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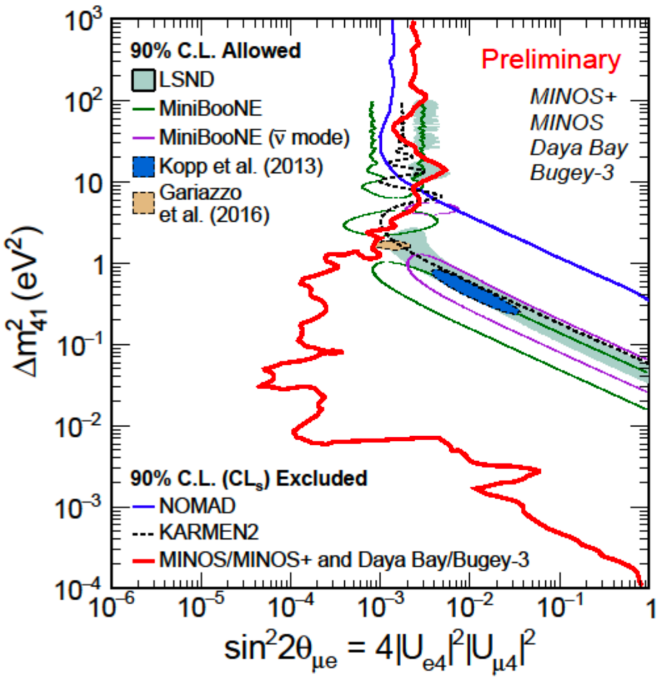
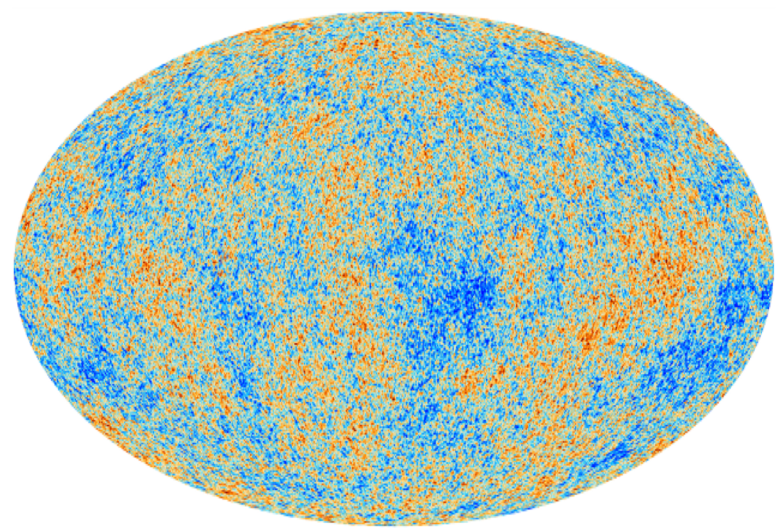
A combined view of sterile-neutrino constraints from CMB and neutrino-oscillation measurements





Justin Evans
University of Manchester

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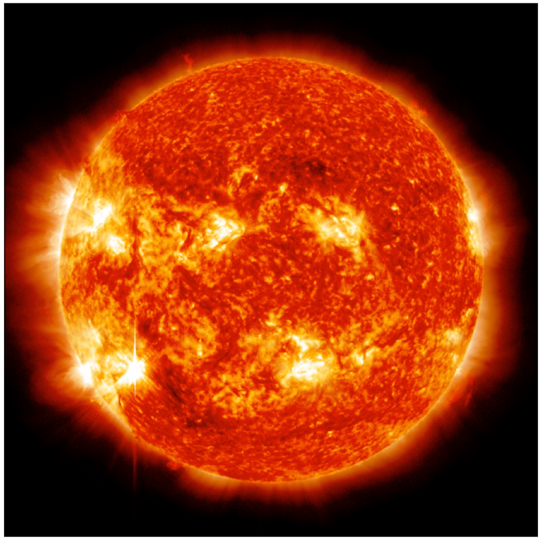
Neutrino oscillation

