Cosmological limits on sterile neutrino mixing parameters

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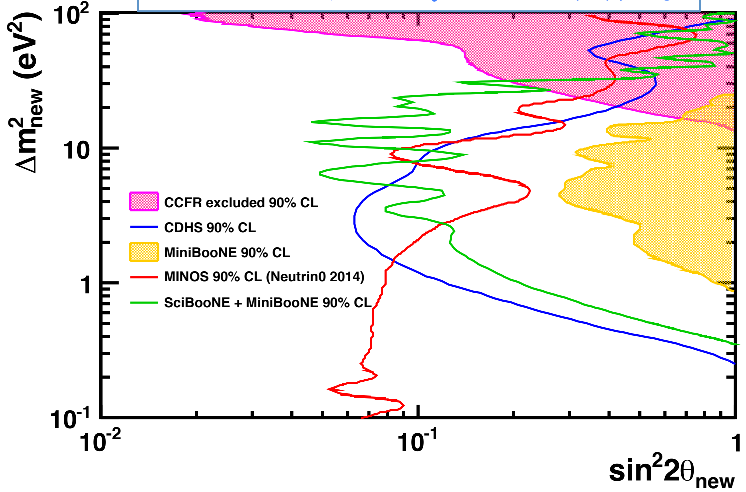
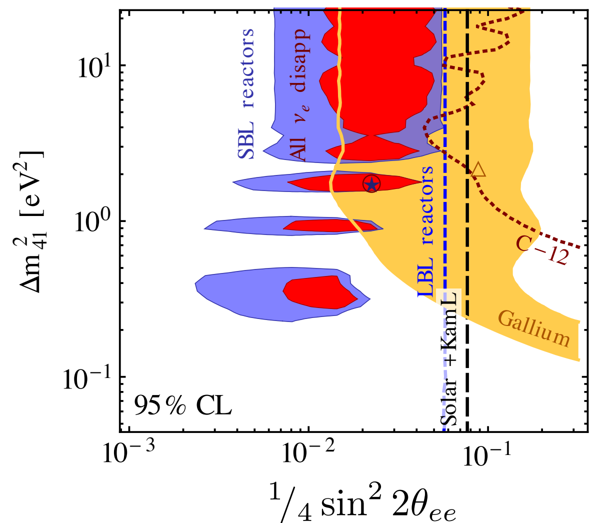
working with F Bezrukov, S Bridle, J Evans, Pawel Guzowski, B Ó Fearraigh &
S Söldner-Rembold, at The University of Manchester
collaboration of Particle Cosmology Theorists, Astrophysicists & HEP

Light sterile neutrino hints

Anokhina *et al*, Eur. Phys. J. C (2017) 77: 23

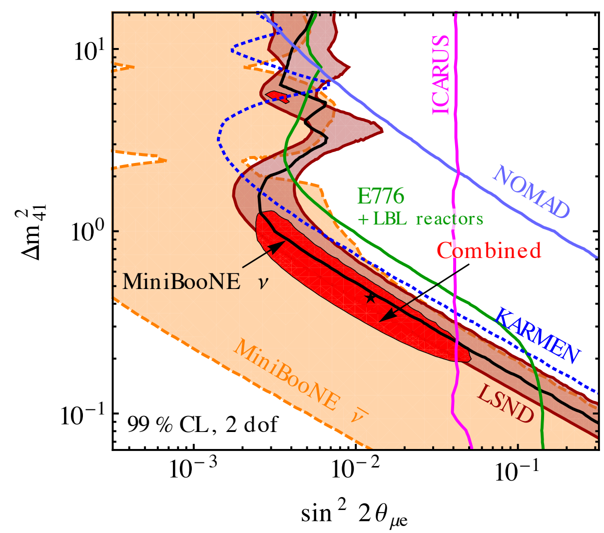


ν_μ disappearance



ν_e disappearance

Kopp *et al*, JHEP 1305, 050 (2013)



$\nu_\mu \rightarrow \nu_e$ appearance

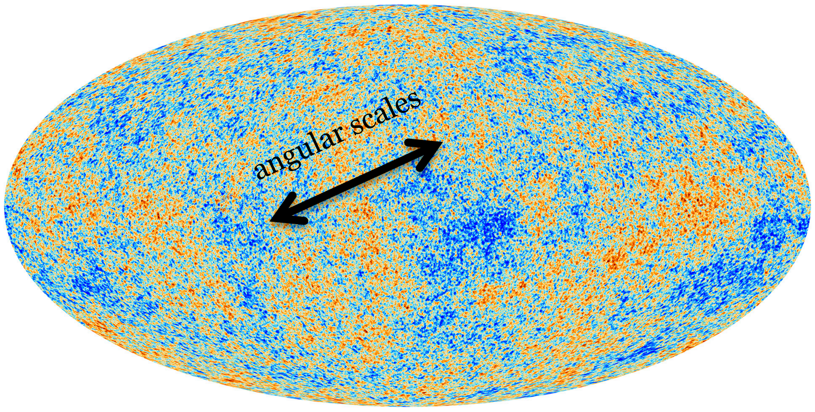
- Hints of a light sterile neutrino from LSND, MiniBooNE, reactor oscillation experiments
- No hints seen in νμ disappearance experiments
- How can cosmological measurements constrain these parameter spaces?
- We have previously published a study for ν_μ disappearance [1]
- In this talk we show new results for ν_e disappearance
- We also extend the method to a (3+1) parameterization, to apply it to $\nu_\mu \rightarrow \nu_e$ appearance

[1] Phys Lett B 764, 322 (2016)

Sterile ν in cosmology

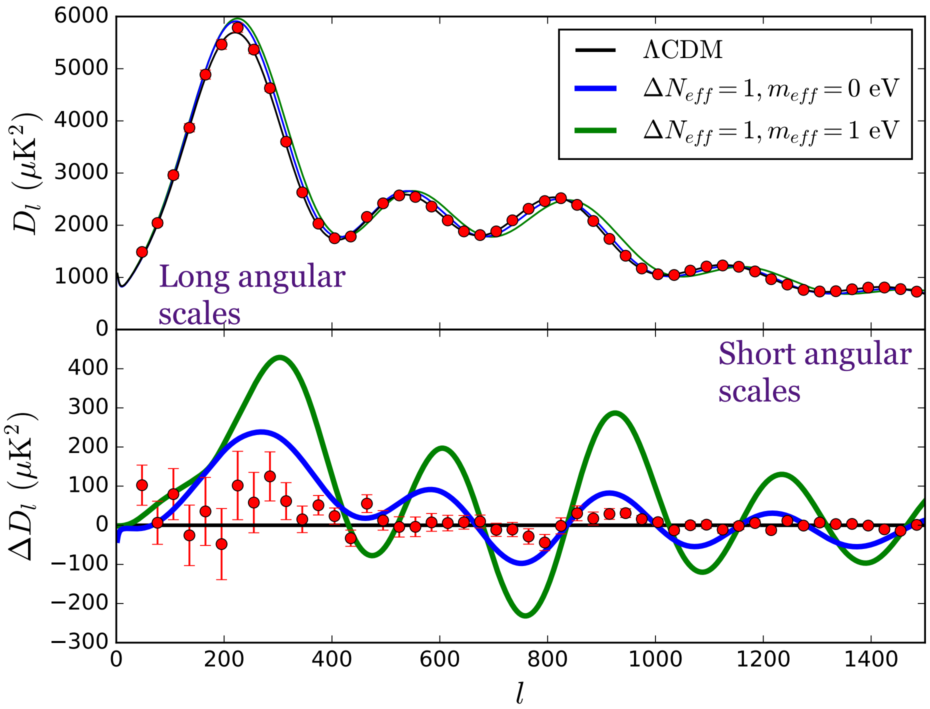
- Sterile neutrino has an effect on cosmic microwave background
- Additional radiative degrees of freedom in early universe will
  - accelerate expansion of the universe, leading to smaller characteristic angular scales
  - if massive, there is damping due to radiation–matter transition

