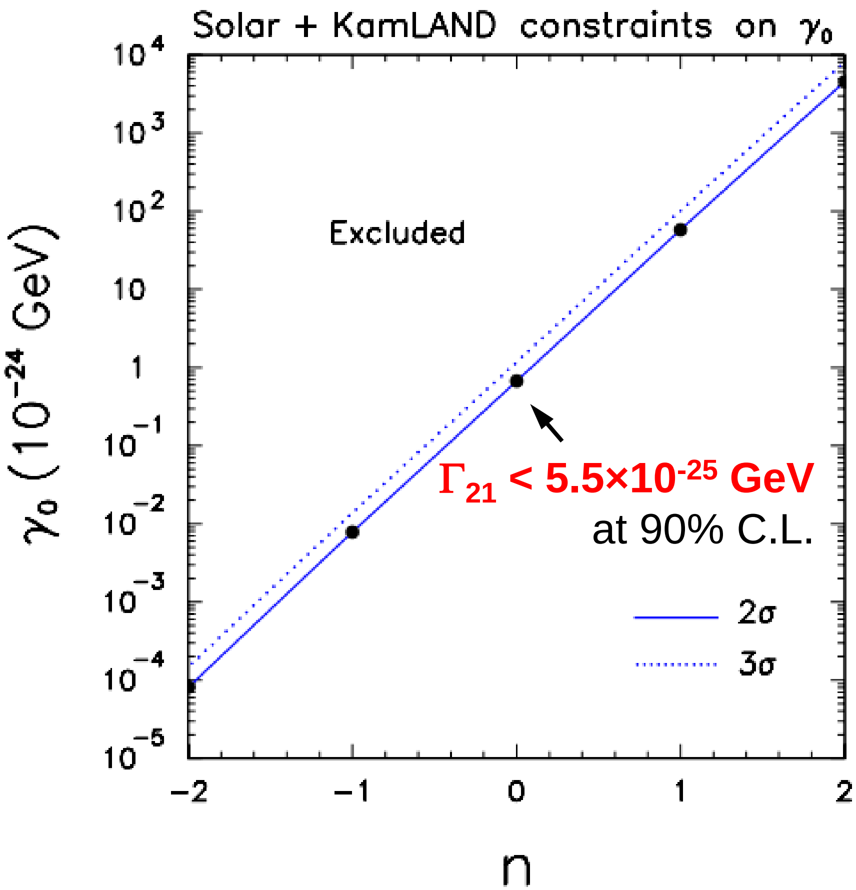


- Solar scale oscillations strongly constrain decoherence
- Sensitive to lower frequency Δm^2_{21}
- Decoherence coupling is dominated by Γ_{21}



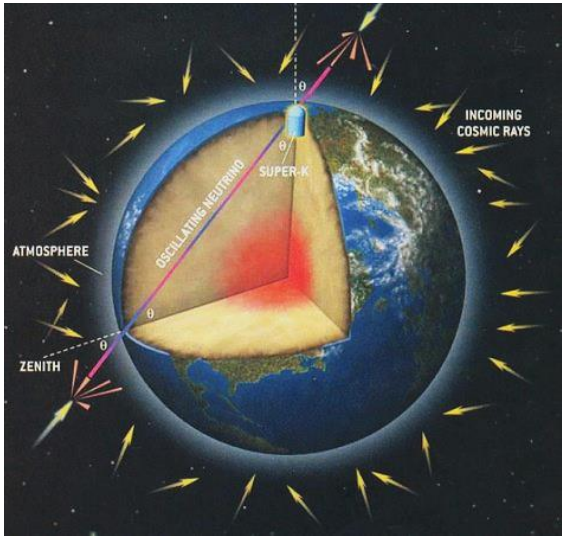




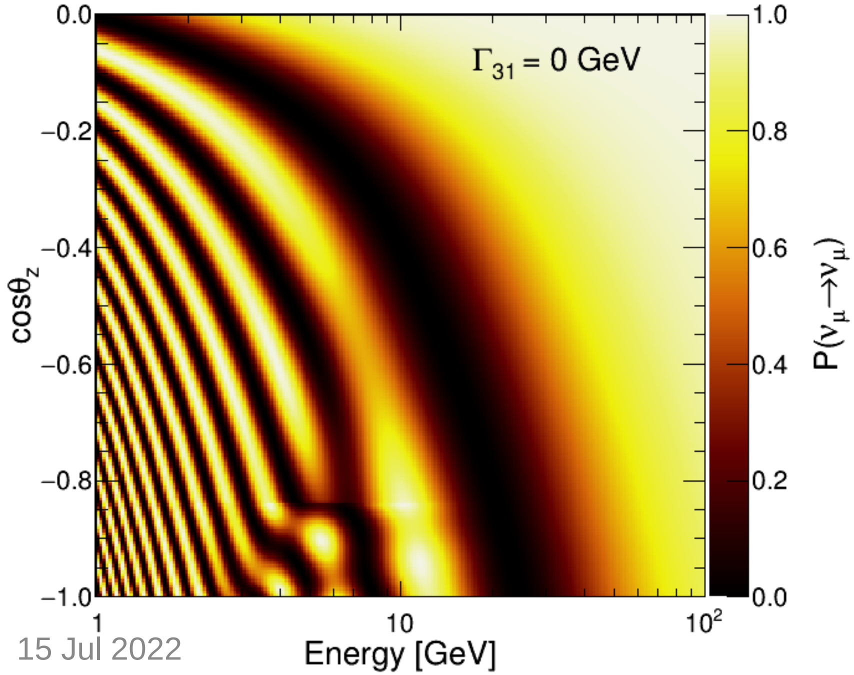


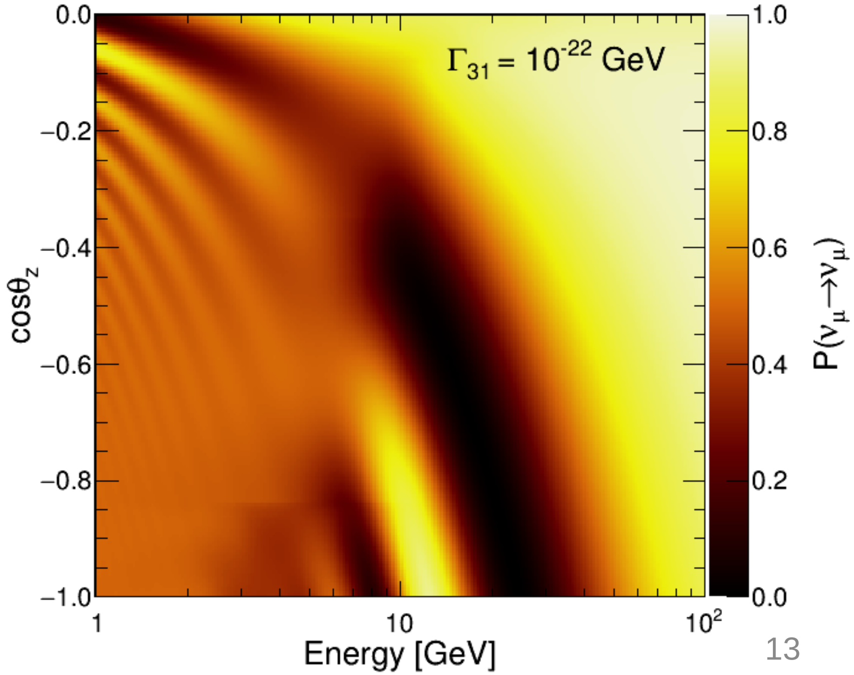
Fogli et al, PRD 76, 033006 (2007)

Atmospheric Neutrinos



- Very long baselines available
- Strong matter effects give interesting patterns
- Great source for characterizing energy dependence of possible decoherence effects

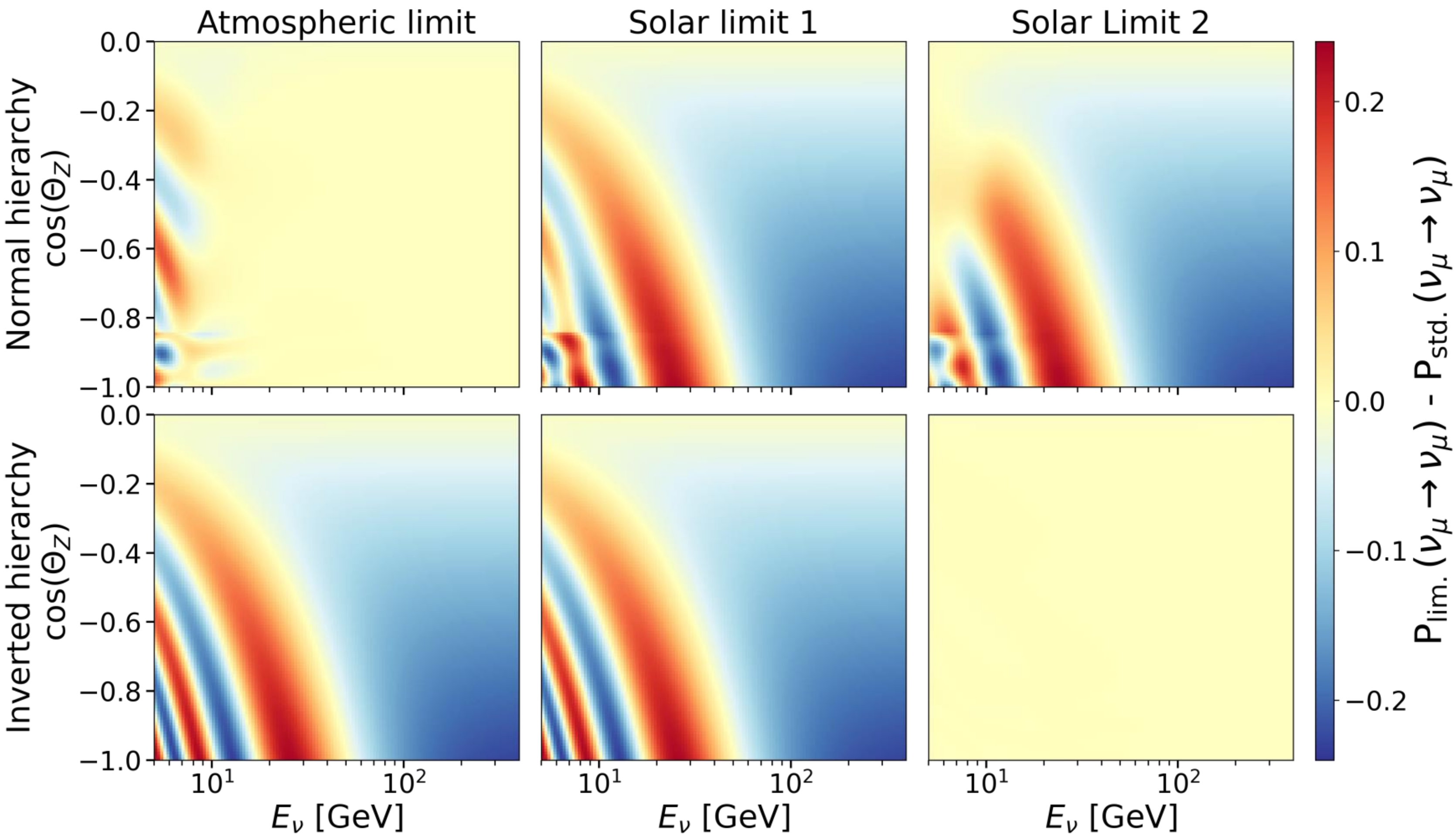




Atmospheric Neutrinos

- For completeness, consider 3 limiting cases

$\Gamma_{21} = 0 \rightarrow$ Atm. Limit
$\Gamma_{32} = 0 \rightarrow$ Solar Limit 1
$\Gamma_{31} = 0 \rightarrow$ Solar Limit 2



