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Direct comparison of sterile neutrino constraints from cosmological data, ν_e disappearance data and $\nu_\mu \rightarrow \nu_e$ appearance data in a (3+1) model

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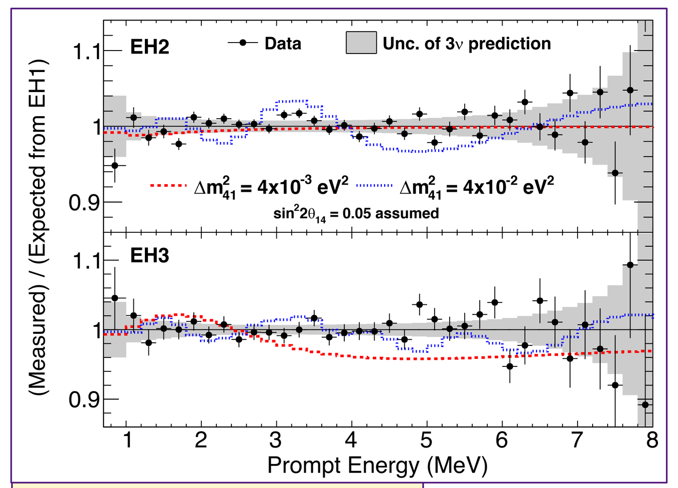
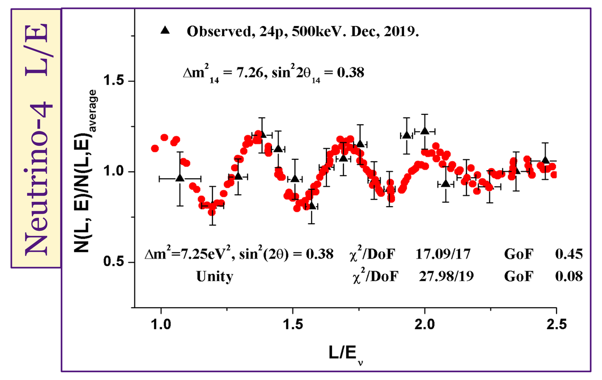
ν_e disappearance data

- Hints of a light sterile neutrino in ν_e disappearance experiments come from the Reactor Antineutrino Anomaly [2], the Gallium anomalies [3], and the Neutrino-4 [4] experiment
- Recent exclusion limits are set by several reactor experiments, including Daya Bay [5], PROSPECT [6], NEOS [7], and DANSS [8]