Characterized by two parameters:
ΔN_{eff} – additional degrees of freedom
m_{eff} – effective sterile mass

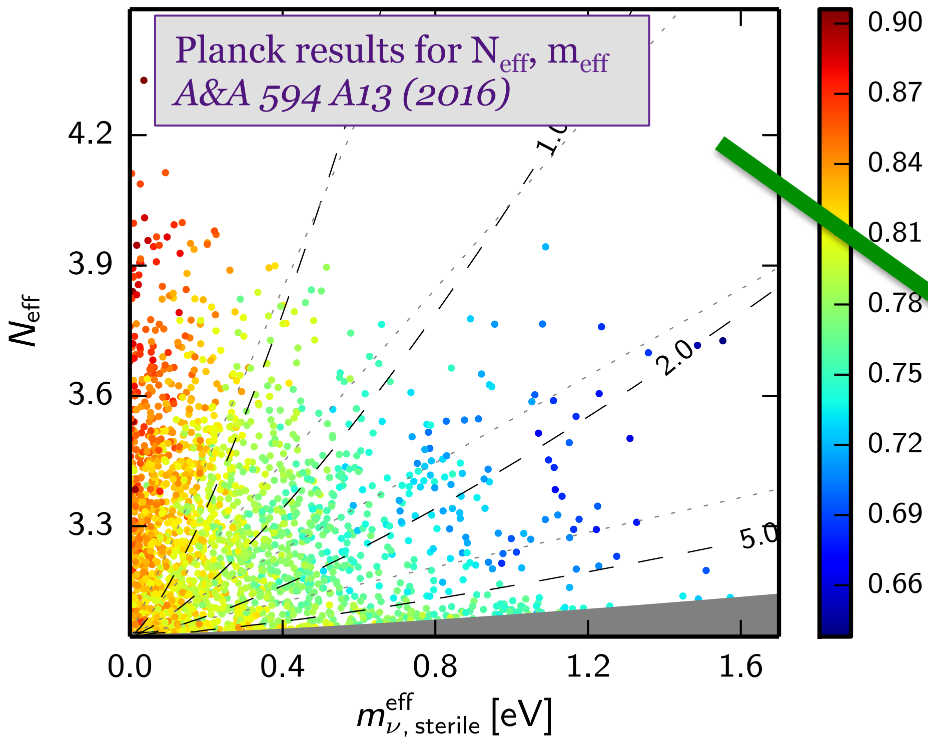


Planck map of CMB temperature

Angular power spectrum



Planck constraints

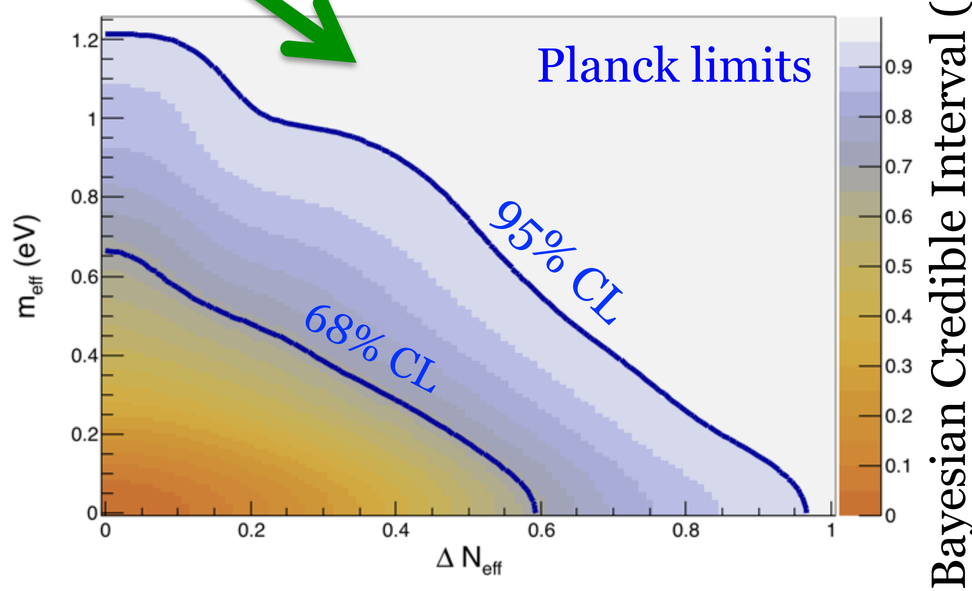


ΔN_{eff} – additional degrees of freedom

$$\Delta N_{eff} = N_{eff} - 3.046$$

m_{eff} – effective sterile mass

KDE



We use the Planck Markov-Chain MC public data release and kernel density estimation (KDE) method to extract limits in two-dimensional parameter space

Sterile ν thermalisation

See for example, *Phys. Rev. D 86, 053009*

$$\Delta N_{\text{eff}} = 1 \rightarrow \text{One } \textbf{fully thermalised } \nu_s \text{ flavour.}$$

$$\Delta N_{\text{eff}} < 1 \rightarrow \text{Small mixing angle. } T_{\text{sterile}} \neq T_{\text{active}}$$

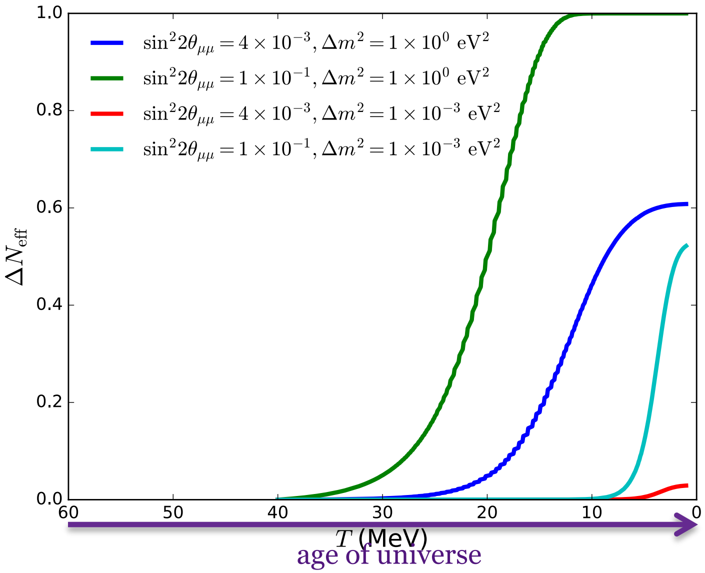
- We use the code LASAGNA [1] to solve the evolution equations
- Evolution in early universe from T~100 MeV to T~1 MeV
- Integrate over momentum distribution to obtain ΔN_{eff}