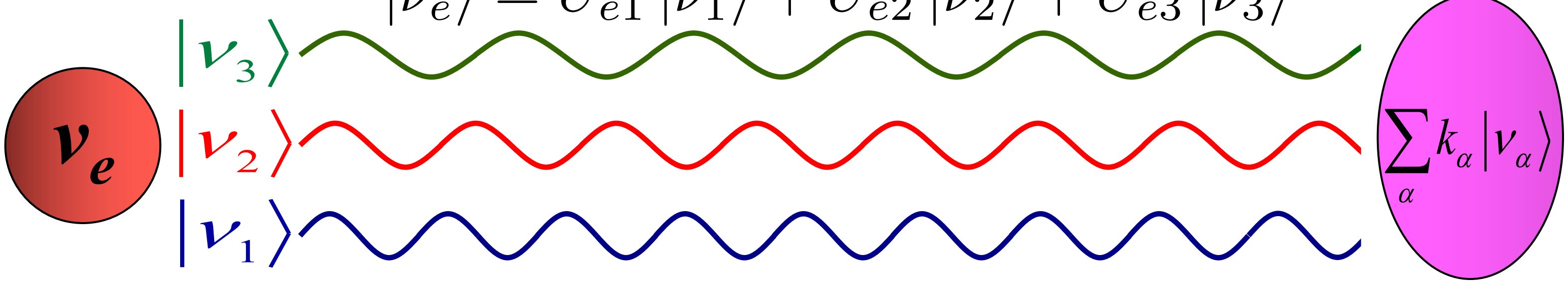


$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

Neutrino created by a weak process:
Eigenstate of flavour

Does not arrive in a flavour eigenstate;
Detection collapses wavefunction back into a flavour eigenstate