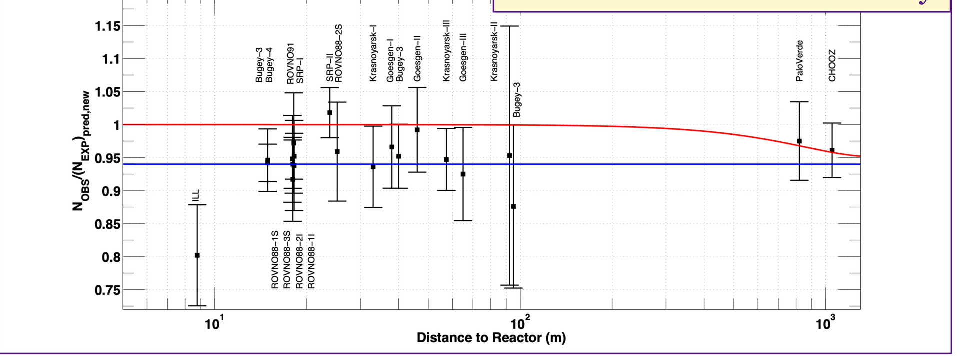


Daya Bay energy spectrum

Neutrino-4 L/E

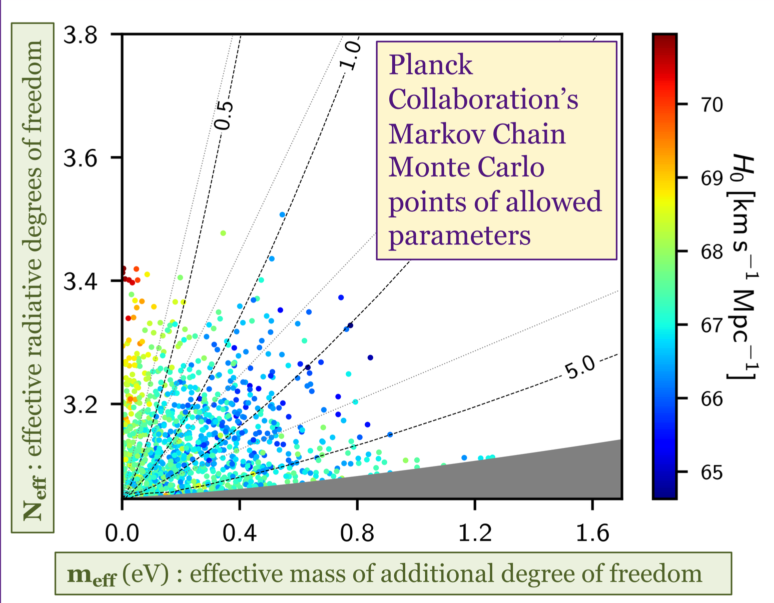


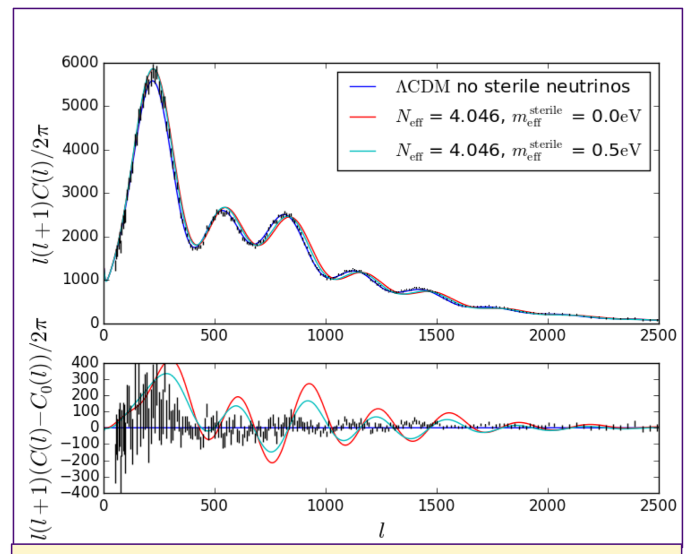
Reactor Antineutrino Anomaly



Cosmological limits on sterile neutrinos

- Planck [1] measures the temperature fluctuations of the Cosmic Microwave Background
- Additional radiation density (e.g. from a sterile neutrino) at the time of decoupling:
  - Influences expansion of the early Universe, changes characteristic scales
  - Imprints on the peak sizes and positions in the CMB angular power spectrum
- ***Is it possible to directly compare the limits from Planck and hints or limits from terrestrial neutrino experiments in the same parameter space?***



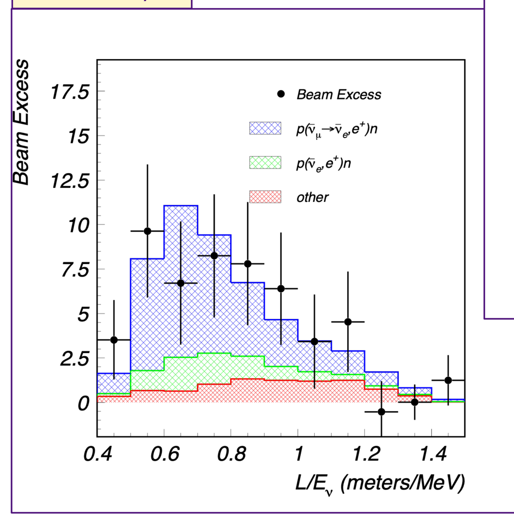


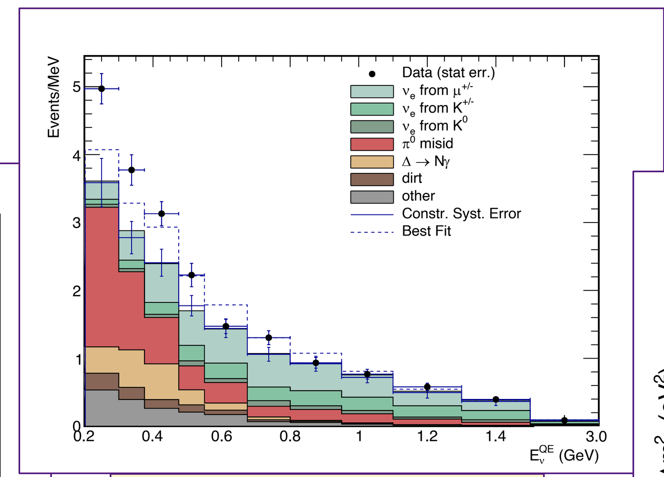
How CMB power spectrum is affected by an aditional relativistic degree of freedom