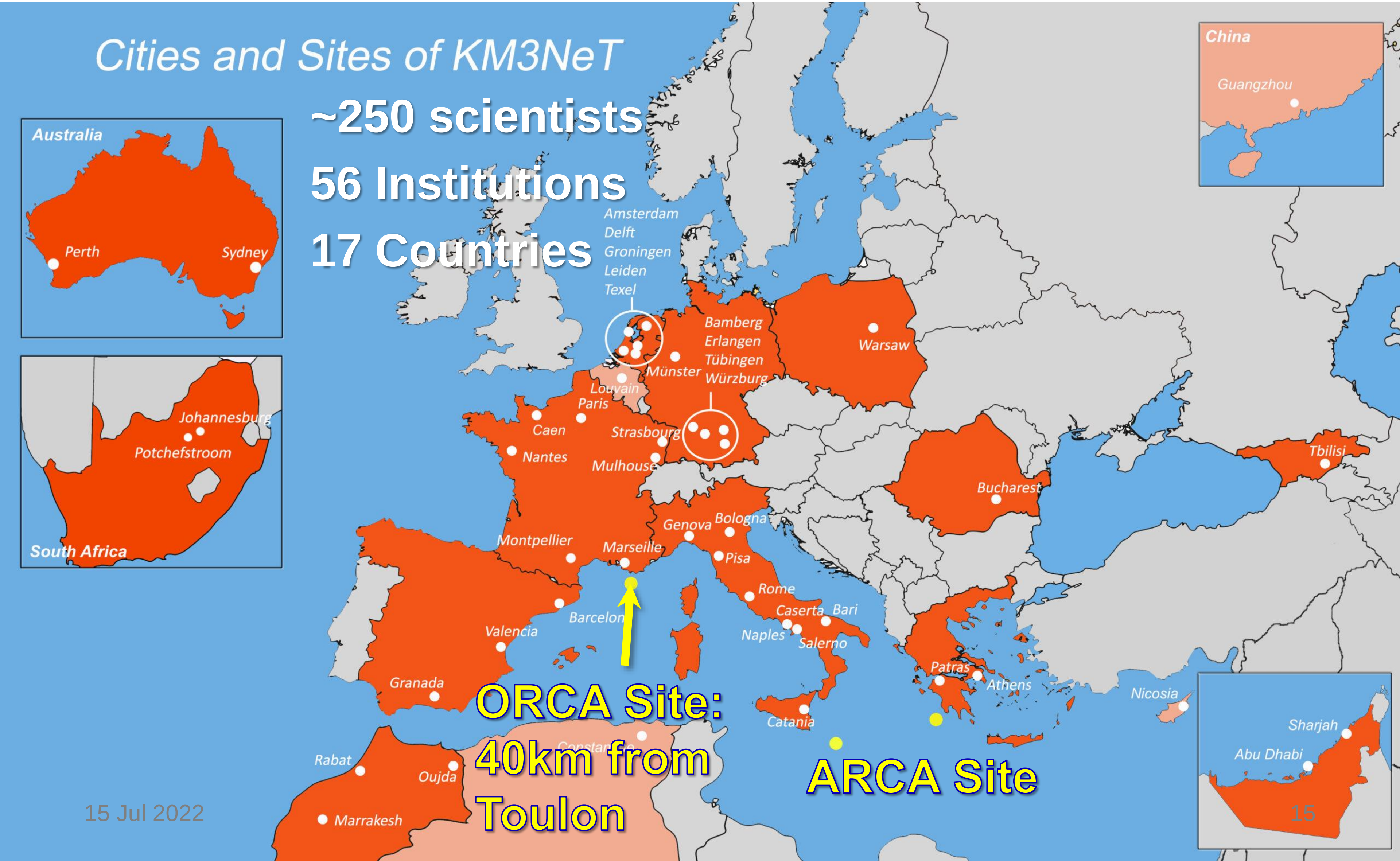
KM3NeT Collaboration

www.km3net.org

~250 scientists

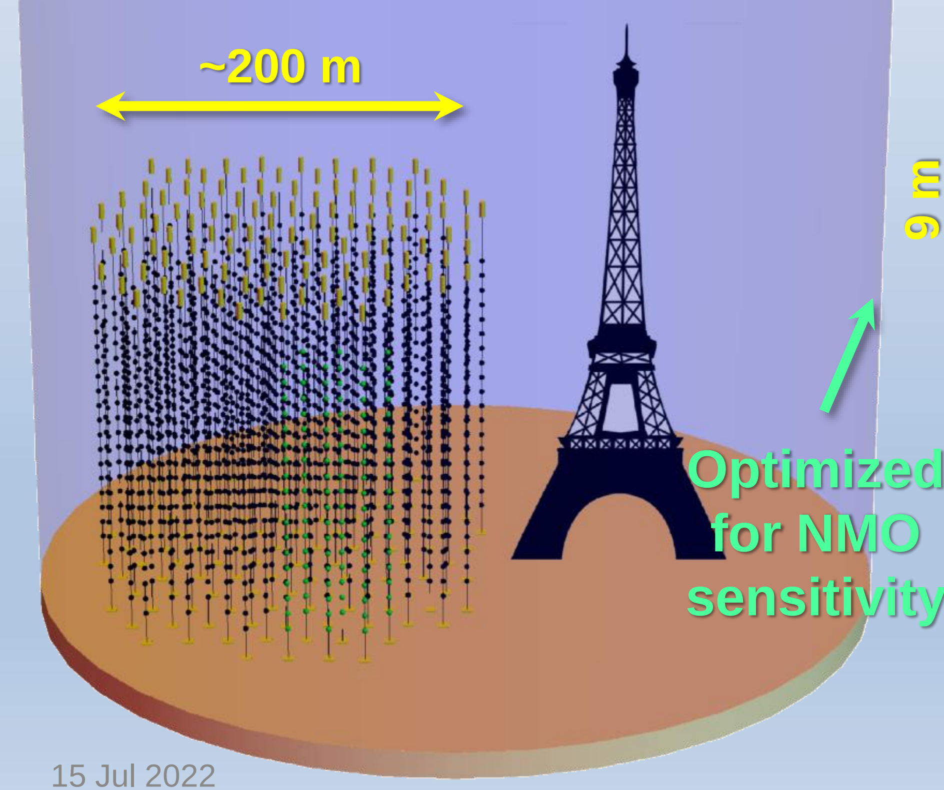
56 Institutions

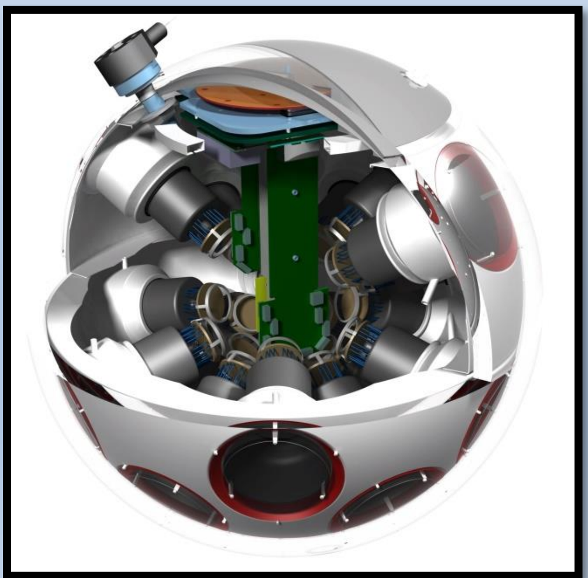
17 Countries



The ORCA Detector

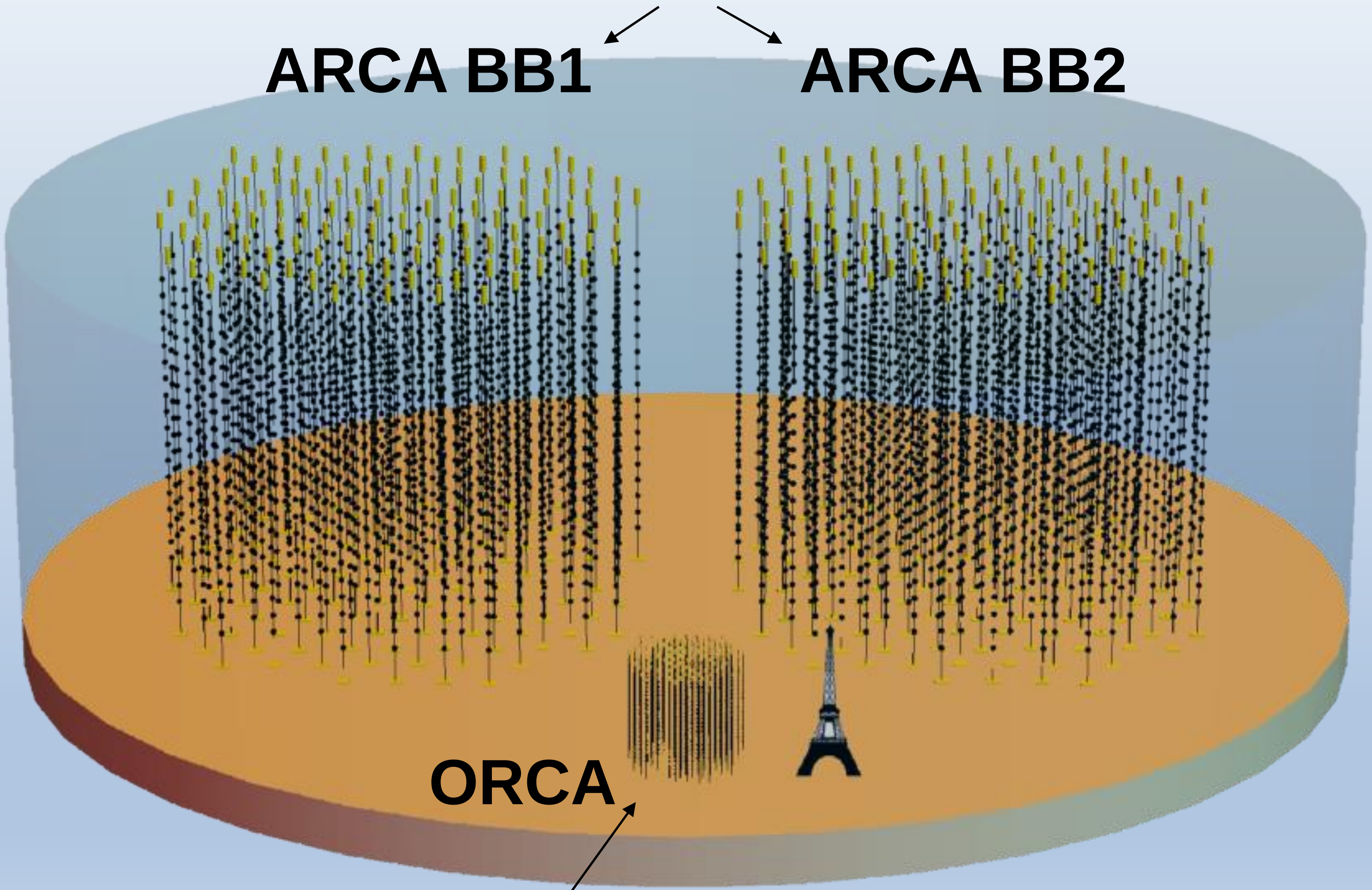
- **~7 Mt** instrumented
- **115** strings **(~60 kt > 2 × SK)**
- **18** DOMs / str **(~3 kt ~ MINOS)**
- **31** PMTs / DOM
- Total: **64k PMTs**





Two Detector Scales

36m vert. x 90m horiz. spacing TeV - PeV