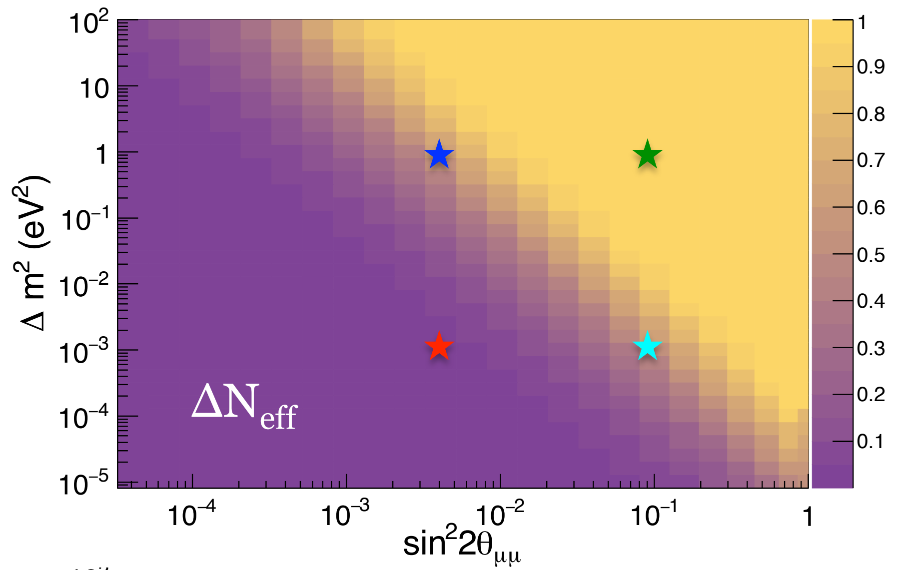
$$\Delta N_{\text{eff}}(t) = \frac{\int \mathrm{d}p\, p^3 f_0 (\mathrm{Tr}\rho(t,p) - 3)}{\int \mathrm{d}p\, p^3 f_0}$$

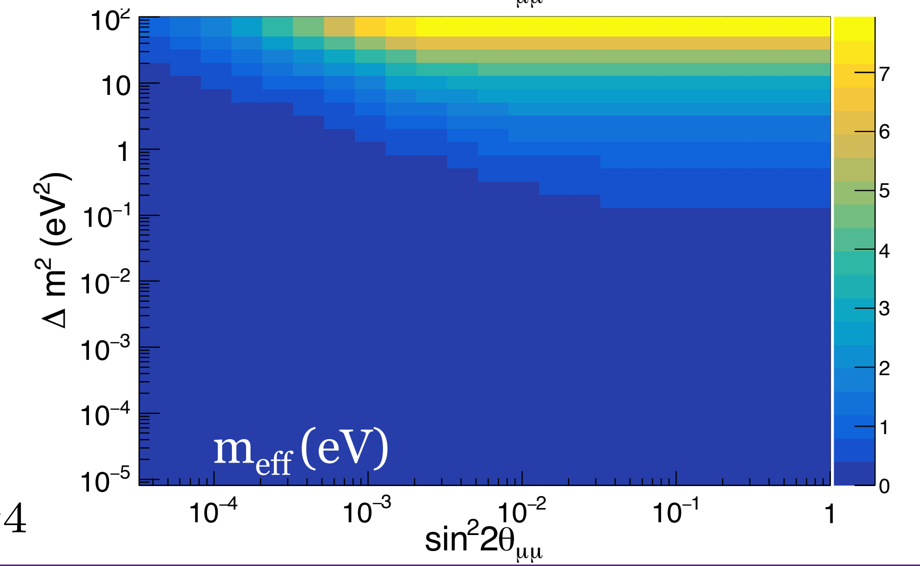
(f_o is the Fermi-Dirac distribution)

[1] JCAP (2013) 04, 032

ν_μ disappearance





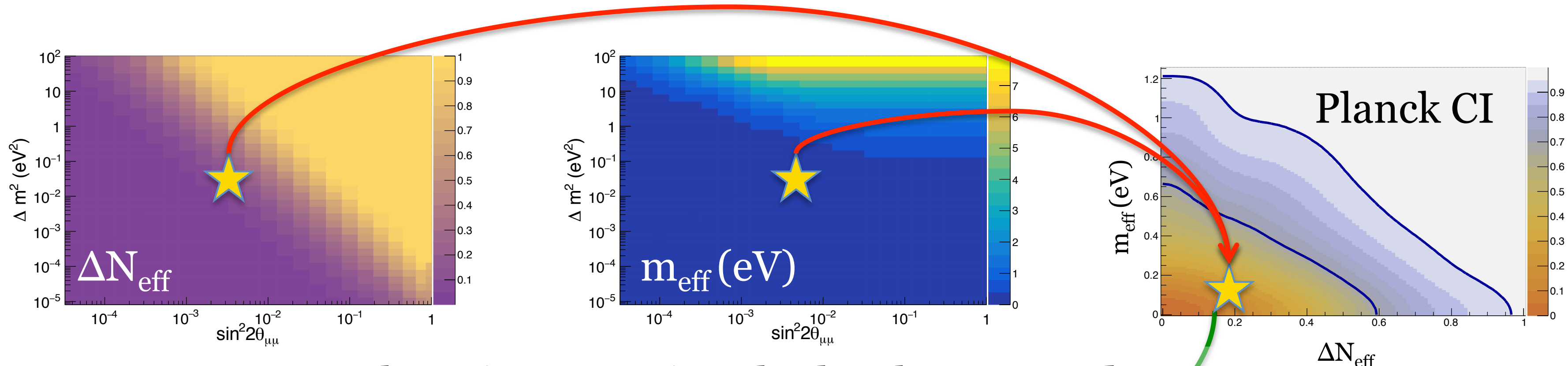


Described in *Phys Lett B 764, 322*, working in 1 active + 1 sterile neutrino (1+1) scenario

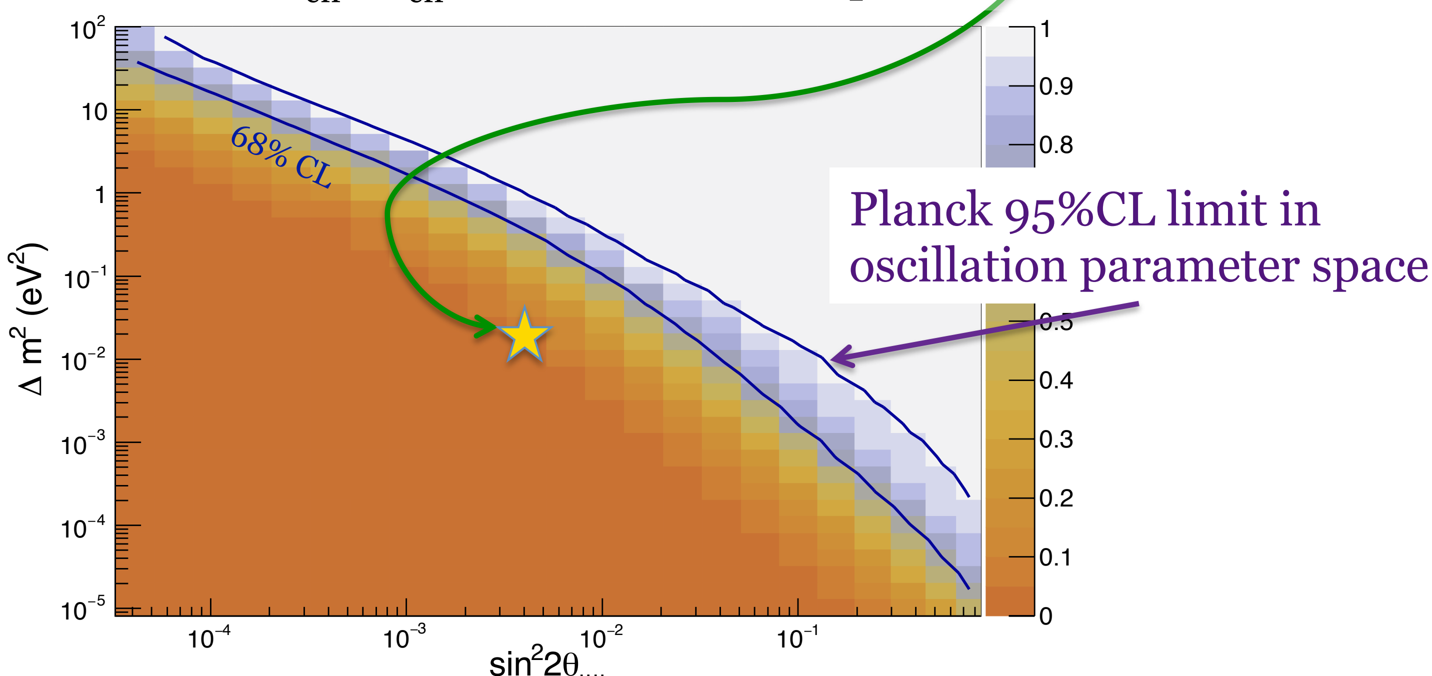
We calculate ΔN_{eff} over the whole (θ,Δm^2) parameter space