$\nu_\mu \rightarrow \nu_e$ appearance data

- Hints of light sterile neutrino seen by the LSND [10] and MiniBooNE [11] experiments
  - within a minimal (3+1) model, they require a O(1 eV) sterile neutrino
- A combination [12] of MINOS [13] and Daya Bay [5] limits on θ_{24} and θ_{14} respectively, can exclude much but not all of the allowed regions in the parameter space

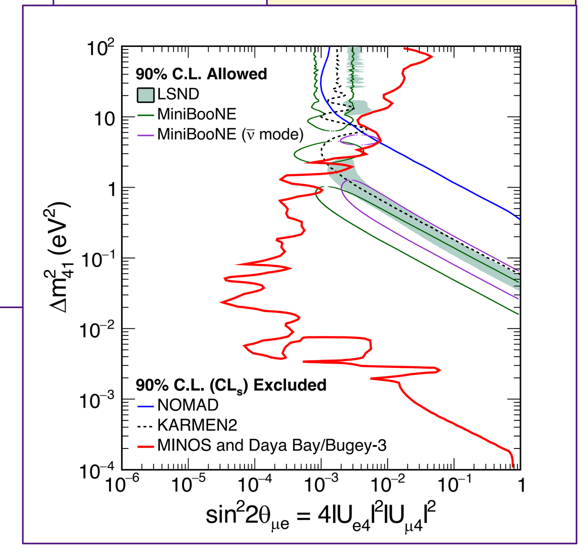
LSND L/E





MiniBooNE energy spectrum

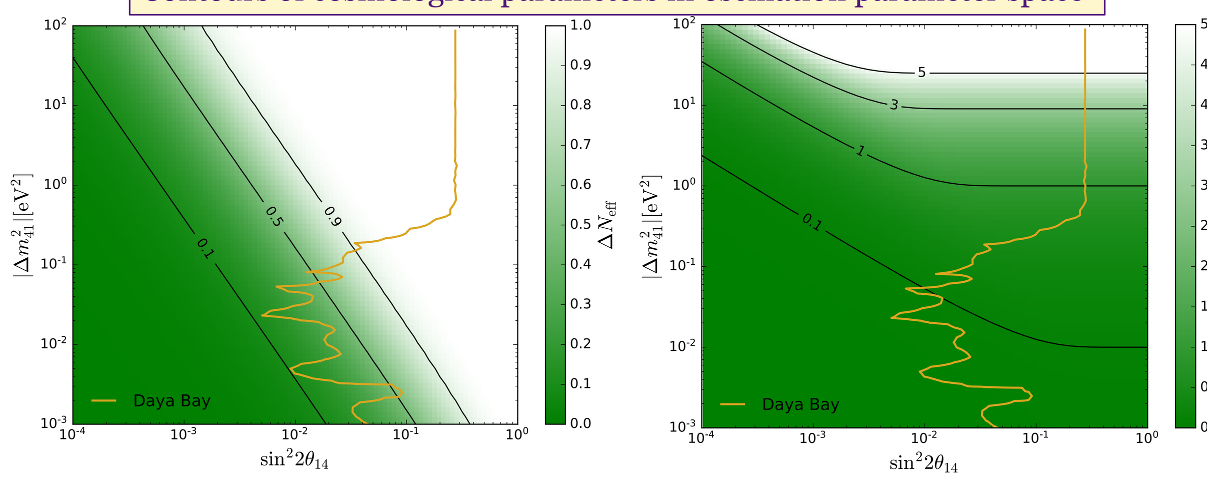
MINOS / Day Bay combined limit



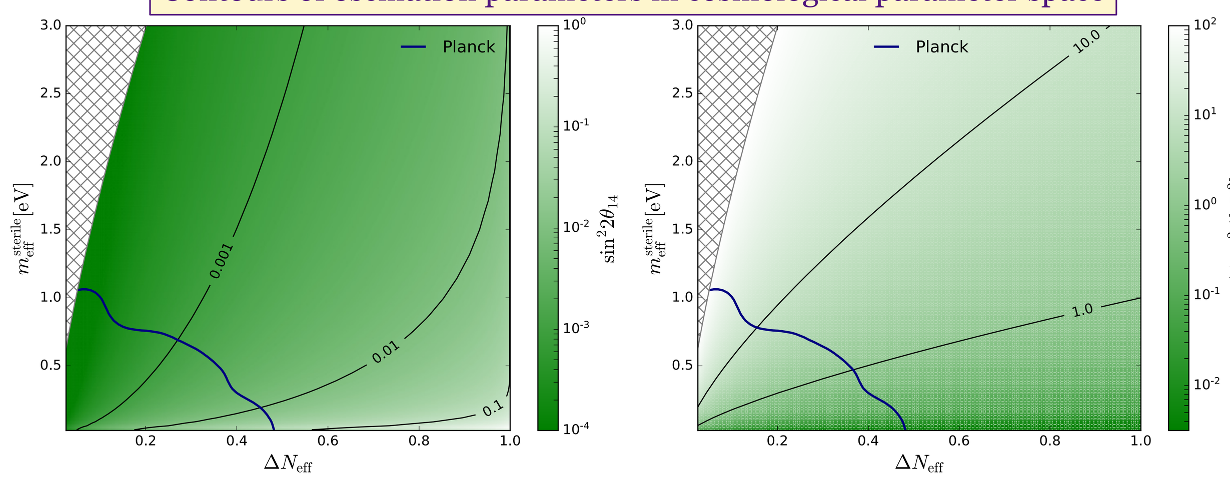
Converting between the cosmological and θ_{ee} parameter spaces

- LASAGNA [9] is used to solve differential equations describing the evolution of the early Universe
  - Calculate ΔN_{eff} ($=N_{eff}-3.046$) for the (1+1) active-sterile oscillation parameters (Δm^2, $\sin^2 2\theta$)
    - $m_{eff} = (\Delta N_{eff})^{3/4} m_4$
- Inverse map from ΔN_{eff} and m_{eff} to the active-sterile mixing parameters is calculated at the same time.
- 95% CL Planck limits taken from the density of the Markov Chain Monte Carlo points provided by the Planck collaboration