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

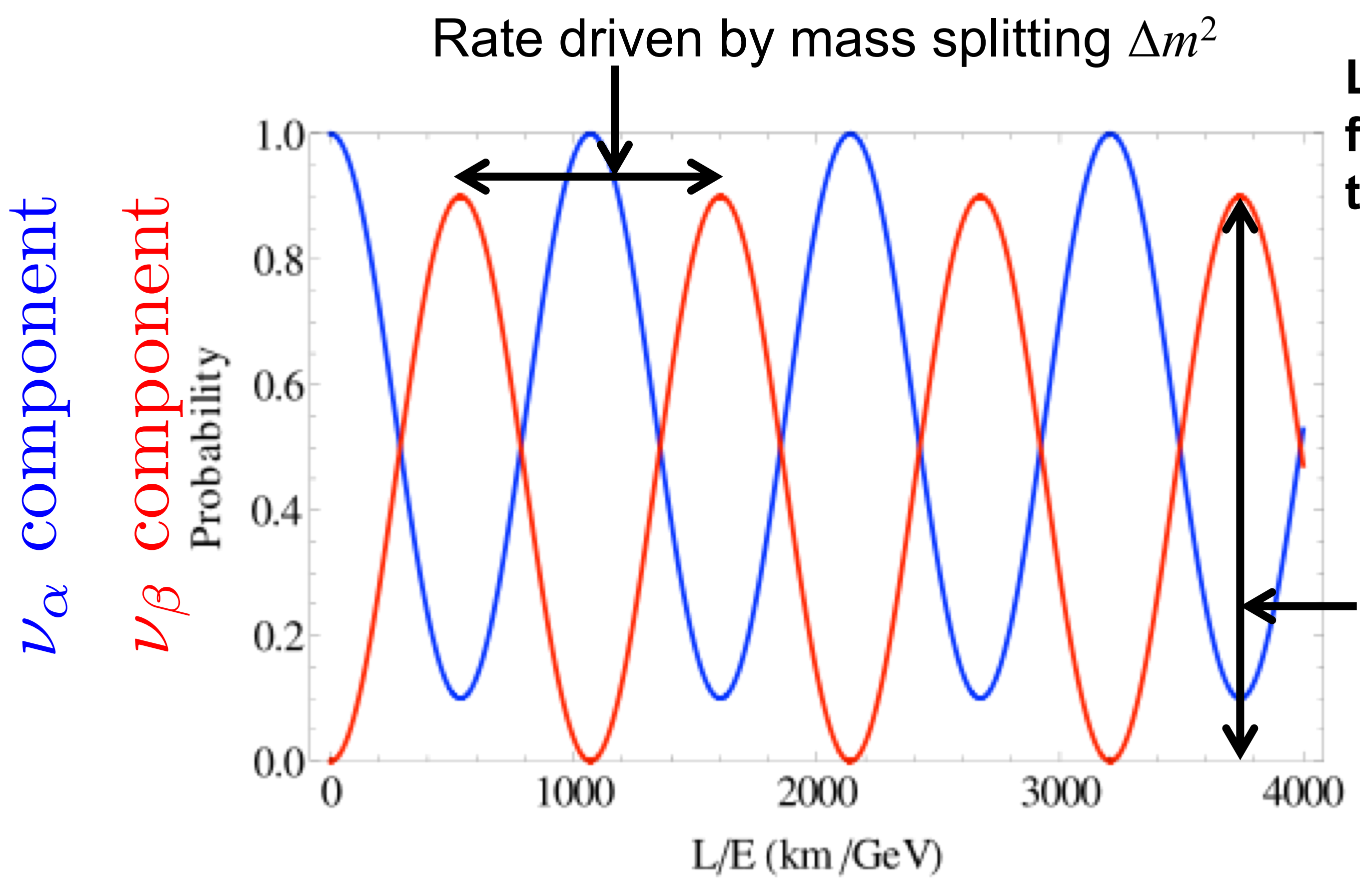


The relative phases of the mass eigenstates change

