Searches for Exotic Oscillations in Atmospheric Neutrinos

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U.S. DEPARTMENT OF ENERGY | Office of Science — NSF — Duke UNIVERSITY — SUPER SK

Super-Kamiokande

- Water Cherenkov detector
- 22.5 kton fiducial mass
- ~1 km underground
- 40% photo-coverage of inner detector
- Active veto outer detector

Atmospheric Neutrinos: wide range of energies and distances

Fully Contained — Sub-GeV — Multi-GeV — Partially Contained — Up-going μ

10 km to 13,000 km

100's of MeV — Few GeV — 1 TeV+

FC Sub-GeV, FC Multi-GeV, PC Stop, PC Through
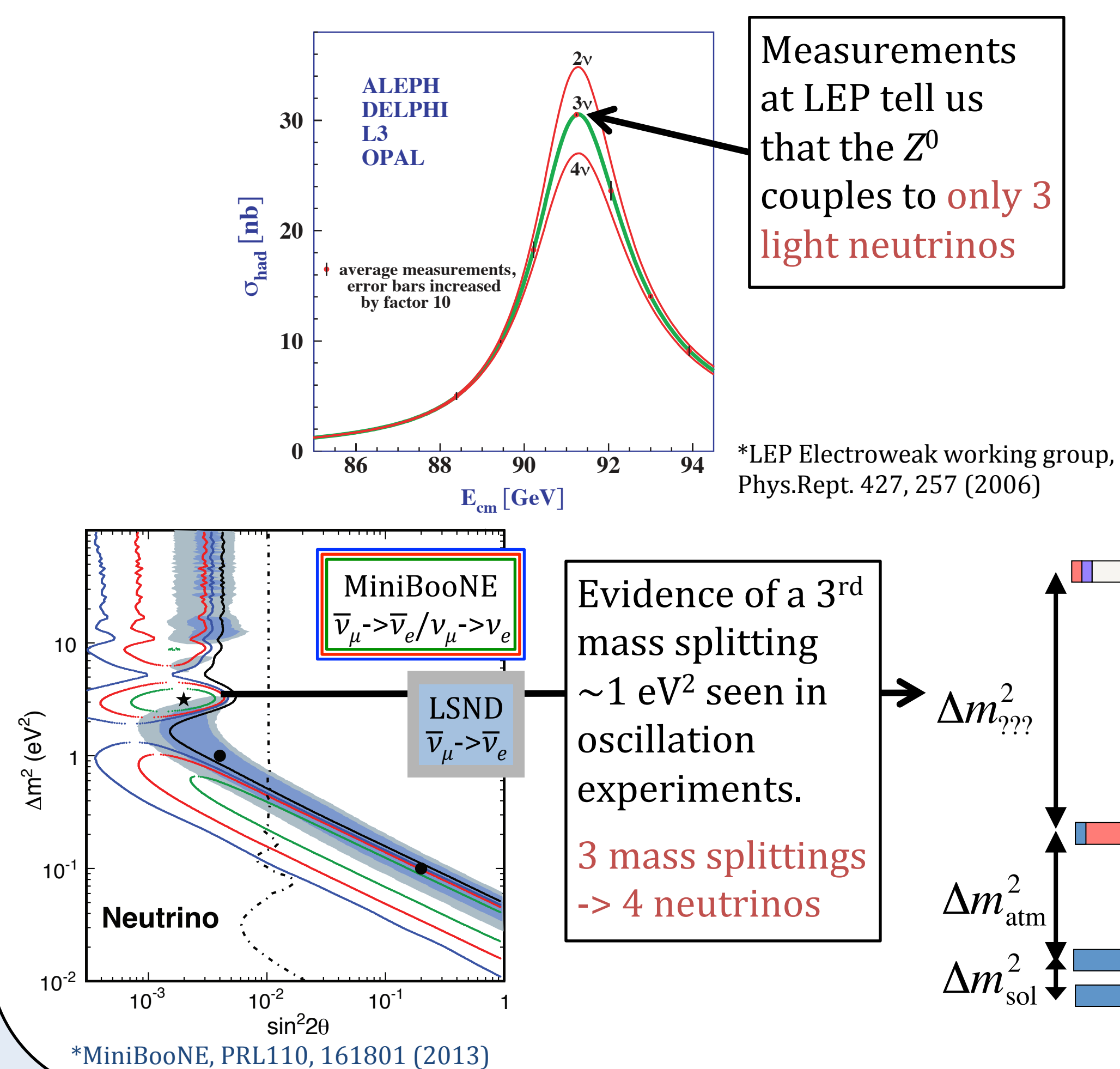Up-μ Stop, Up-μ Through, Up-μ Showering
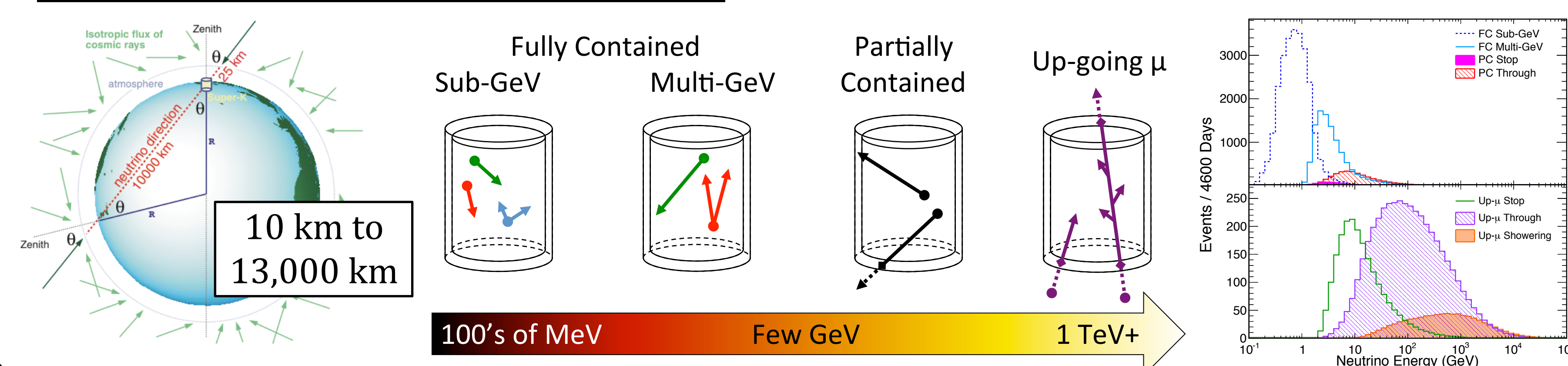
Systematic Errors