Then calculate $m_{eff} = (\Delta N_{eff})^{3/4} m_4$

How to translate Planck limit into ($\theta,\Delta m_2$) space

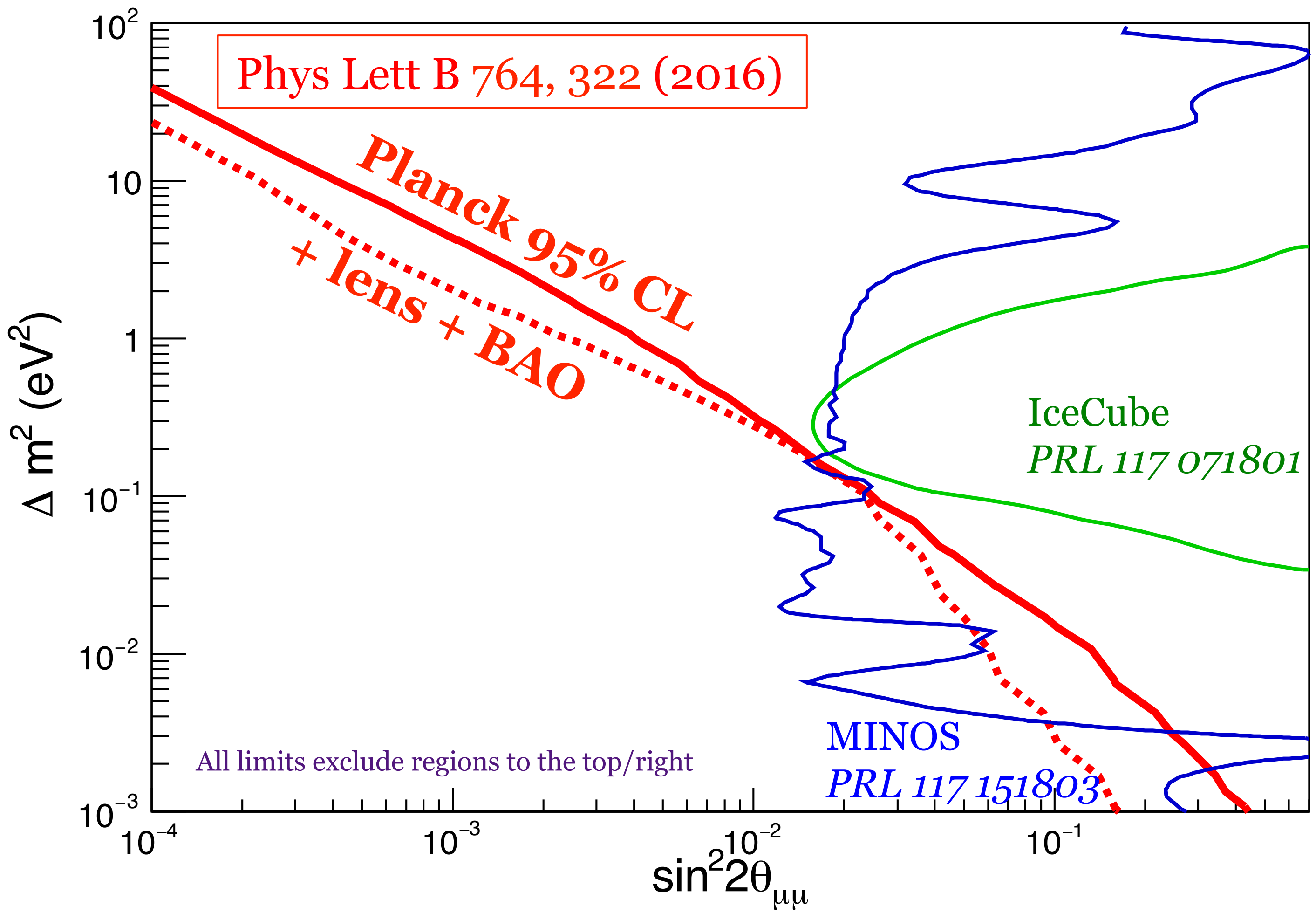


Combine (ΔN_{eff}, m_{eff}) with Planck CI to produce…



ν_μ disappearance

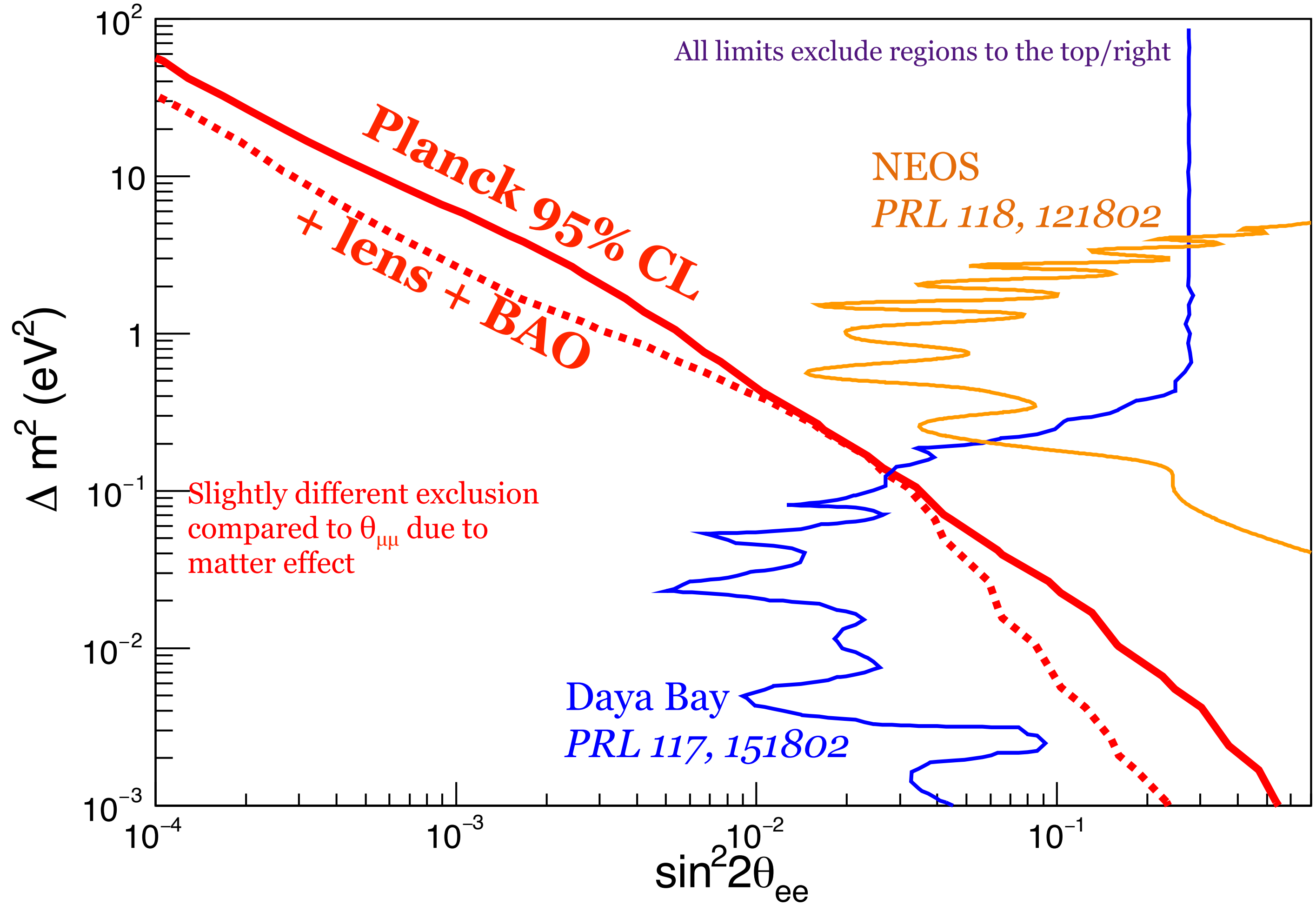
How does this compare to oscillation searches?