Contours of cosmological parameters in oscillation parameter space

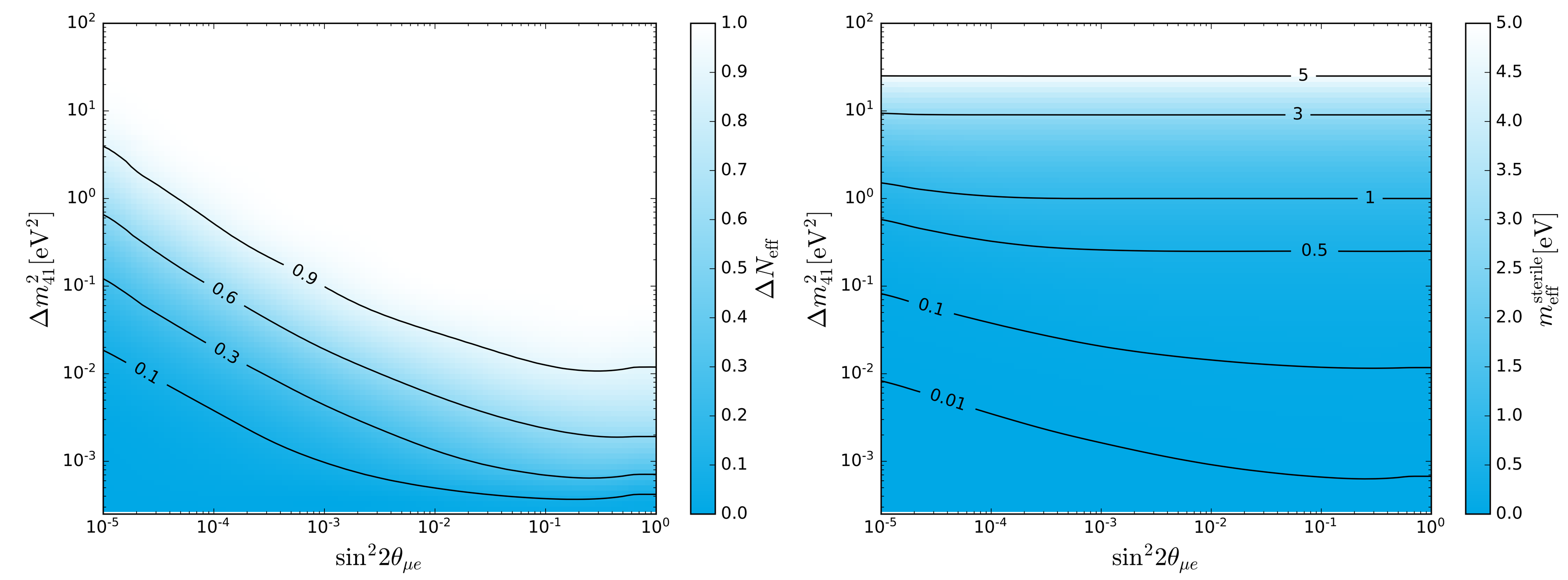


Contours of oscillation parameters in cosmological parameter space



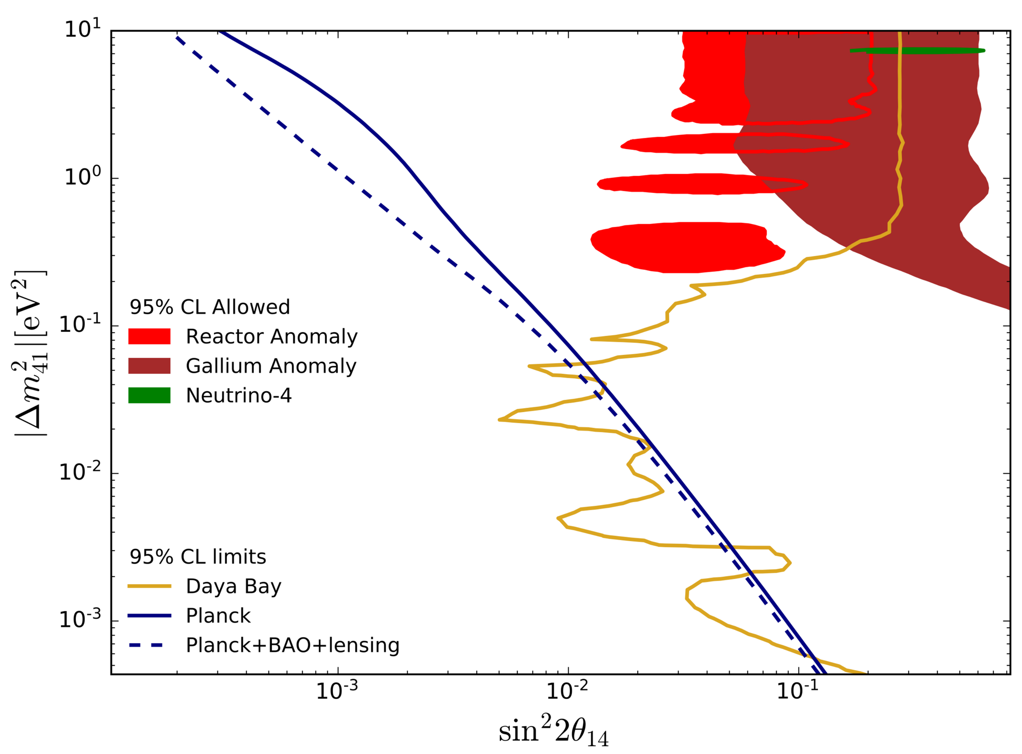
Converting between the cosmological and $\theta_{\mu e}$ parameter spaces