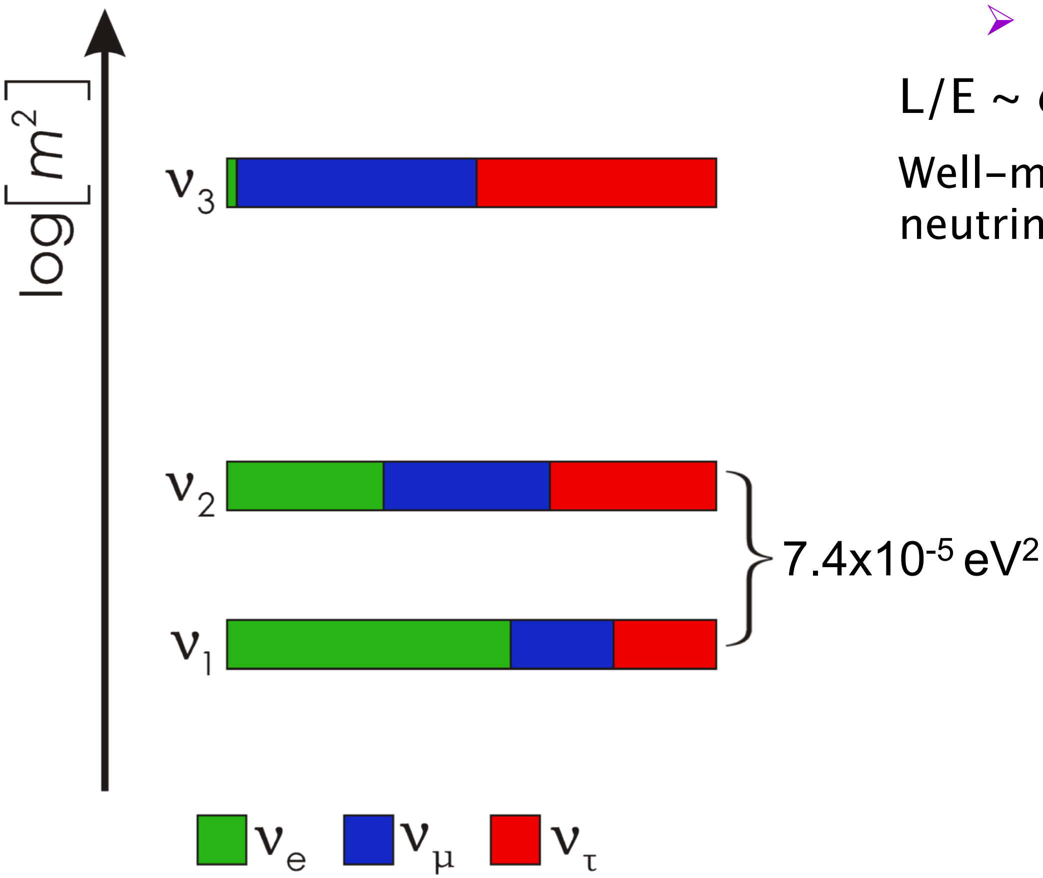
Neutrino oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2_{21}[\text{eV}^2]L[\text{km}]}{E[\text{GeV}]}\right)$$