ν_e disappearance

NEW RESULT

Very similar procedure performed for ν_e



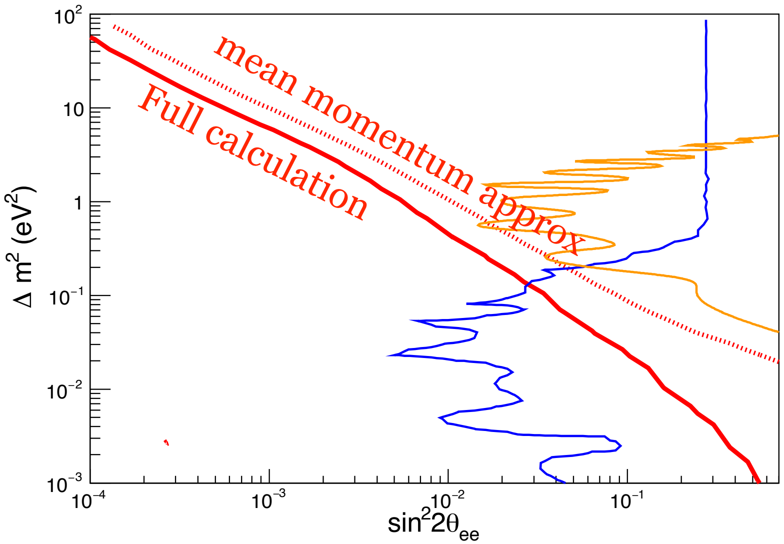
(3+1) modelling

- Previously mentioned work used (1+1) parameter space
  - Only valid for $\nu_x \rightarrow \nu_s$ mixing for single active flavor
- To compare with $\nu_\mu \rightarrow \nu_e$ appearance hints, we need to work with full 3 active + 1 sterile neutrino (3+1) parametrisation
- Evolution calculation depends on mixing angles (θ_{14}, θ_{24}, θ_{34}) between the flavor states and the new, fourth mass state
- To compare with $\nu_\mu \rightarrow \nu_e$ appearance hints, need to project onto $\theta_{\mu e}$ angle:
    - $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$

Mean momentum approximation

- For (3+1) evolution we work in *mean momentum approximation*, given a Fermi-Dirac distribution of neutrino momenta
  - greatly reduces number of equations to solve
- This approximation gives slightly weaker cosmological limits