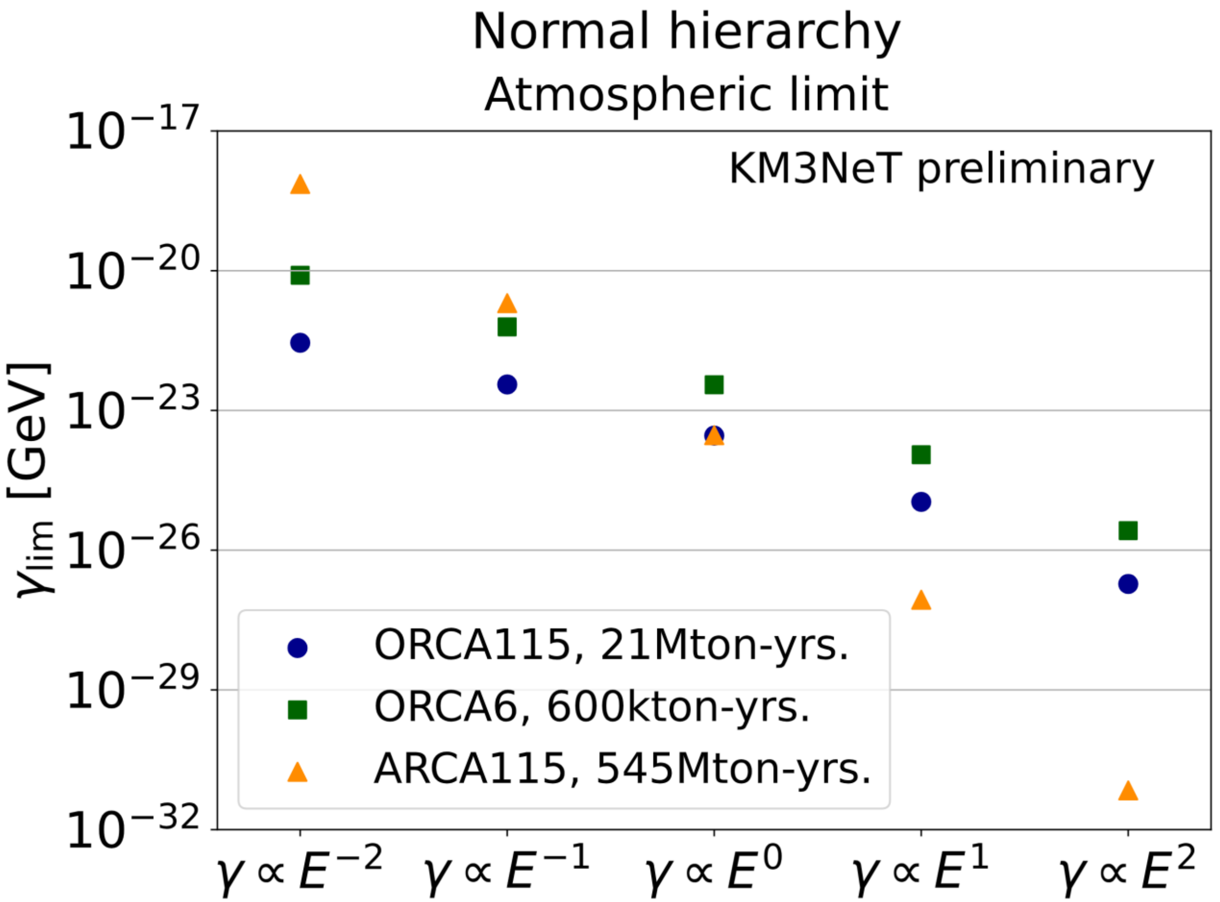


9m vert. x 20m horiz. spacing

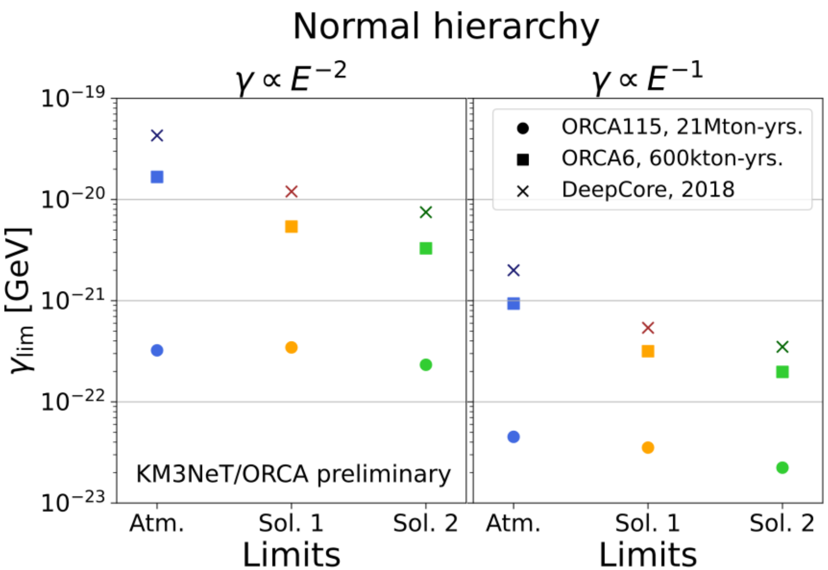
GeV - TeV

Preliminary Sensitivities

- Strong constraints on a wide range of power laws
- ORCA dominates negative powers, ARCA takes over positive ones

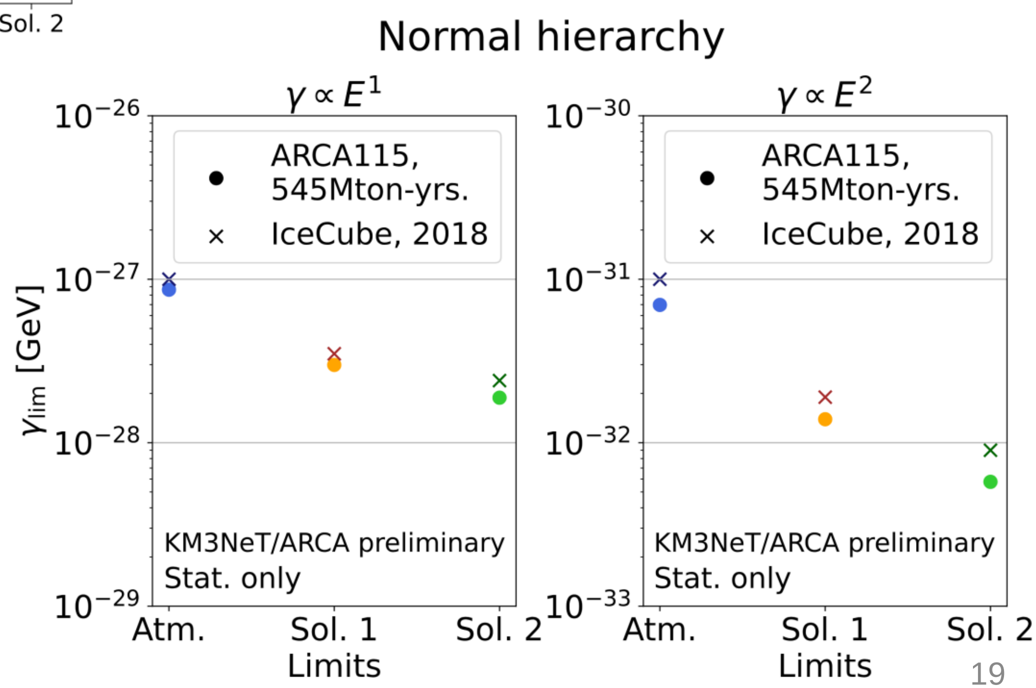


World Leading



- Potential to probe untested values of decoherence parameter
- Current ORCA data may already be stronger than IceCube for negative powers