- Shared with official oscillation analysis and between Sterile and Lorentz Violation analyses
- Covers atmospheric flux, cross-sections, and detector effects
- External constraints with uncertainties from T2K:
  $|\Delta m^2_{32}| = (2.51\pm0.10)\times10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.514\pm0.055$

*T2K Collab., PRL112, 181801 (2014)

Sterile Neutrinos

Oscillations, No Interactions

Measurements at LEP tell us that the Z^0 couples to only 3 light neutrinos

ALEPH DELPHI L3 OPAL

average measurements, error bars increased by factor 10

*LEP Electroweak working group, Phys.Rept. 427, 257 (2006)

MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e / \nu_\mu \to \nu_e$

LSND $\bar{\nu}_\mu \to \bar{\nu}_e$

Evidence of a 3rd mass splitting ~1 eV^2 seen in oscillation experiments.

3 mass splittings -> 4 neutrinos

ν_4, $\Delta m^2_{???}$, ν_3, Δm^2_{atm}, ν_2, Δm^2_{sol}, ν_1

Neutrino

*MiniBooNE, PRL110, 161801 (2013)

Our 3+1 Model: Extendable to 3+N

Assumptions

- No ν_e-sterile oscillations ($|U_{e4}|^2 \to 0$)
- Δm^2 is large, $\sin^2(\Delta m^2 L/4E) \to 0.5$
- Sterile phases neglected

$$P_{\mu\mu} = (1 - |U_{\mu4}|^2)^2 \tilde{P}_{\mu\mu} + |U_{\mu4}|^4$$

Hydrogen-Earth Approx.
- $\tilde{P}_{\mu\mu}$ from standard 3ν osc.
- Includes normal ν_e appearance
- No sterile matter effects

No ν_e Approximation
- $\tilde{P}_{\mu\mu}$ from 2ν osc. with sterile matter effects
- $\tilde{P}_{\mu\mu}$ depends on: $|U_{\tau4}|^2$, $|U_{\mu4}|^2$, θ_{23}, Δm^2_{32}
- No ν_e appearance

*M. Maltoni and T. Schwetz, PRD76, 093005 (2007).