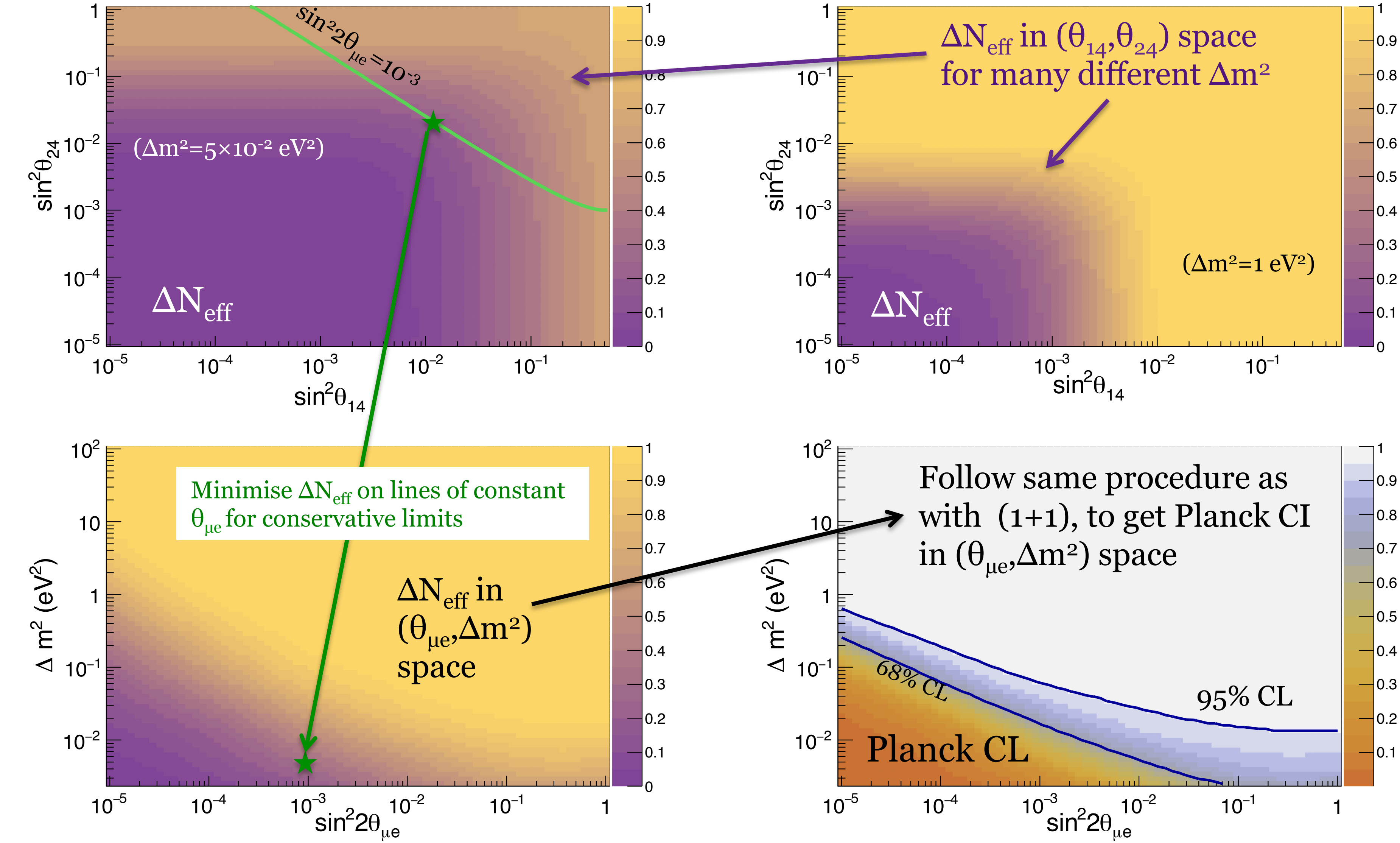
ν_e disappearance limits



Obtaining limits in $\theta_{\mu e}$ space

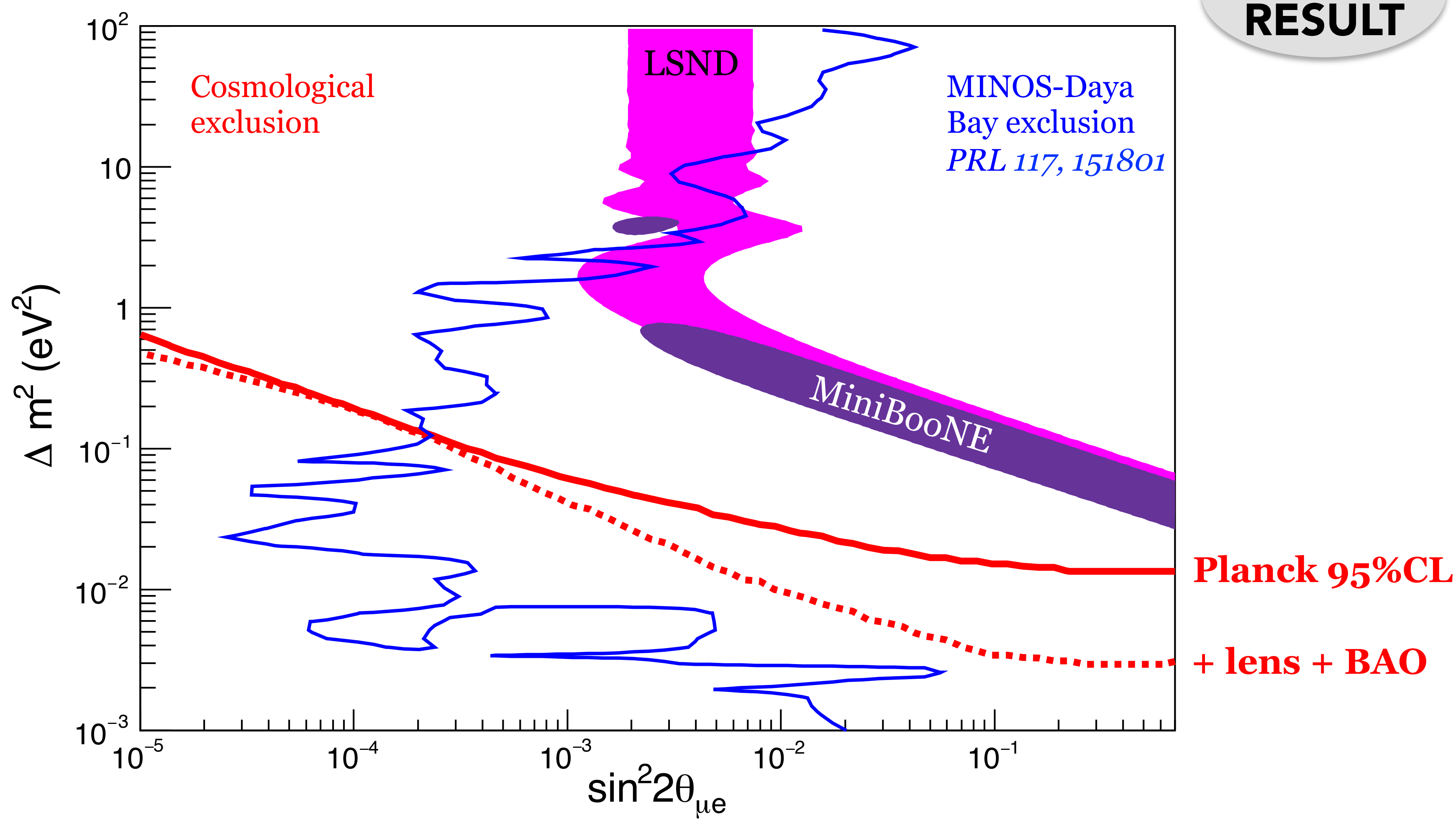
$\Delta m^2 = m_4^2 - m_1^2;\ \ m_4 > m_1$

*All evaluated with $\theta_{34}=0$ – non-zero θ_{34} increases ΔN_{eff}



Planck limit in $\nu_\mu \rightarrow \nu_e$ parameter space

NEW RESULT



$$\Delta m^2 = m_4^2 - m_1^2; \quad m_4 > m_1$$

Conclusion

- Planck limits are complementary and competitive with sterile neutrino oscillation searches
  – Dependence of limit: $\Delta m^2 \propto 1/\sin^2\theta$
- Planck provides a model-dependent limit; could be weaker due to, for example,
  – Primordial lepton-number asymmetry [1]
  – pseudoscalar interaction [2]