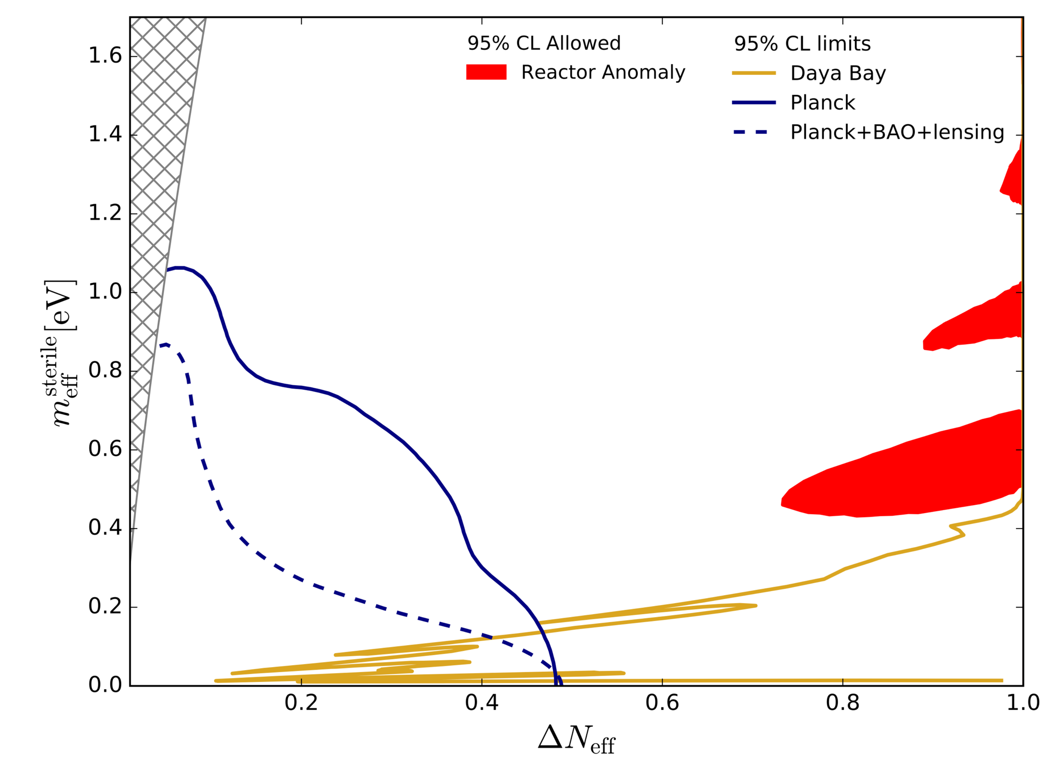
- Evolution of N_{eff} in early universe using Quantum Kinetic Equations [14] and a (3+1) neutrino number density matrix
  - N_{eff} calculated for a given (θ_{14}, θ_{24}, Δm^2) point
- Least constrained value of N_{eff} for a given $\theta_{\mu e}$ found by minimizing over lines of constant $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 2\theta_{24}$
- $m_{eff} = (\Delta N_{eff})^{3/4} m_4$
  - assume $m_1 = 0$



Contours of cosmological parameters in oscillation parameter space

A combined view of the limits on sterile neutrino in the θ_{ee} disappearance space