Signatures: Hydrogen-Earth

Multi-GeV μ-like

- Data
- Standard Osc.
- H-Earth Example

- **Extra disappearance** in all μ-like samples, particularly away from **standard oscillations**.
- Unbiased estimate of $|U_{\mu4}|^2$
- Use only FC, PC bins ➜ $\Delta m^2 > 10^{-2}$ eV^2

Signatures: No ν_e

Stopping Up-μ

- Data
- No ν_e Example
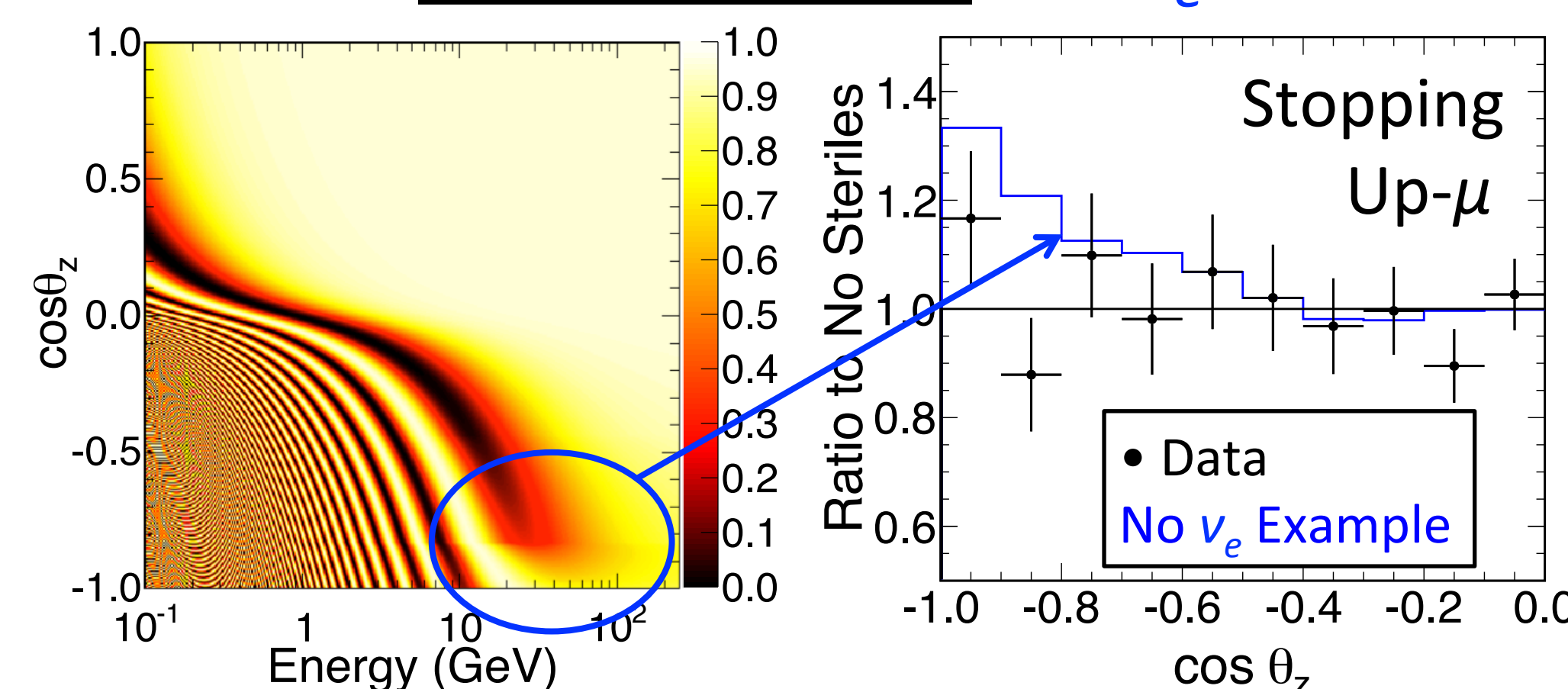
- **Distortion** in most upward going parts of stopping Up-μ and though-going PC stopping
- Biased estimate of $|U_{\mu4}|^2$
- Up-μ bins important for sterile matter effects ➜ $\Delta m^2 > 0.8$ eV^2