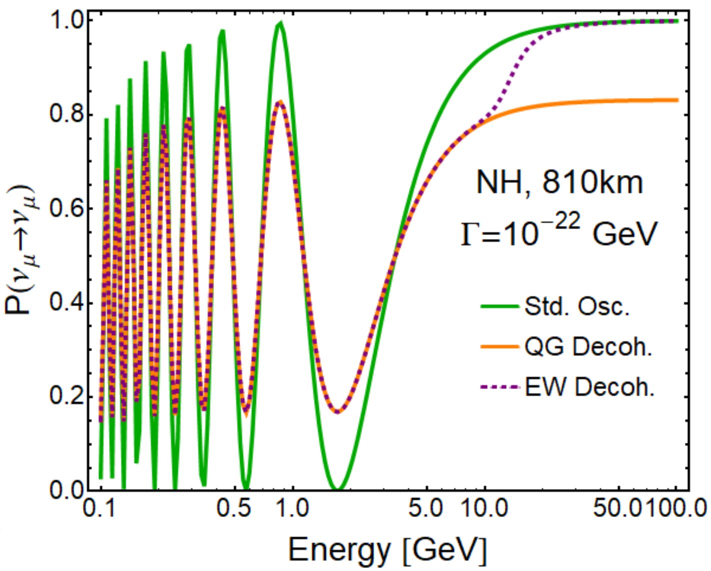
- At high energies, ARCA is competitive with current IceCube boundaries
- Caveat: no systematics yet

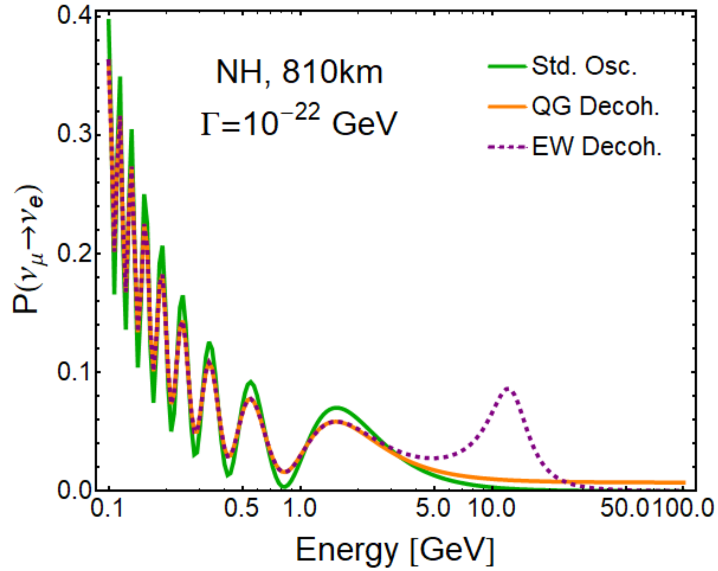


Epilogue

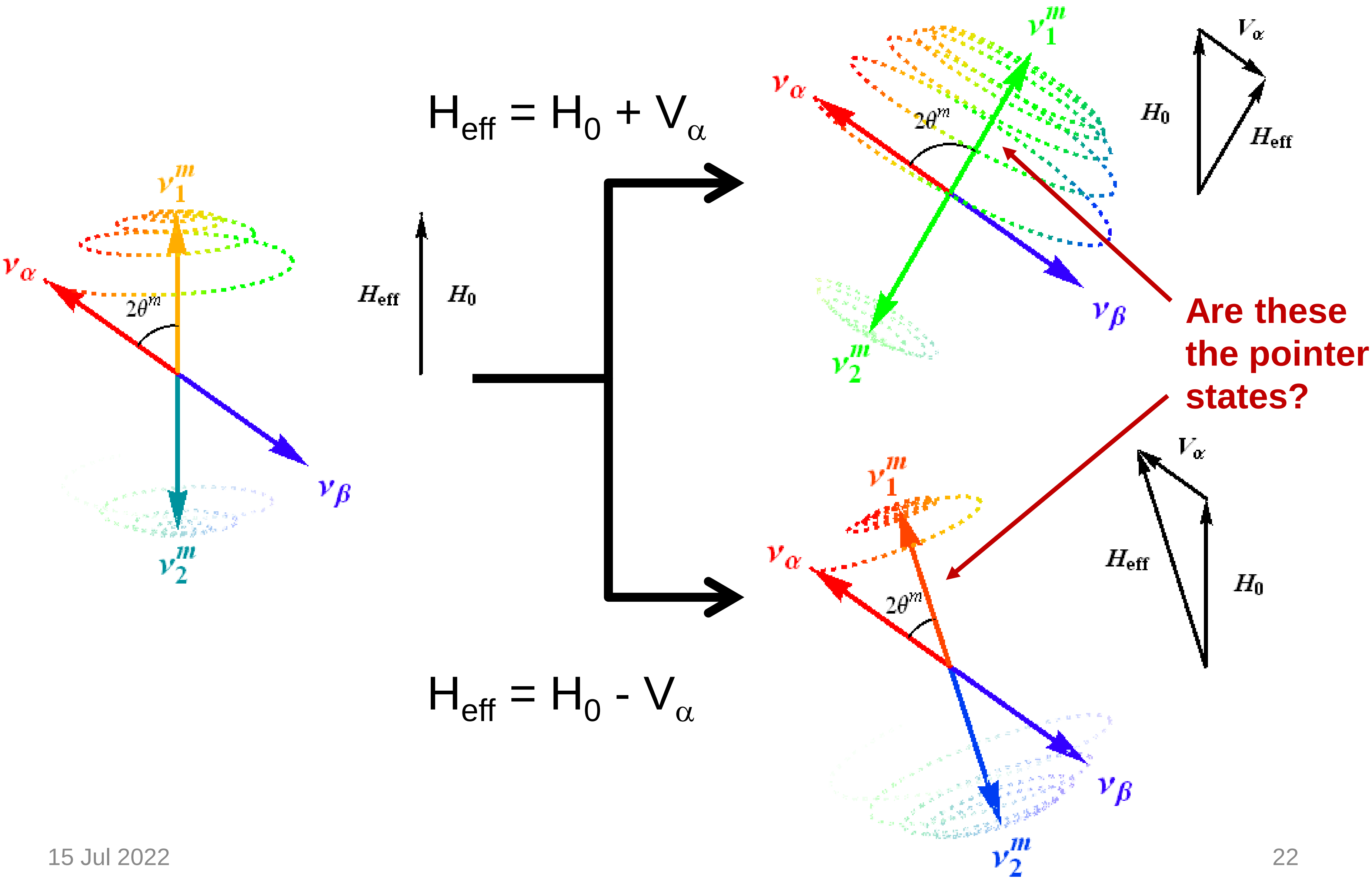
Energy Conservation

- Simple constraint equation: $\partial_t \mathrm{tr}[H\rho] = 0$
- But which H is conserved?
  - Vacuum? Decoherence is due to neutrino mass measurement (QG-like?)
  - Matter? Decoherence is due to effective neutrino energy (EW-like?)
- Most analyses assume the latter
- Carpio et al, argue this violates the Born-Markov assumptions of the Lindblad master equation [PRD 97, 115017 (2018); PRD 100, 015035 (2019)]
- Effect is small at low energies, but becomes relevant at the resonance
- Also important role from neutrino mass ordering





Matter Effects w/ Deco.



Summary

- Decoherence in neutrino oscillations may be a strong probe of quantum gravity effects
- With increasing precision, more sophisticated phenomenological treatments are now required
- KM3NeT will be able to probe never tested regions of parameter space
- Relationship with matter effects needs to be better understood, especially for atmospheric neutrinos
- For more details:
  - Master's Thesis [1]
  - Poster at Neutrino 2022 [2]

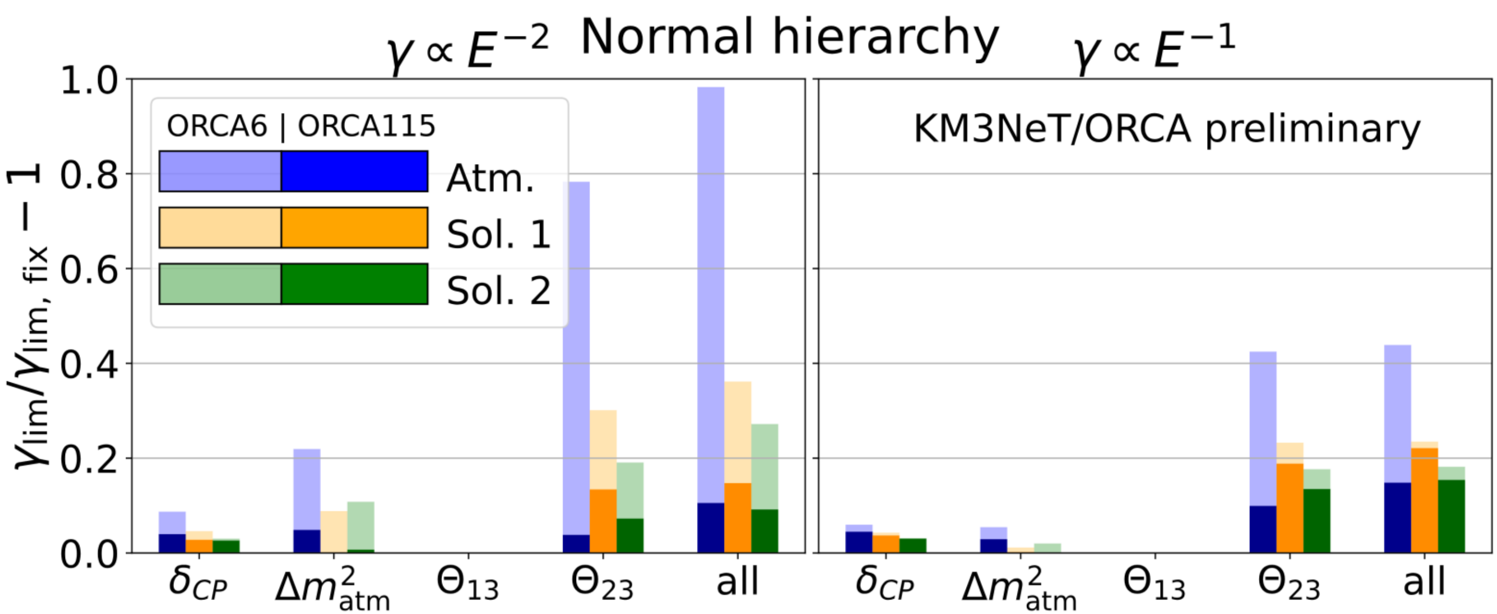
[1] https://ecap.nat.fau.de/wp-content/uploads/2022/03/KM3NeT_THES_2022_Sensitivity_Decoherence_Nadja_Lessing.pdf
[2] https://zenodo.org/record/6781033

Thank you!