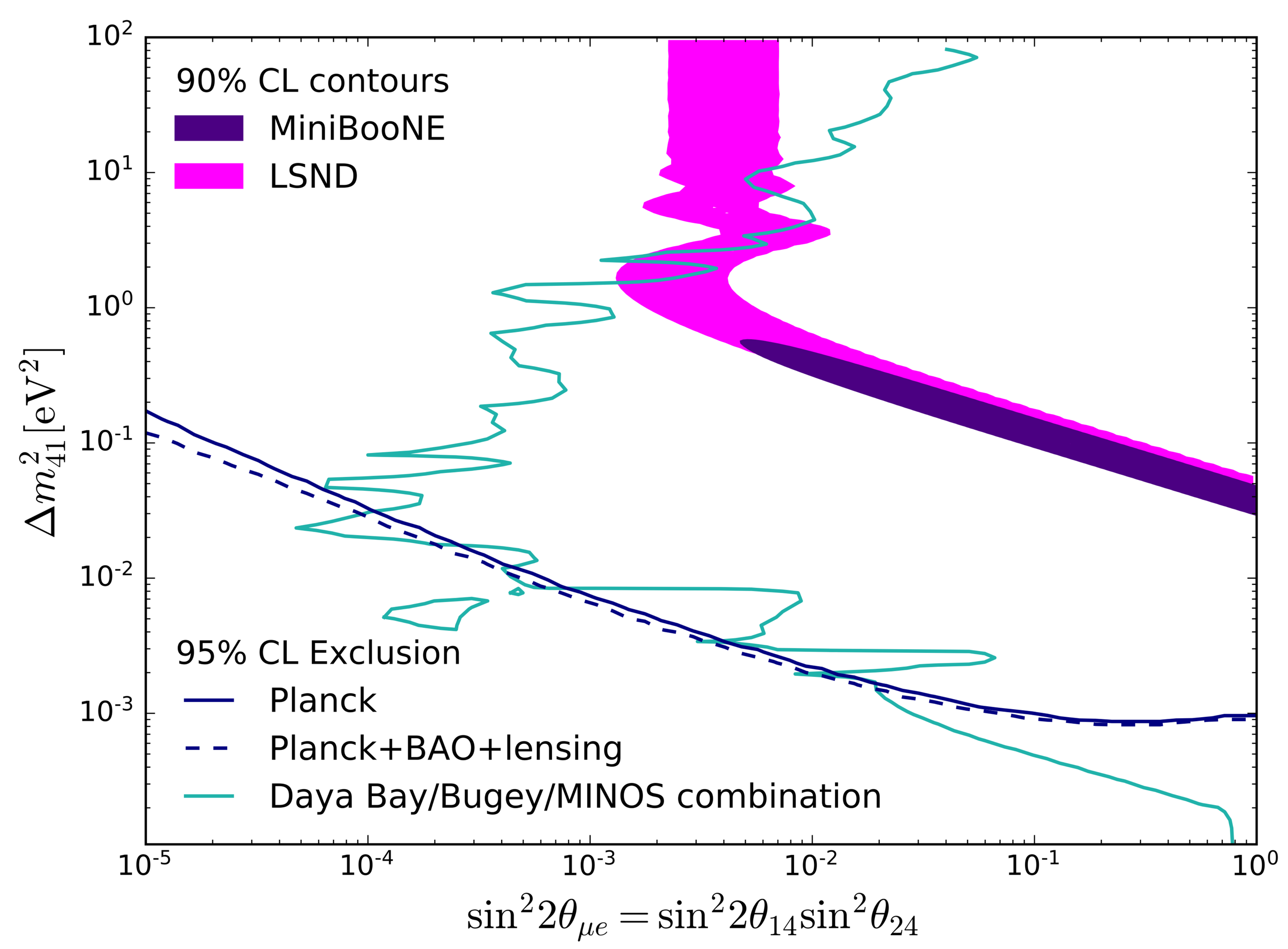




- Drawn in the oscillation parameter space:
  - Planck limit stronger than most oscillation experiments
  - Of the recent reactor limits, only Daya Bay provides additional constraints at low Δm^2
- Drawn in the cosmology parameter space:
  - Day Bay provides more stringent constraints than Planck, at high regions of ΔN_{eff} and low regions of m_{eff}
  - Sterile neutrino hints appear to be ruled out

The Planck exclusion contour in the $\theta_{\mu e}$ sterile neutrino appearance space

- Cosmological data rules out the complete parameter space required to explain the appearance anomalies within the minimal (3+1) model and standard cosmology
- The Planck limit is
  - stronger than MINOS/Daya Bay for large sterile neutrino masses
  - similar for $10^{-1.5} > \Delta m^2 > 10^{-3}$ eV²
  - weaker for small sterile neutrino masses
- The cosmological limits could be weakened through, for example
  - introducing new interactions between neutrinos [15]
  - introducing an initial lepton number asymmetry in the early universe [16]
  - introducing reheating at low temperatures [17]



[1] Planck 2018 results, arXiv:1807.06209 [2] PRD 83, 073006 [3] PRD 78, 073009 [4] JETP 109 4, 213 [5] PRL 117, 151802 [6] PRL 121, 251802 [7] PRL 118, 121802 [8] PLB 787, 56 [9] JCAP 2013, 032 [10] PRD 64, 112007 [11] PRL 121, 221801
[12] PRL 117, 151801 [13] PRL 117, 151803 [14] PRD 87, 113010 [15] PRL 112, 031802; PRD 91, 065021; PRD 90, 113009; JCAP 2015, 011 [16] PRD 74, 085015; PRL 75, 4350; PRD 87, 073006 [17] PRD 92, 123534; PRD 62, 023506; JCAP 2008, 029