Results: Hydrogen-Earth $|U_{\mu4}|^2$

Kopp et al. Global Fit to ν_e appearance and disappearance

MiniBooNE+SciBooNE

SK

99% C.L.
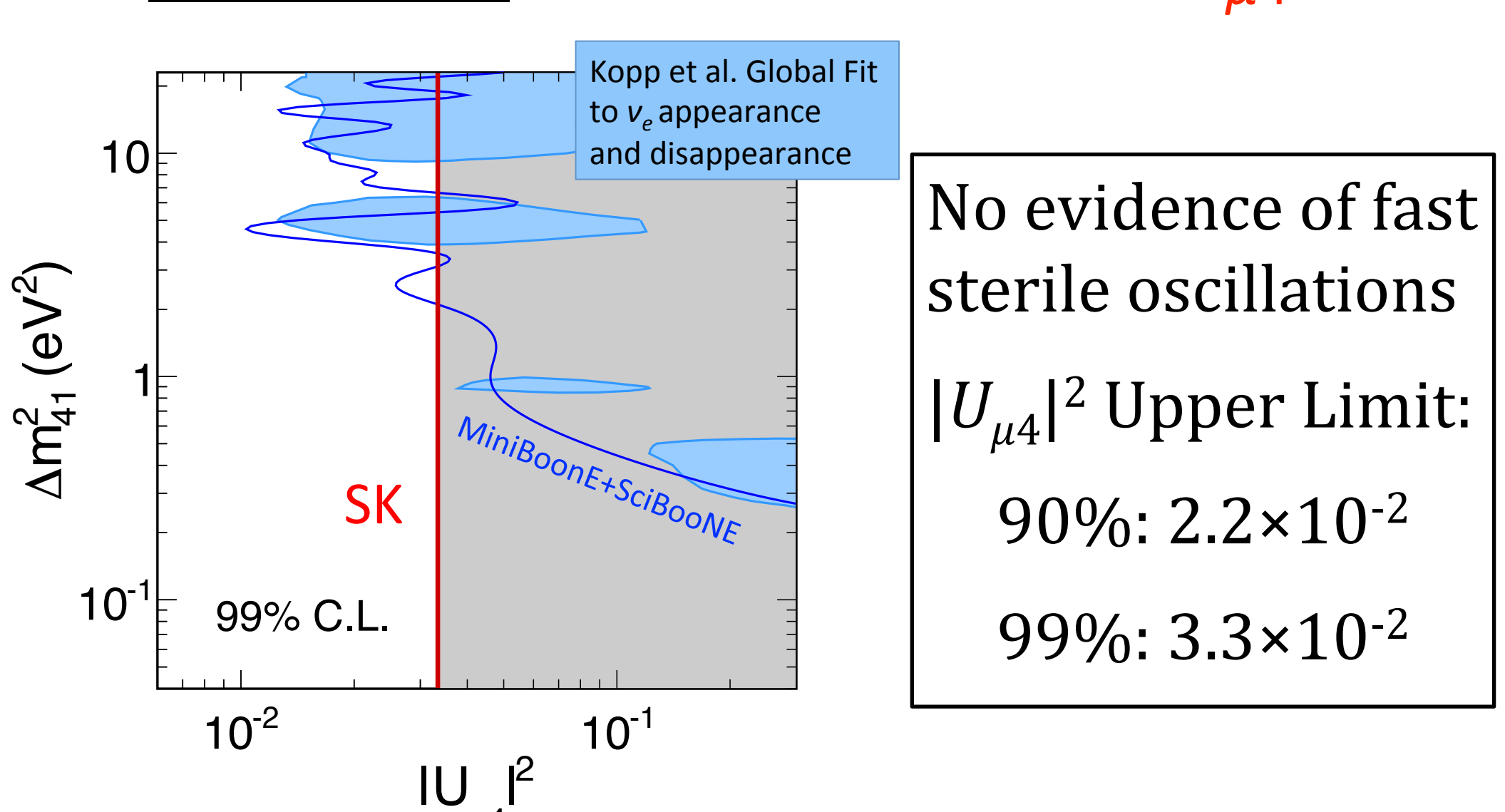
No evidence of fast sterile oscillations