Systematics Impact

Parameter	Central value (IH)	Prior
Δm^2_{atm} [eV^2]	$2.515 \cdot 10^{-3}$ ($-2.498 \cdot 10^{-3}$)	free
Δm^2_{sol} [eV^2]	$7.42 \cdot 10^{-5}$	fixed
Θ_{12} [°]	33.44	fixed
Θ_{13} [°]	8.57	0.13
Θ_{23} [°]	49.2	free
δ_{CP} [°]	149 (287)	free

Parameter	Prior
Energy slope	0.3
Energy scale	0.06
Zenith angle slope	0.02
$\nu_e/\bar{\nu}_e$	0.07
$\nu_\mu/\bar{\nu}_\mu$	0.05
$(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$	0.02
n_{showers}	free
n_{middles}	free
n_{tracks}	free



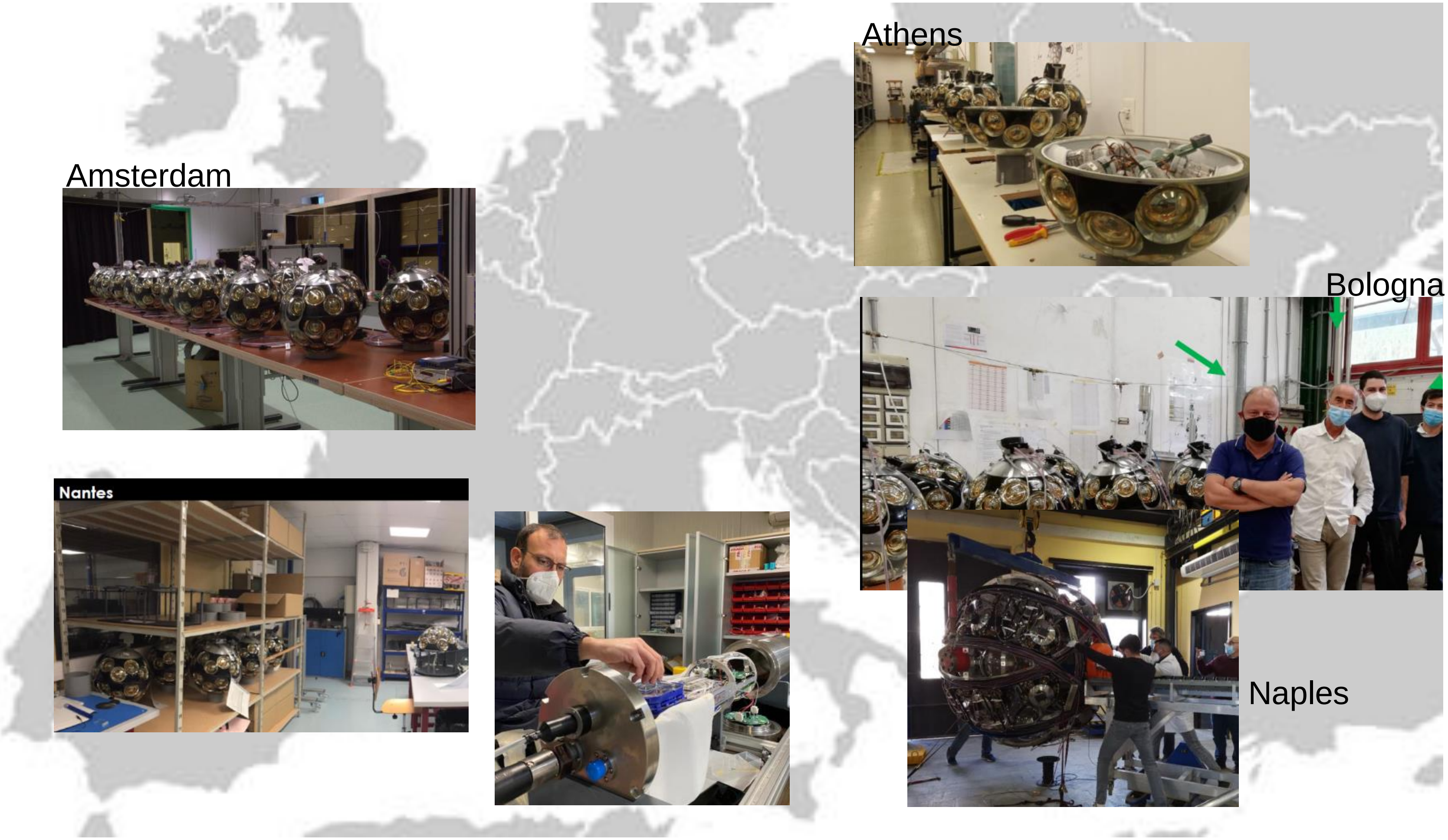
Current Limits

		$n=-2$	$n=-1$	$n=0$	$n=1$	$n=2$
Normal Ordering	**IceCube (this work)**					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$2.8\cdot10^{-18}$	$4.2\cdot10^{-21}$	$\mathbf{4.0\cdot10^{-24}}$	$\mathbf{1.0\cdot10^{-27}}$	$\mathbf{1.0\cdot10^{-31}}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$6.8\cdot10^{-19}$	$1.2\cdot10^{-21}$	$\mathbf{1.3\cdot10^{-24}}$	$\mathbf{3.5\cdot10^{-28}}$	$\mathbf{1.9\cdot10^{-32}}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$5.2\cdot10^{-19}$	$9.2\cdot10^{-22}$	$9.7\cdot10^{-25}$	$2.4\cdot10^{-28}$	$9.0\cdot10^{-33}$
	DeepCore (this work)					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$\mathbf{4.3\cdot10^{-20}}$	$2.0\cdot10^{-21}$	$8.2\cdot10^{-23}$	$3.0\cdot10^{-24}$	$1.1\cdot10^{-25}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$\mathbf{1.2\cdot10^{-20}}$	$5.4\cdot10^{-22}$	$2.1\cdot10^{-23}$	$6.6\cdot10^{-25}$	$2.0\cdot10^{-26}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$7.5\cdot10^{-21}$	$3.5\cdot10^{-22}$	$1.4\cdot10^{-23}$	$4.2\cdot10^{-25}$	$1.1\cdot10^{-26}$
Inverted Ordering	**IceCube (this work)**					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$6.8\cdot10^{-19}$	$1.2\cdot10^{-21}$	$\mathbf{1.3\cdot10^{-24}}$	$\mathbf{3.5\cdot10^{-28}}$	$\mathbf{1.9\cdot10^{-32}}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$5.2\cdot10^{-19}$	$9.2\cdot10^{-22}$	$9.8\cdot10^{-25}$	$2.4\cdot10^{-28}$	$9.0\cdot10^{-33}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$2.8\cdot10^{-18}$	$4.2\cdot10^{-21}$	$\mathbf{4.1\cdot10^{-24}}$	$\mathbf{1.0\cdot10^{-27}}$	$\mathbf{1.0\cdot10^{-31}}$
	DeepCore (this work)					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$\mathbf{1.4\cdot10^{-20}}$	$5.8\cdot10^{-22}$	$2.2\cdot10^{-23}$	$7.5\cdot10^{-25}$	$2.3\cdot10^{-26}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$8.3\cdot10^{-21}$	$3.6\cdot10^{-22}$	$1.4\cdot10^{-23}$	$4.7\cdot10^{-25}$	$1.3\cdot10^{-26}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$\mathbf{5.0\cdot10^{-20}}$	$2.3\cdot10^{-21}$	$9.4\cdot10^{-23}$	$3.3\cdot10^{-24}$	$1.2\cdot10^{-25}$
	Previous Bounds					
	SK (two families) [7]		$2.4\cdot10^{-21}$	$4.2\cdot10^{-23}$		$1.1\cdot10^{-27}$
	MINOS (γ_{31},γ_{32}) [32]		$\mathbf{2.5\cdot10^{-22}}$	$1.1\cdot10^{-22}$	$2\cdot10^{-24}$	
	KamLAND (γ_{21}) [15]		$\mathbf{3.7\cdot10^{-24}}$	$6.8\cdot10^{-22}$	$1.5\cdot10^{-19}$	

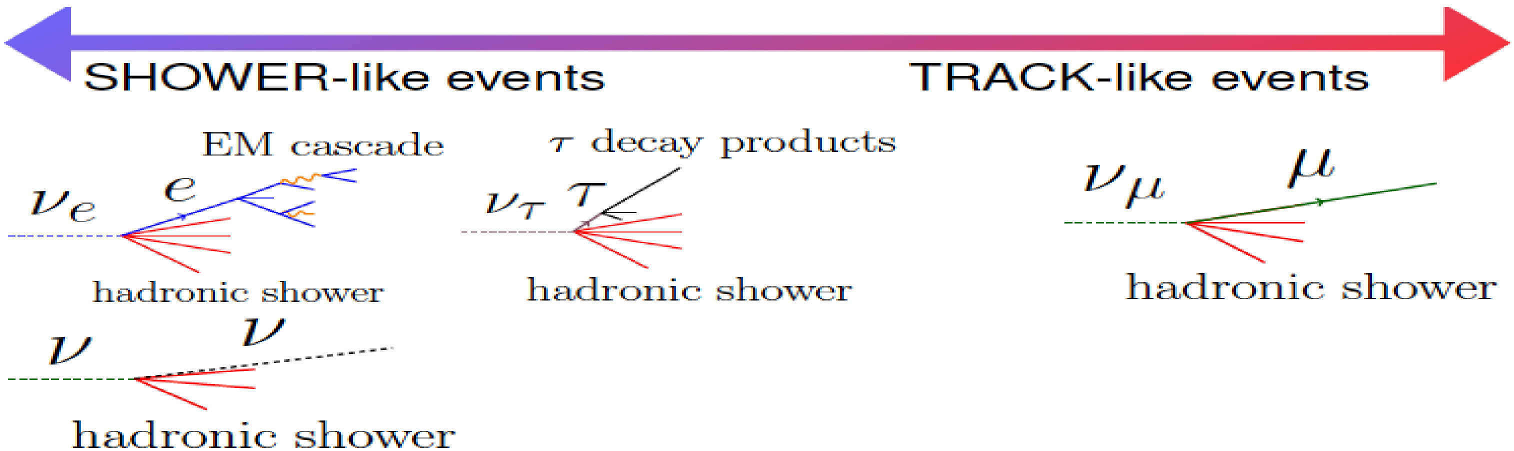
Coloma et al: EPJC 78, 614 (2018)