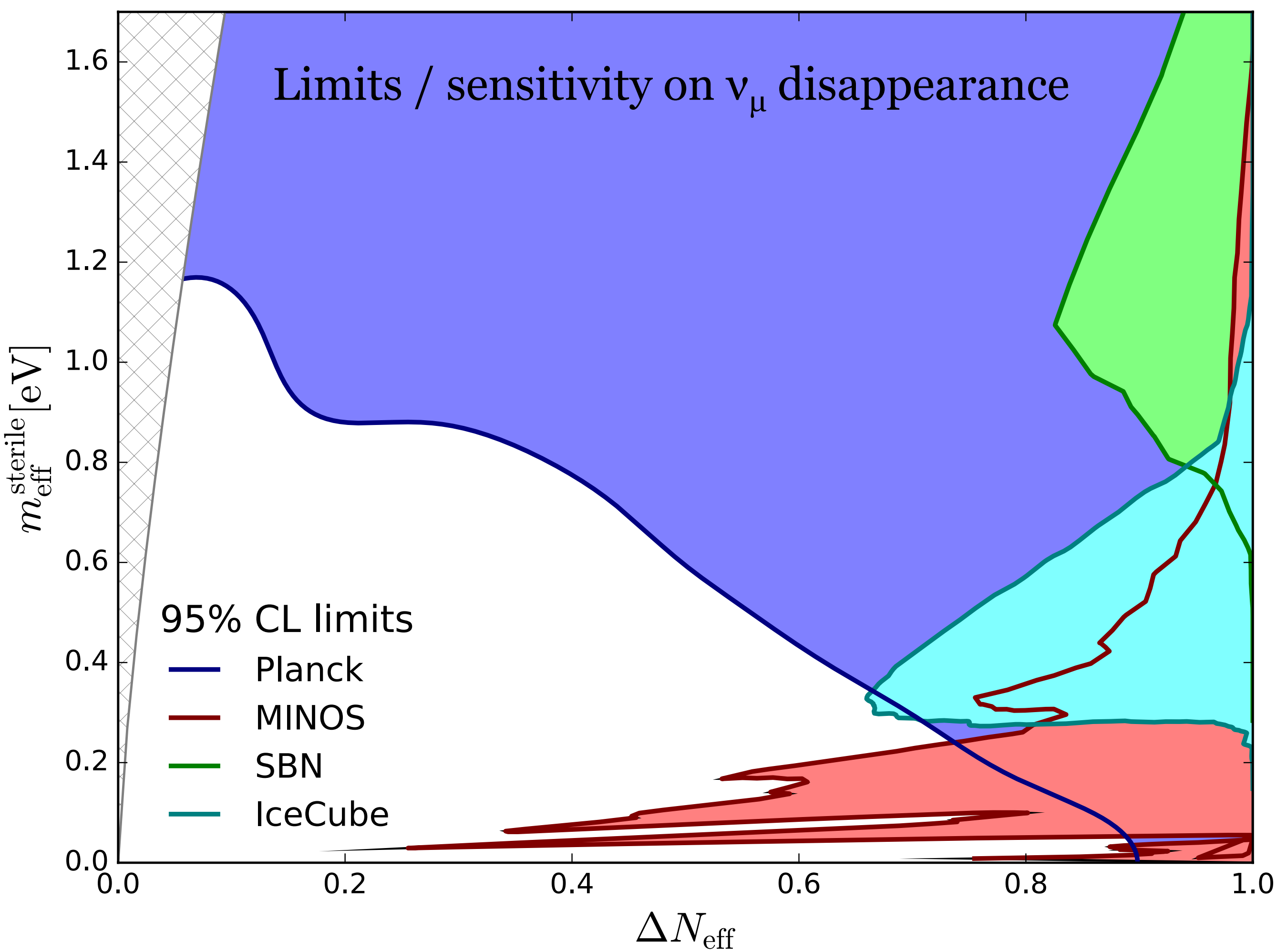
Or stronger due to,

- $\theta_{34} = 0$ assumption
- mean momentum approximation

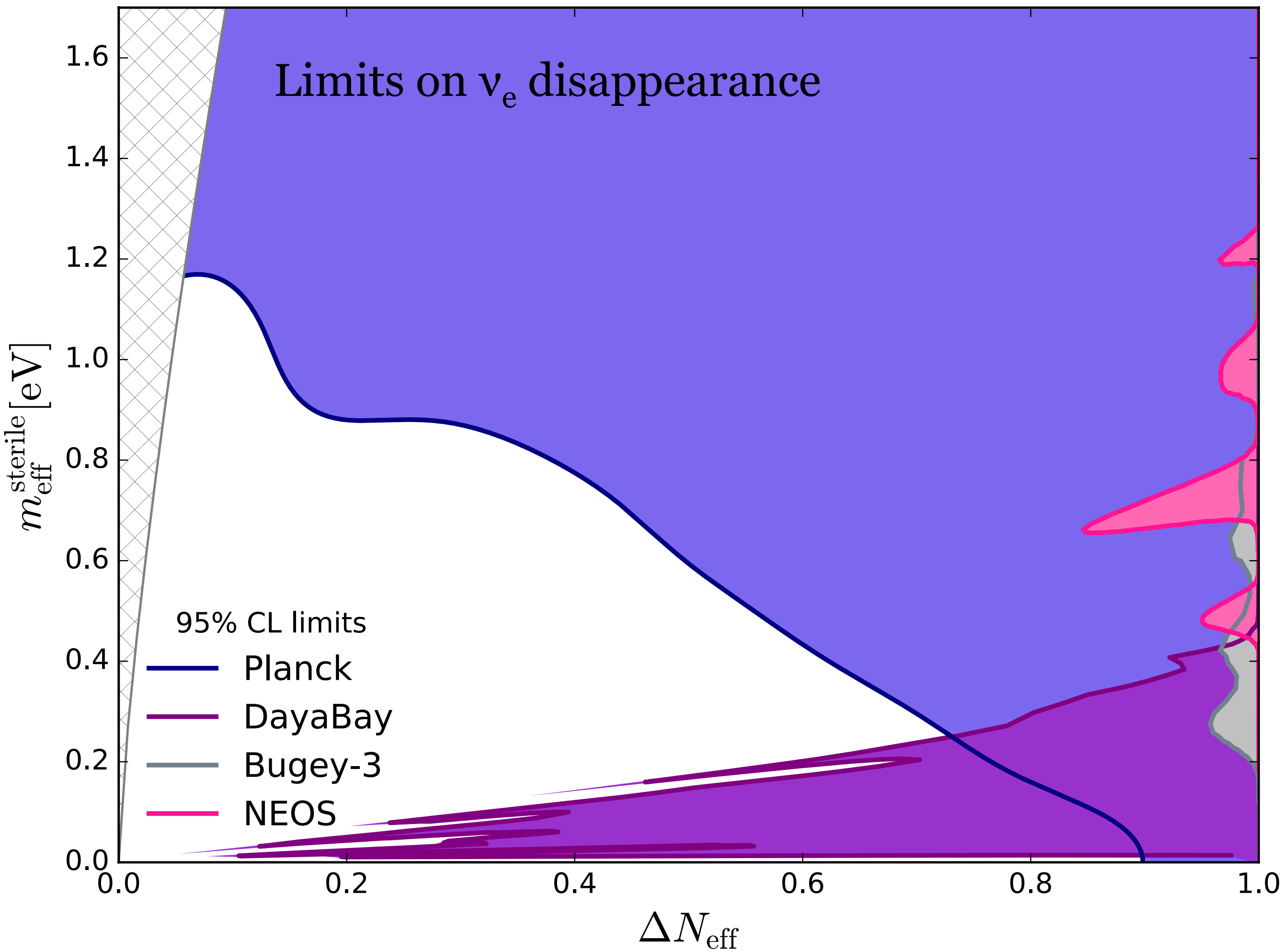
[1] Hannestad *et al* JCAP07(2012)025 [2] Archidiacono *et al* JCAP08(2016)067