$|U_{\mu4}|^2$ Upper Limit:
90%: 2.2×10^{-2}
99%: 3.3×10^{-2}

*MiniBooNE and SciBooNE Collaborations, PRD86, 5, 052009 (2012)
*Kopp, Machado, Maltoni, Schwetz, JHEP 5, 50 (2013)

Results: No ν_e $|U_{\tau4}|^2$, $|U_{\mu4}|^2$
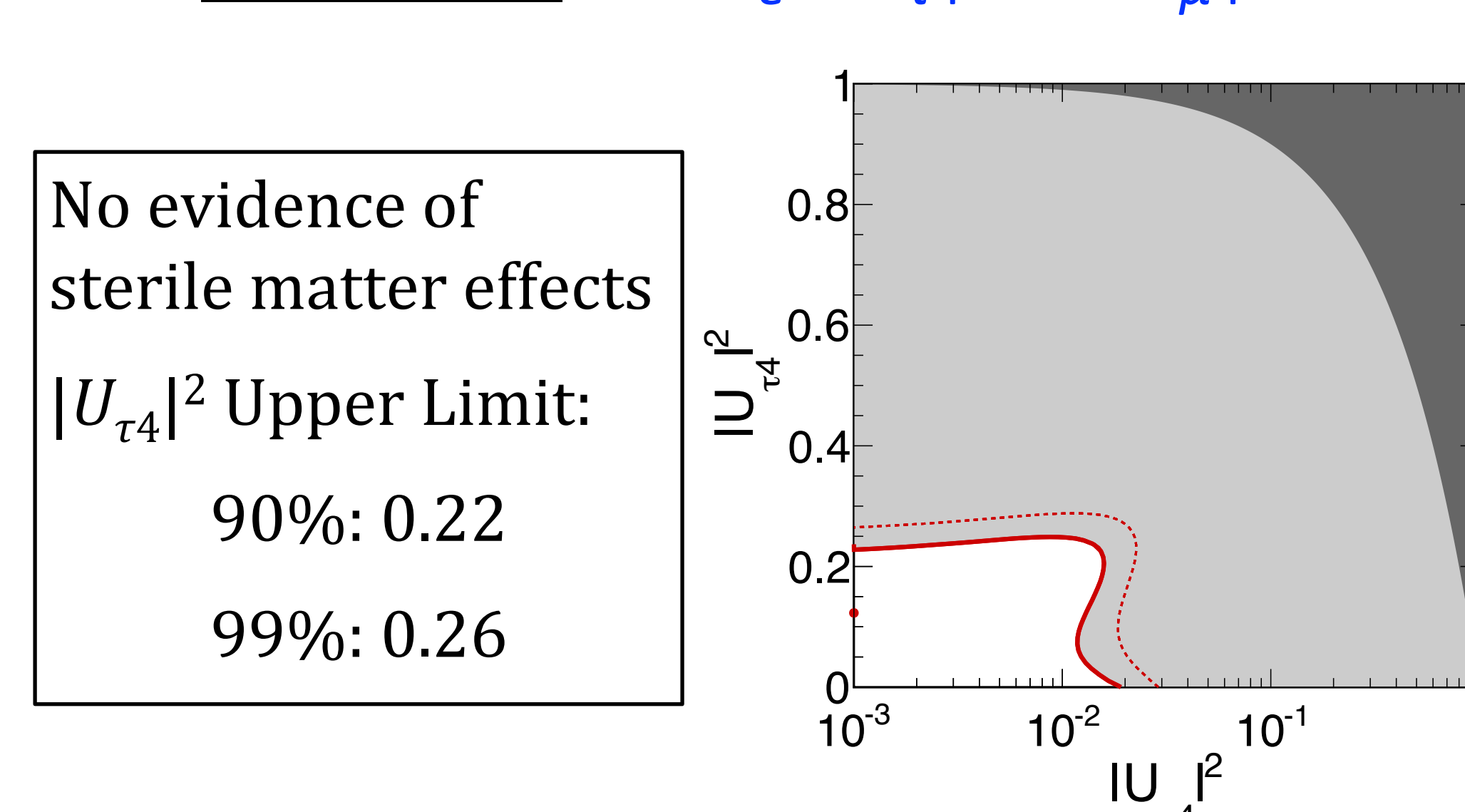
No evidence of sterile matter effects