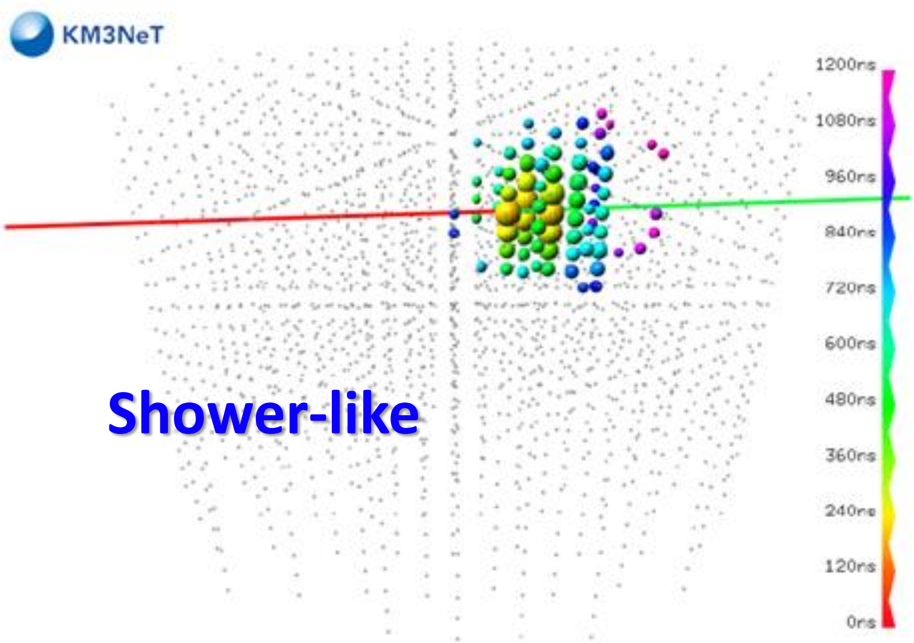
Production ongoing around Europe

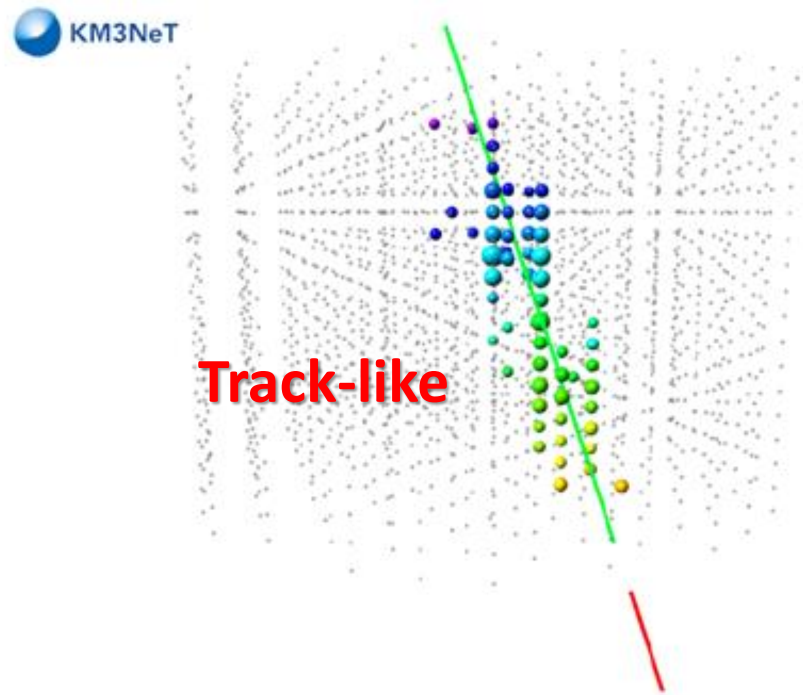
- **ORCA: 10 lines operational since July 2022**
- **ARCA: 19 lines operational since June 2022**



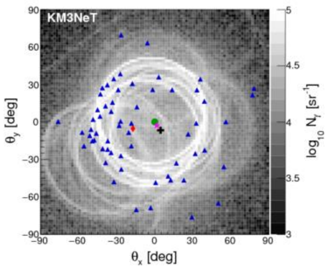
Measuring Neutrinos





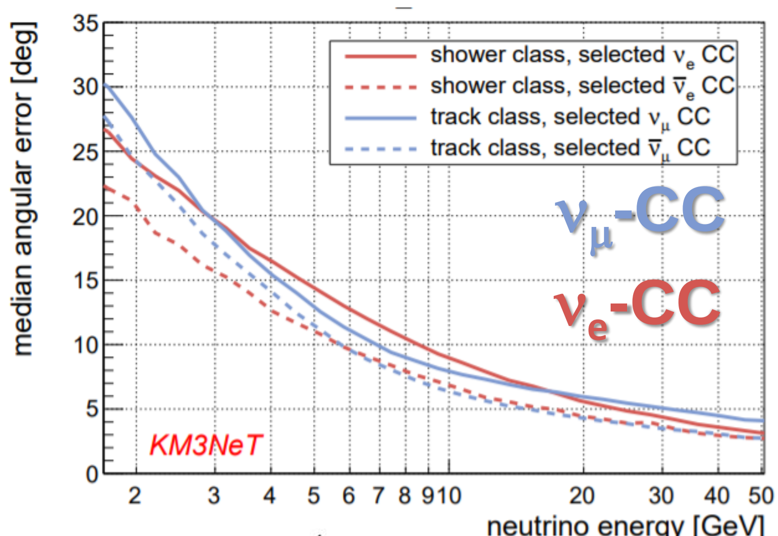


Reco Performance

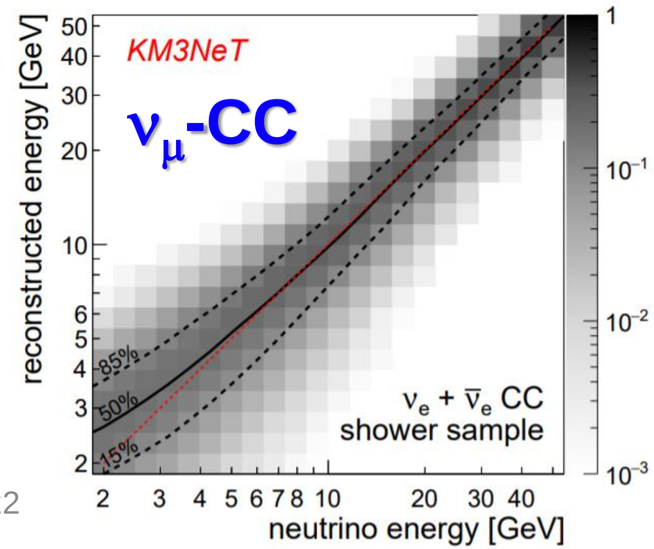


- Energy resolution: ~25% (Close to limit arXiv:1612.05621)
- Angular resolution: Better than 15 degrees at relevant energies

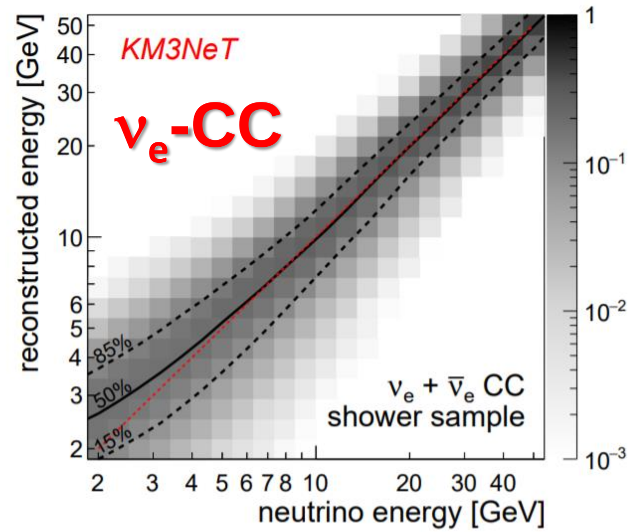
θ Res.



E Res.



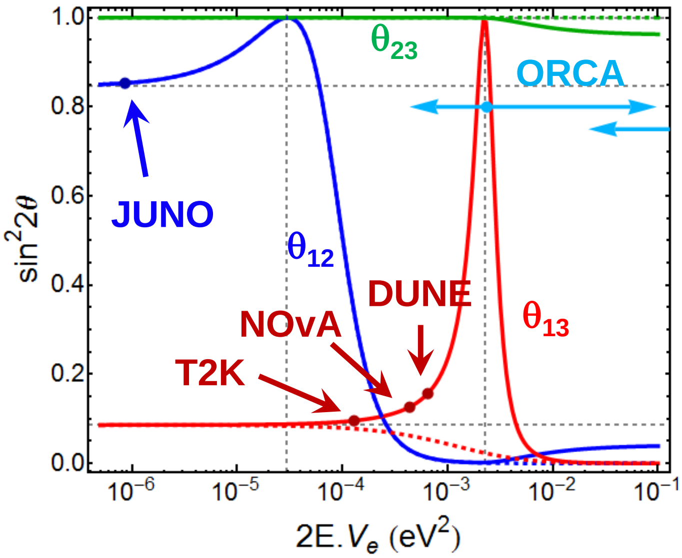
E Res.



3ν Formulas

$$\mathcal{P}_{\mu\mu}^{(3\nu)} = 1 - 2\sum_{j>k}\{|\tilde{U}_{\mu j}|^2|\tilde{U}_{\mu k}|^2(1 - e^{-\Gamma_{jk}L}\cos\tilde{\Delta}_{jk}L)\},$$

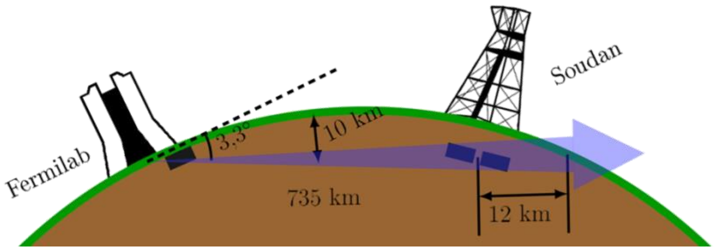
$$\begin{aligned}\mathcal{P}_{\mu\mu}^{(3\nu)} \approx 1 &- \frac{1}{2}\sin^2\tilde{\theta}_{13}\sin^2 2\theta_{23}[1 - e^{-\Gamma_{21}L}\cos 2\tilde{\phi}_-] \\ &- \frac{1}{2}\cos^2\tilde{\theta}_{13}\sin^2 2\theta_{23}[1 - e^{-\Gamma_{32}L}\cos 2\tilde{\phi}_+] \\ &- \frac{1}{2}\sin^2 2\tilde{\theta}_{13}\sin^4\theta_{23}[1 - e^{-\Gamma_{31}L}\cos 2\tilde{\phi}_0],\end{aligned}$$