EXTRA SLIDES

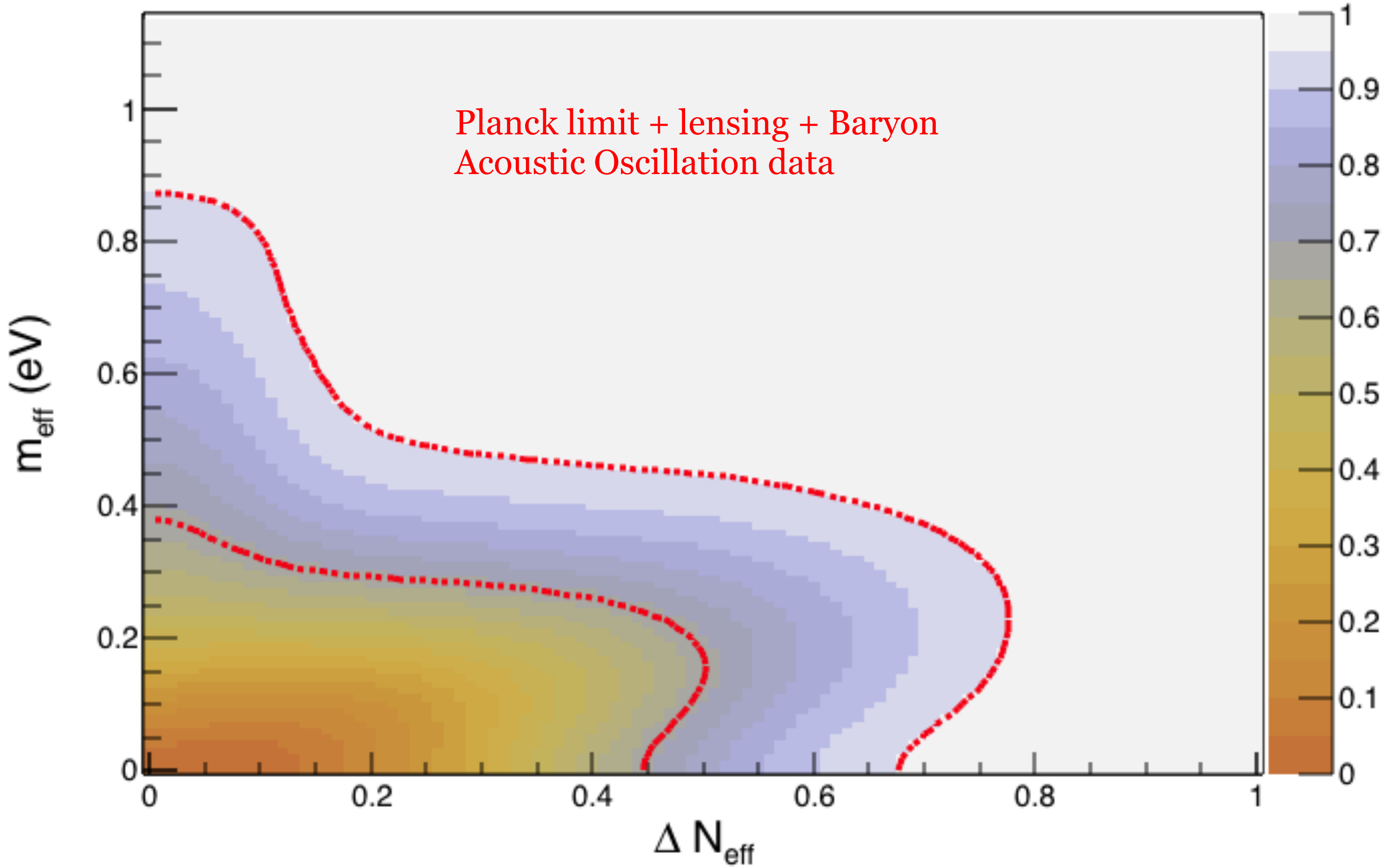
Limits in cosmological parameter space



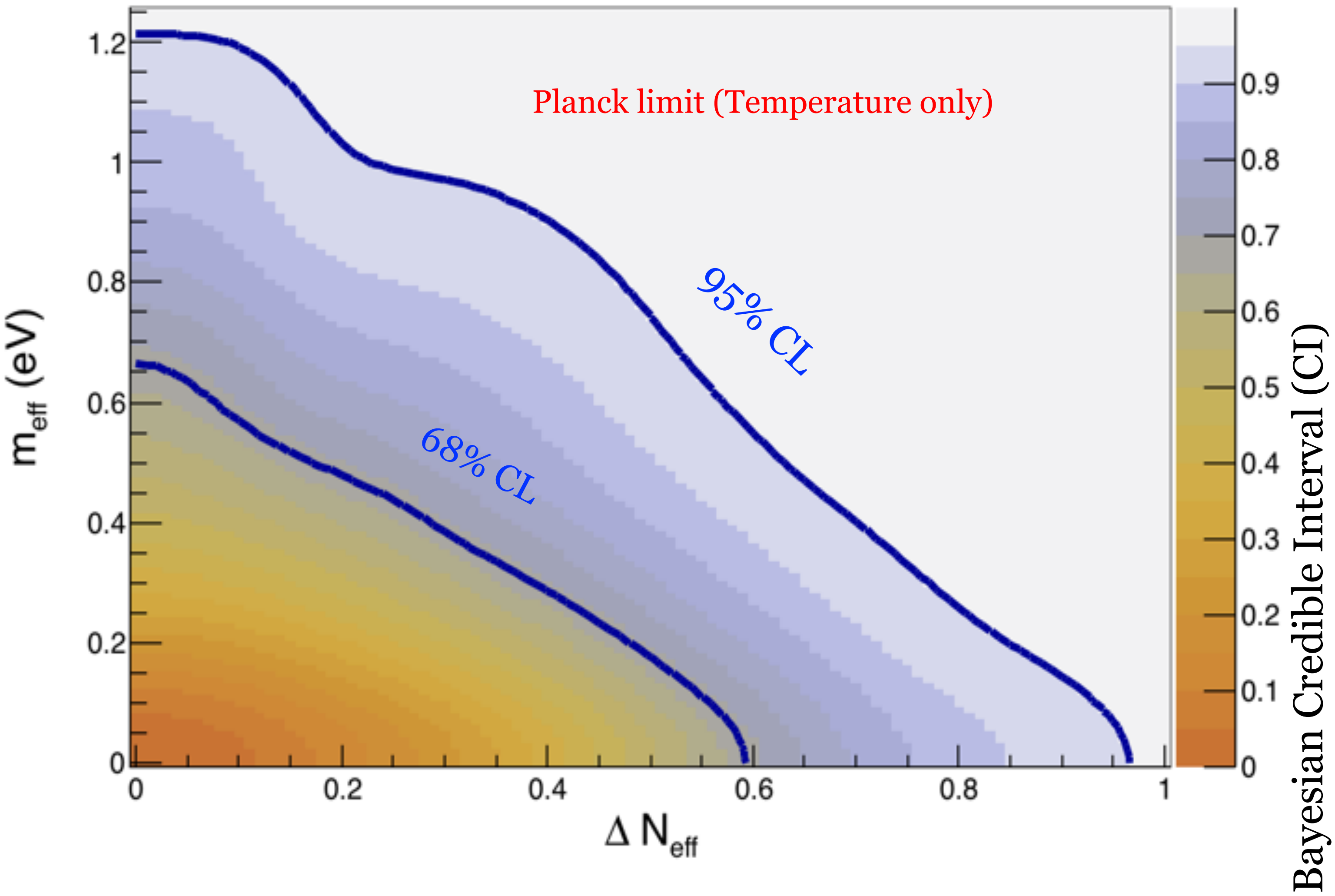
Limits in cosmological parameter space



Additional cosmological constraints



Additional cosmological constraints



Sterile ν thermalisation

See for example, *Phys. Rev. D 86, 053009*

$$-i\dot{\rho} = \mathcal{H}_{\mathrm{V}} + \mathcal{H}_{\mathrm{M}} + \mathcal{H}_{\mathrm{C}}$$

- Schrödinger equation (using comoving-observer time derivative)
  - Neutrino number density tensor as function of momentum *p*
  - Vacuum oscillation term
    - Mixing angles & mass-squared differences
  - Matter effect
    - coherent scattering with background electrons & neutrinos
  - Collision term
    - incoherent neutrino-(anti)neutrino scattering & annihilation
- Evolution in early universe from T~100 MeV to T~1 MeV
- Integrate over momentum distribution to obtain ΔN_{eff}

$$\Delta N_{\mathrm{eff}}(t) = \frac{\int \mathrm{d}p\, p^3 f_0 (\mathrm{Tr}\rho(t,p) - 3)}{\int \mathrm{d}p\, p^3 f_0}$$

(f_o is the Fermi-Dirac distribution)

Evolution equations in full

Alessandro Mirizzi, Ninetta Saviano,
Gennaro Miele, and Pasquale Dario Serpico
Phys. Rev. D 86, 053009

$$i\frac{d\varrho}{dx} = +\frac{x^2}{2m^2\,y\,\overline{H}}\,[\mathcal{U}^\dagger\mathcal{M}^2\mathcal{U},\varrho] + \frac{\sqrt{2}G_F\,m^2}{x^2\,\overline{H}}\left[\left(-\frac{8\,y\,m^2}{3\,x^2\,m_W^2}\mathsf{E}_\ell - \frac{8\,y\,m^2}{3\,x^2\,m_Z^2}\mathsf{E}_\nu + \mathsf{N}_\nu\right),\varrho\right] + \frac{x\,C[\varrho]}{m\,\overline{H}}\,,$$

$$\widehat{C}[\rho] = -\frac{i}{2}G_F^2\,m^4(\{\mathsf{S}^2,\rho-\mathsf{I}\} - 2\mathsf{S}(\rho-\mathsf{I})\mathsf{S} + \{\mathsf{A}^2,(\rho-\mathsf{I})\} + 2\mathsf{A}(\bar{\rho}-\mathsf{I})\mathsf{A})$$