$|U_{\tau4}|^2$ Upper Limit:
90%: 0.22
99%: 0.26

Lorentz Violation

Standard Model Extension

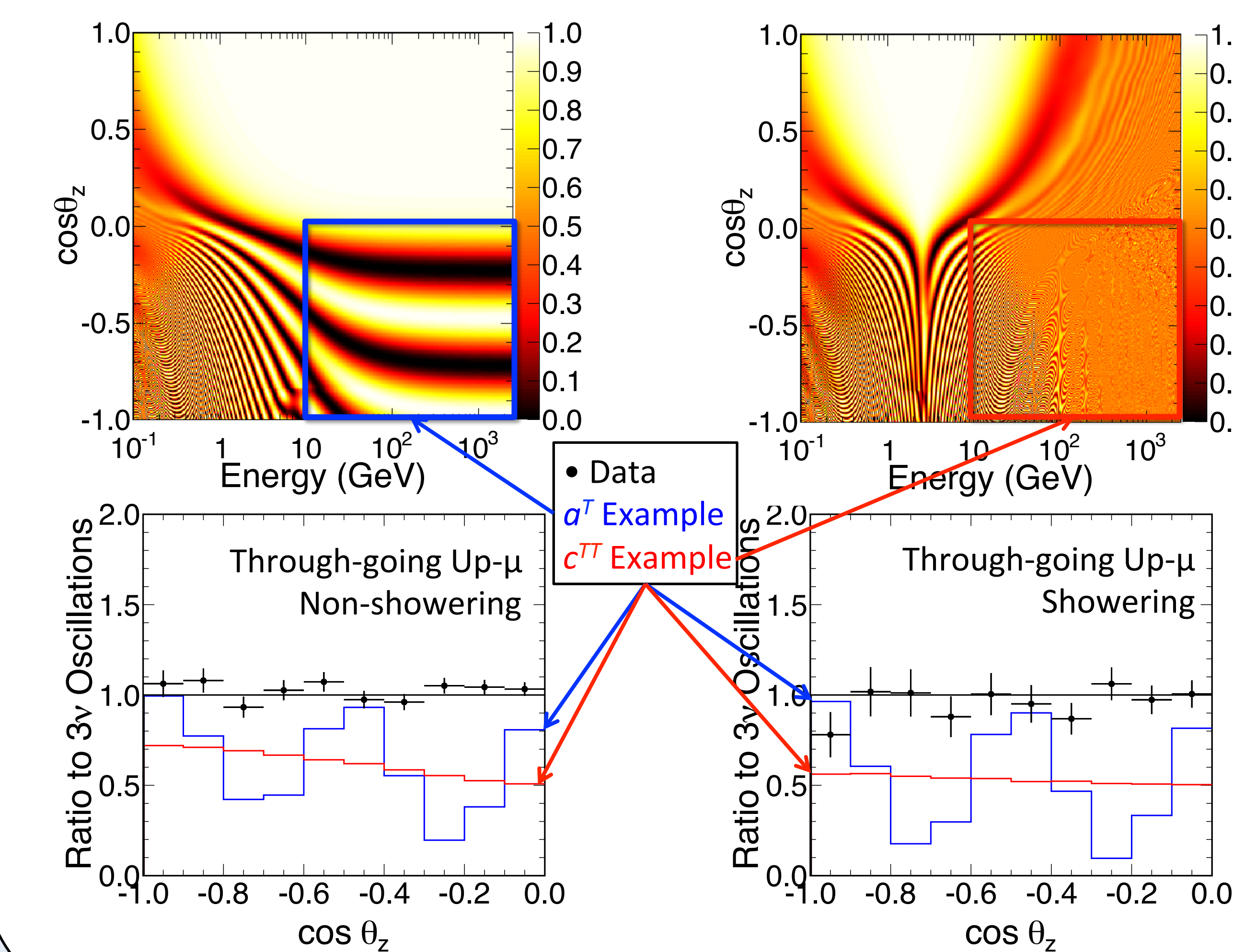$$H = U\Delta U^\dagger + V_e + H_{LV}$$

Vacuum Osc. — Matter Effects

$$H_{LV} = \pm \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ a^T_{e\mu} & 0 & a^T_{\mu\tau} \\ a^T_{e\tau} & a^T_{\mu\tau} & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ c^{TT}_{e\mu} & 0 & c^{TT}_{\mu\tau} \\ c^{TT}_{e\tau} & c^{TT}_{\mu\tau} & 0 \end{pmatrix}$$