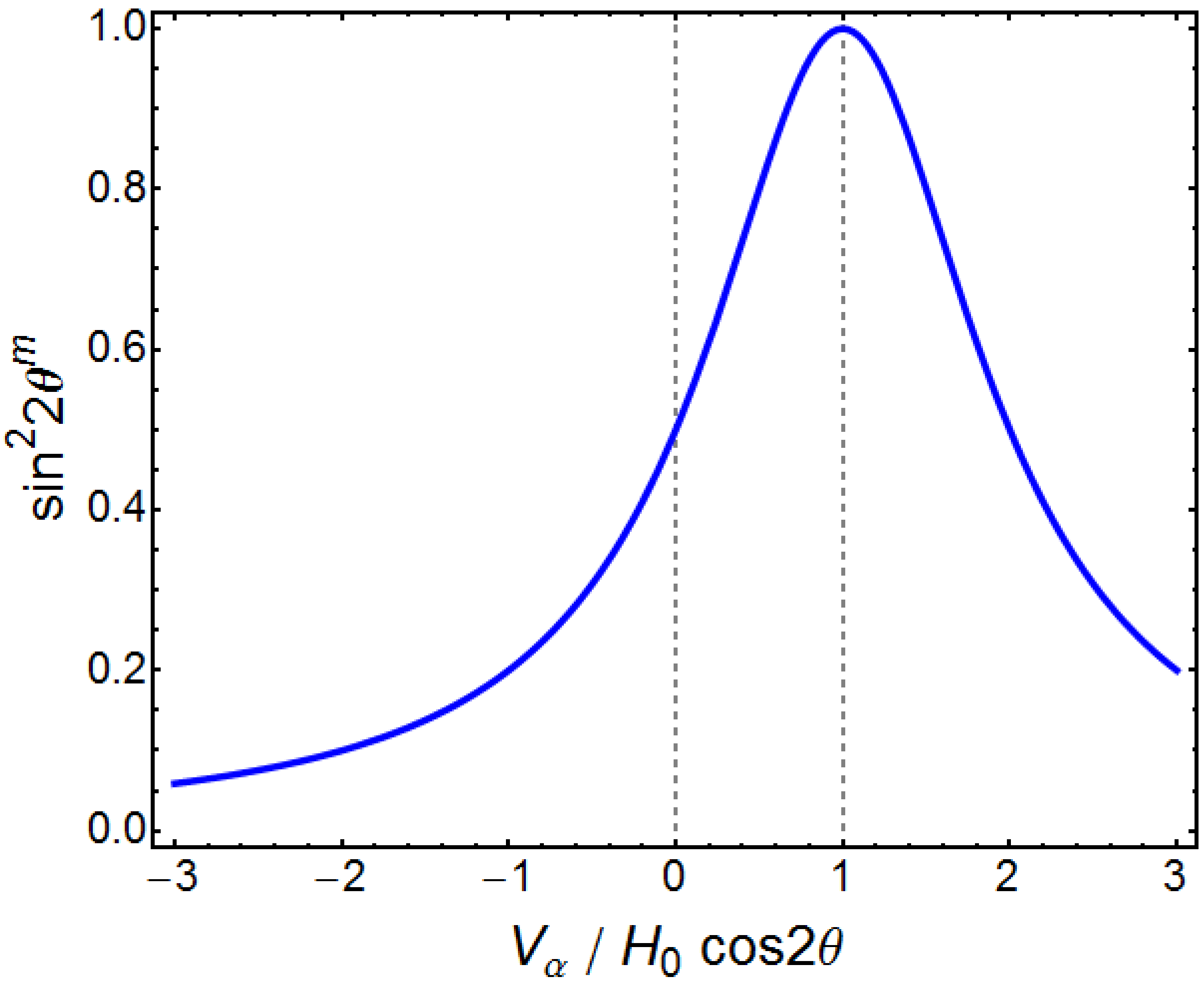
where

$$\tilde{\phi}_0 \equiv \phi\sqrt{(\cos 2\theta_{13} - \hat{A})^2 + \sin^2 2\theta_{13}},$$

$$\tilde{\phi}_\pm \equiv \frac{1}{2}[(1+\hat{A})\phi \pm \tilde{\phi}_0],$$

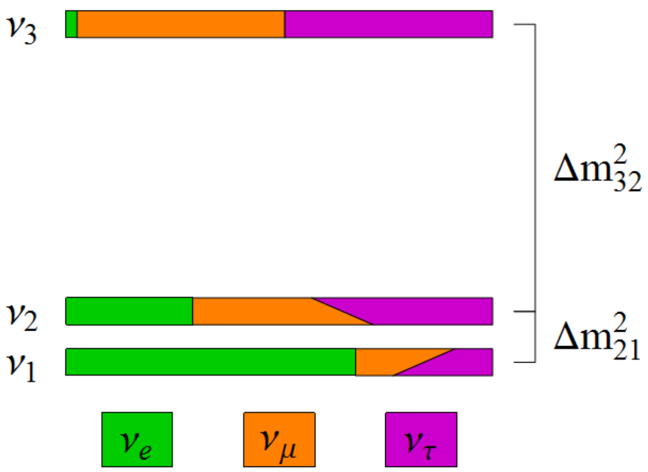


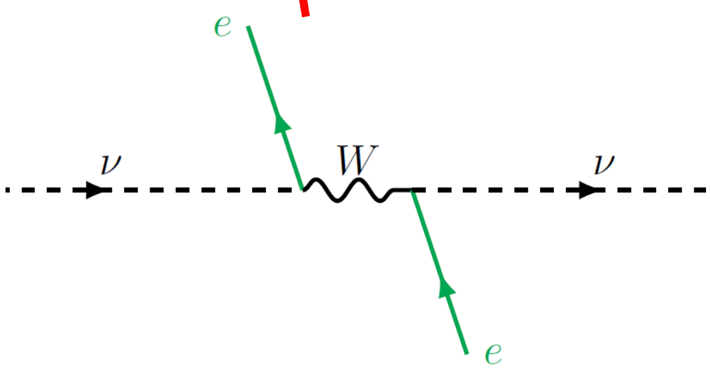
Matter Effects



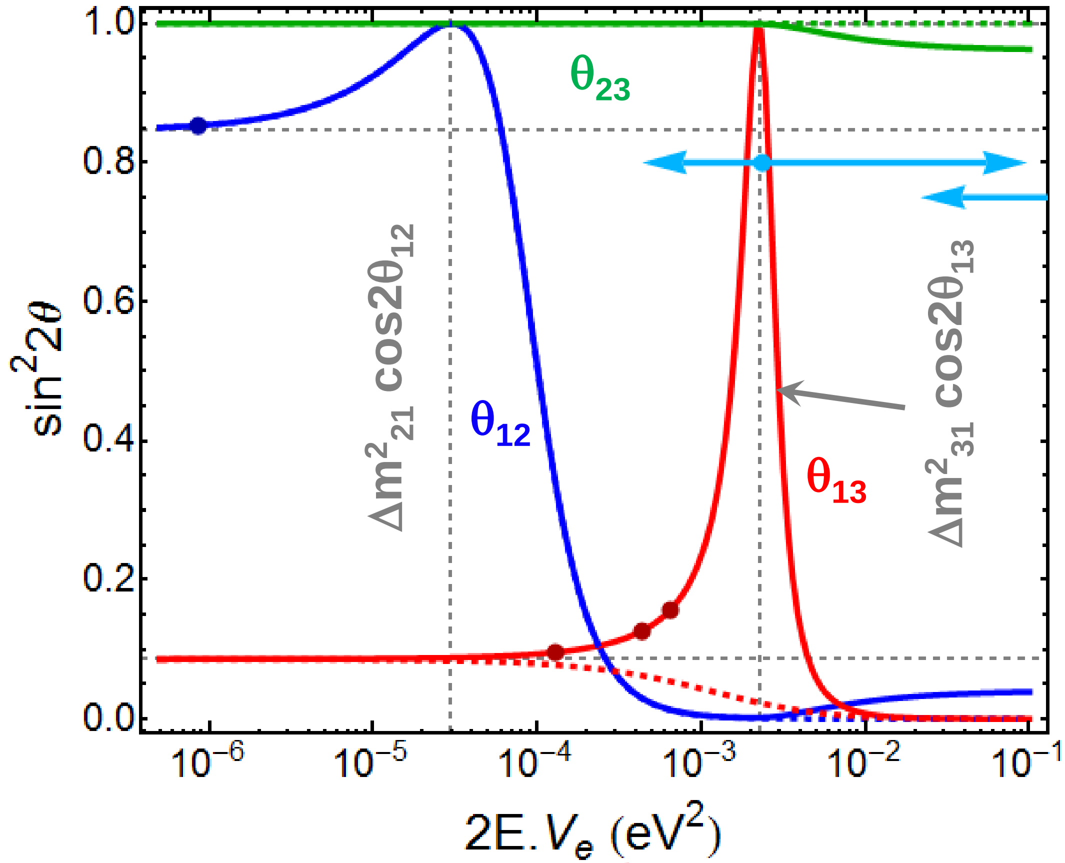
Matter Effects

$$\overbrace{H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger}^{\mathbf{H_0}} + \overbrace{V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}^{\mathbf{V}}$$