- All the properties of the Standard Model & General Relativity
- Adds all general Lorentz- and CPT-violating terms
- T, TT – isotropic parameters

- Often, H_{LV} treated as a perturbation
- **SK cannot treat as perturbation** – L and E are too large
- Instead, we diagonalize the full Hamiltonian

*D. Colladay, V.A. Kostelecky, PRD55, 6760 (1997)   *ibid., PRD58, 116002 (1998)
*V.A. Kostelecky, PRD69, 105009 (2004)   *G. Amelino-Camelia et al., AIP Conf.Proc. 758, 30 (2005)
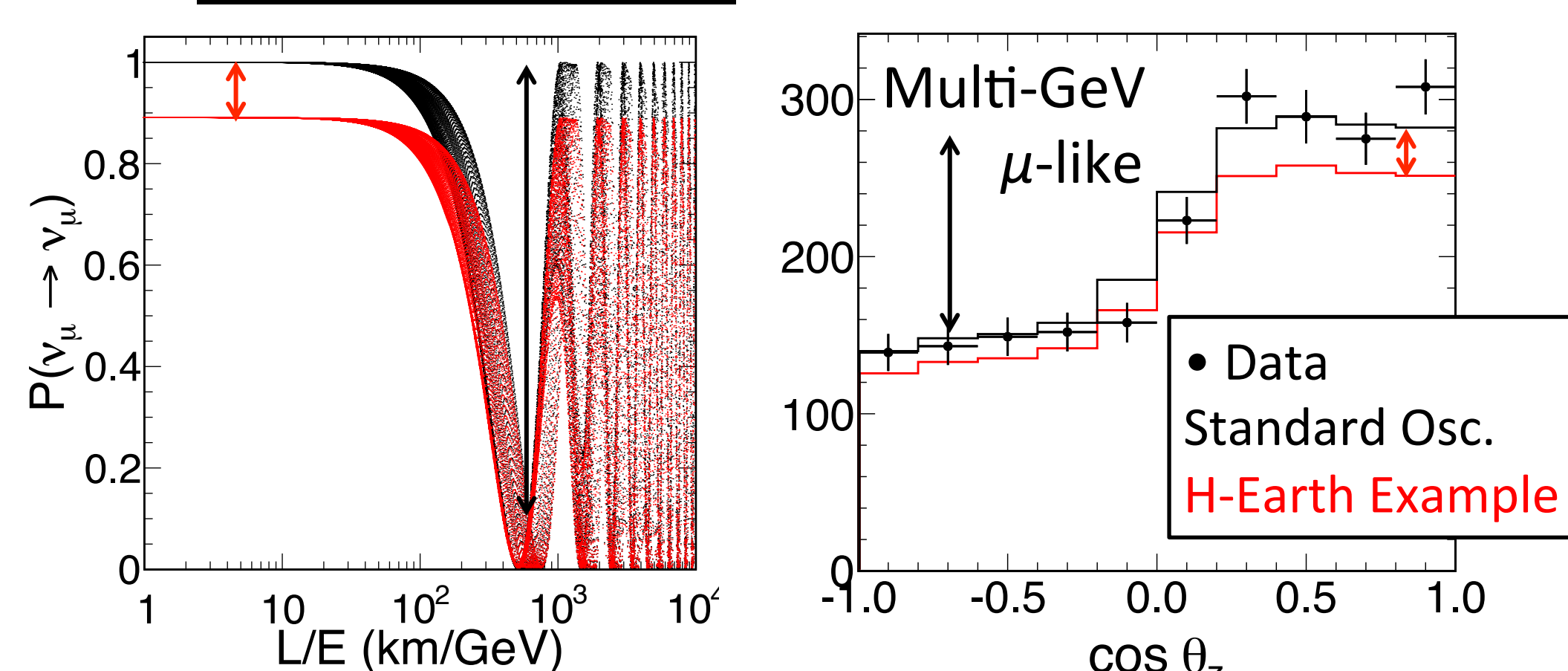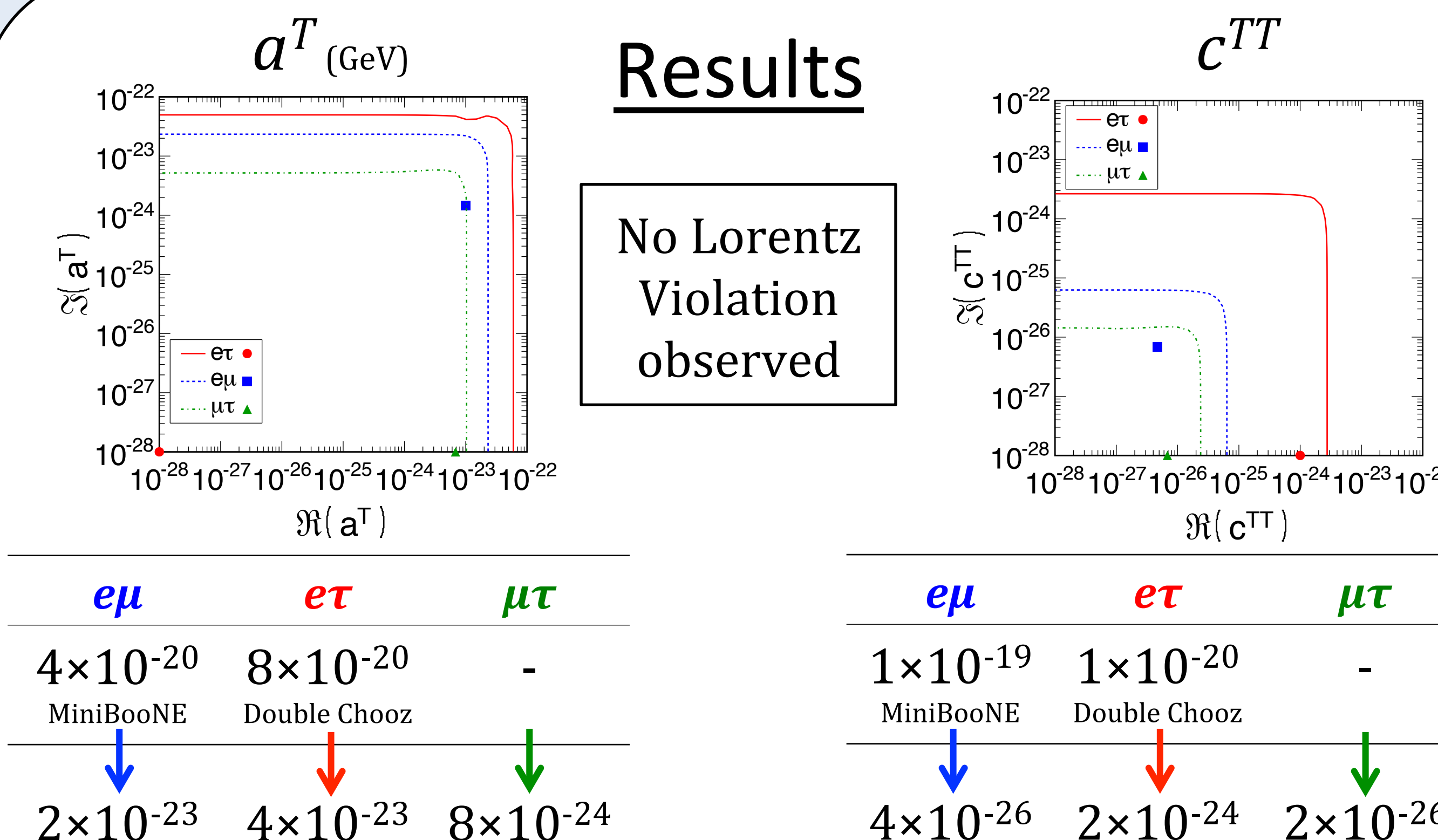
Signatures

- Data
- a^T Example
- c^{TT} Example

Through-going Up-μ Non-showering

Through-going Up-μ Showering

Results

a^T (GeV) — c^{TT}

eτ, eμ, μτ

No Lorentz Violation observed

	$e\mu$	$e\tau$	$\mu\tau$
	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-
	2×10^{-23}	4×10^{-23}	8×10^{-24}

	$e\mu$	$e\tau$	$\mu\tau$
	1×10^{-19} MiniBooNE	1×10^{-20} Double Chooz	-
	4×10^{-26}	2×10^{-24}	2×10^{-26}