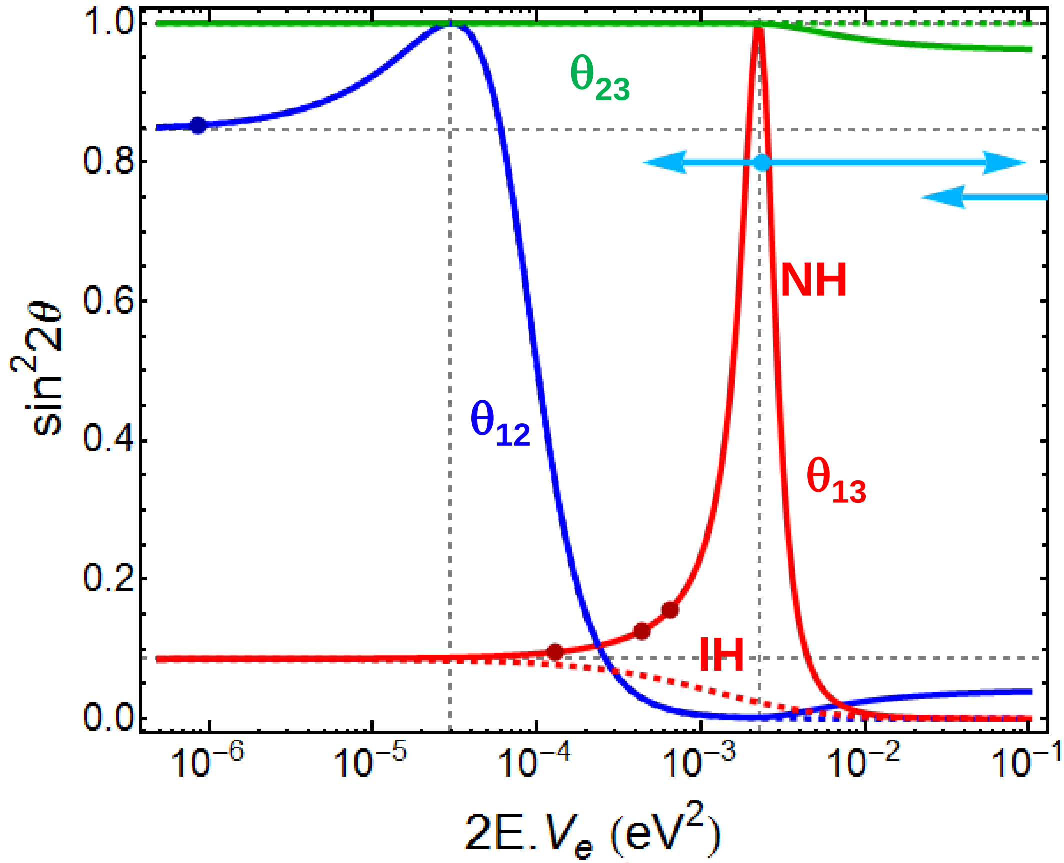


Resonances



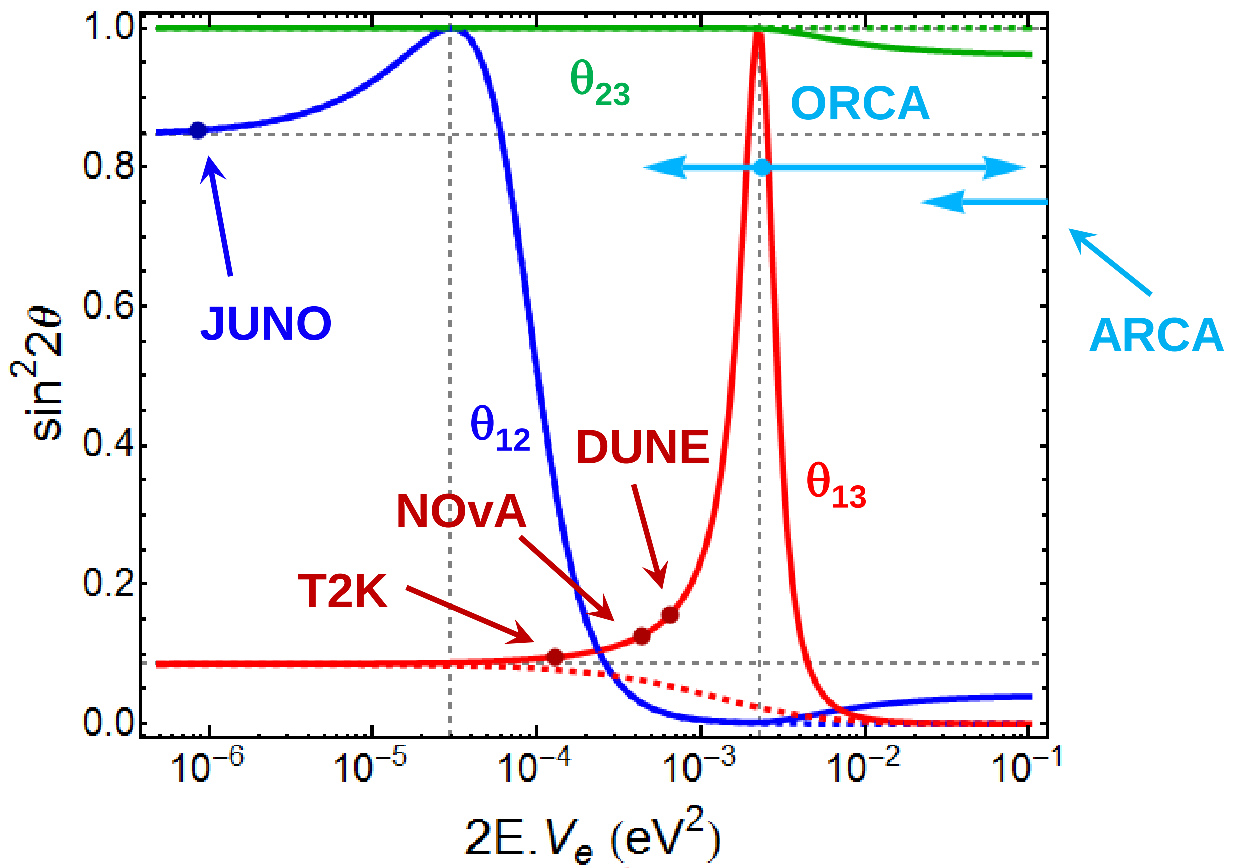
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Resonances



$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

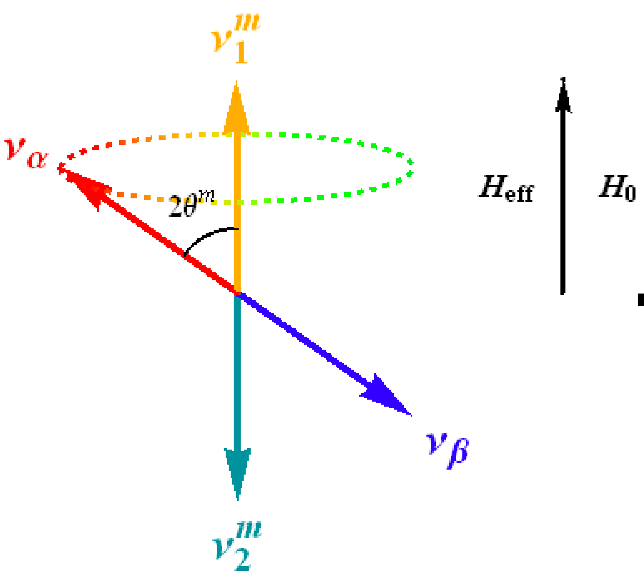
Resonances

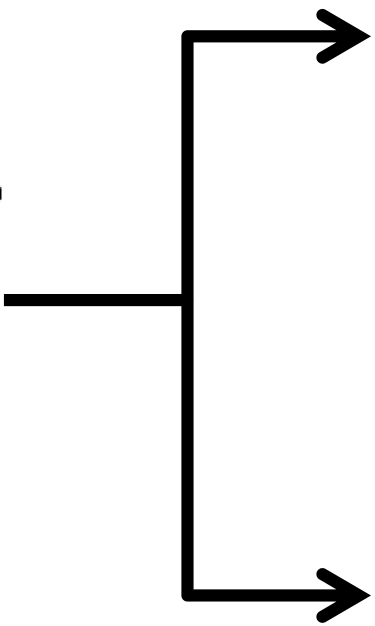


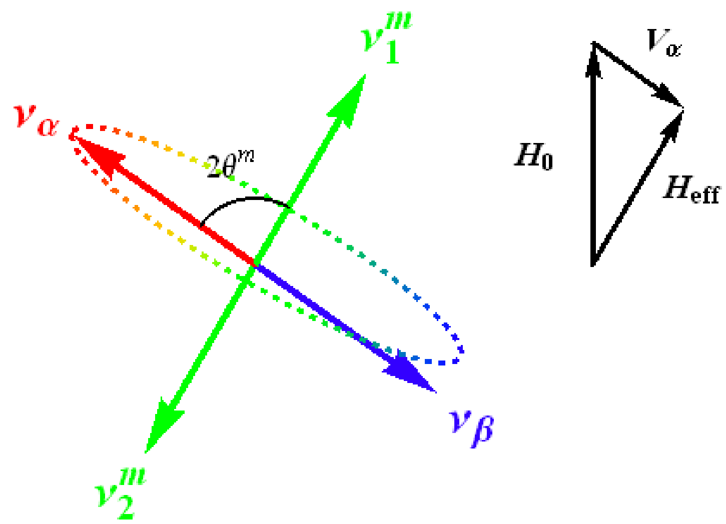
$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

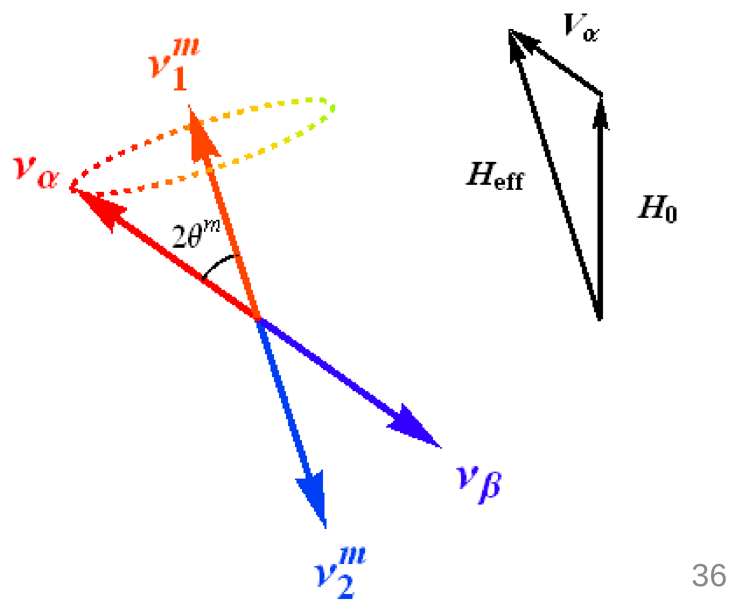
Matter Effects w/o Deco.

$$H_{eff} = H_0 + V_\alpha$$









$$H_{eff} = H_0 - V_\alpha$$

Resonance Formulas

$$\sin^2 2\theta_{13}^m \equiv \sin^2 2\theta_{13} \left(\frac{\Delta m_{31}^2}{\Delta^m m^2} \right)^2$$

Depends on
sign of Δm^2_{31} (NMO)

$$\Delta^m m^2 \equiv \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - 2 E_\nu A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}\,,$$

$$E_{\rm res} \equiv \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2}\, G_F\, N_e} \simeq 7\,\mathrm{GeV} \left(\frac{4.5\,\mathrm{g/cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3}\,\mathrm{eV}^2} \right) \cos 2\theta_{13}\,.$$