L/E at which you see flavour-change tells you the value of Δm^2



The three-neutrino picture



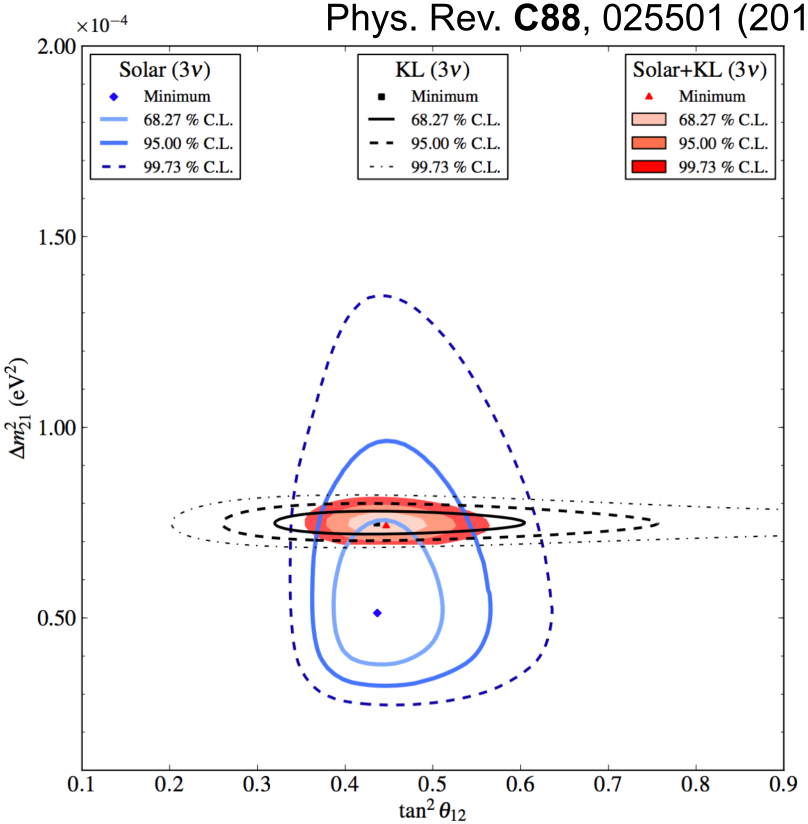
Smallest mass splitting

- ‘Solar’ mass splitting

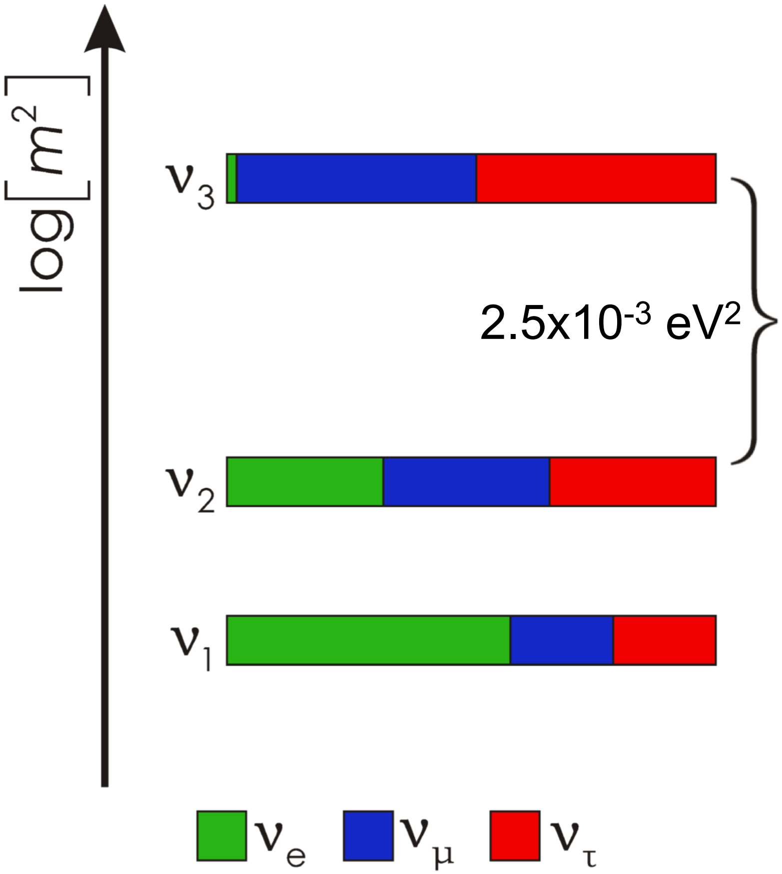
L/E ~ $\mathcal{O}(10^5$ km/GeV)

Well-measured with both solar and reactor neutrinos

Phys. Rev. **C88**, 025501 (2013)



The three-neutrino picture

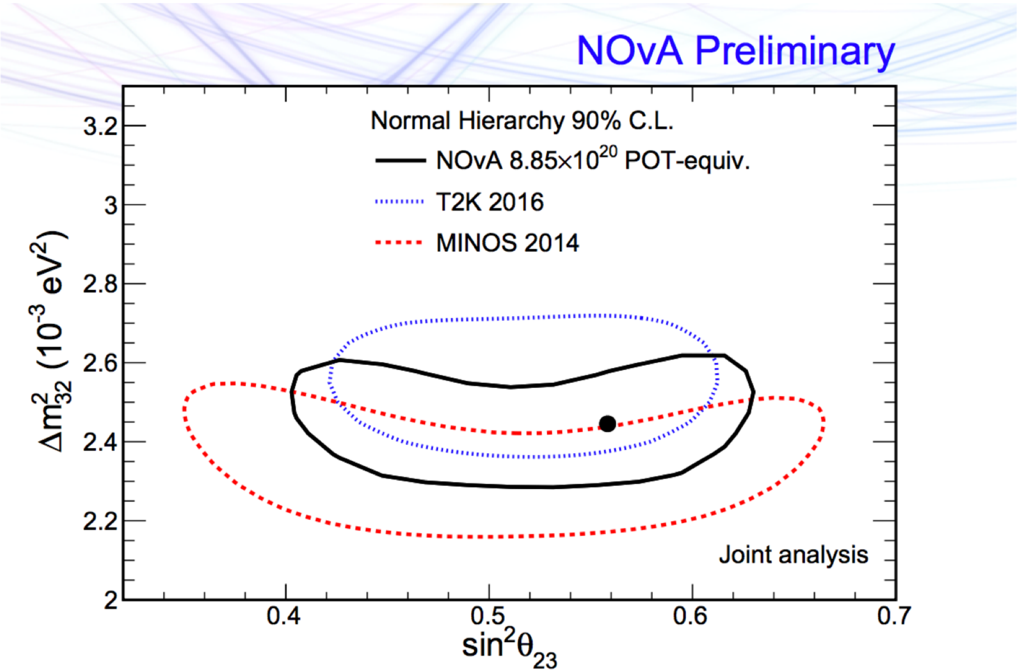


Largest mass splitting

- 'Atmospheric' mass splitting

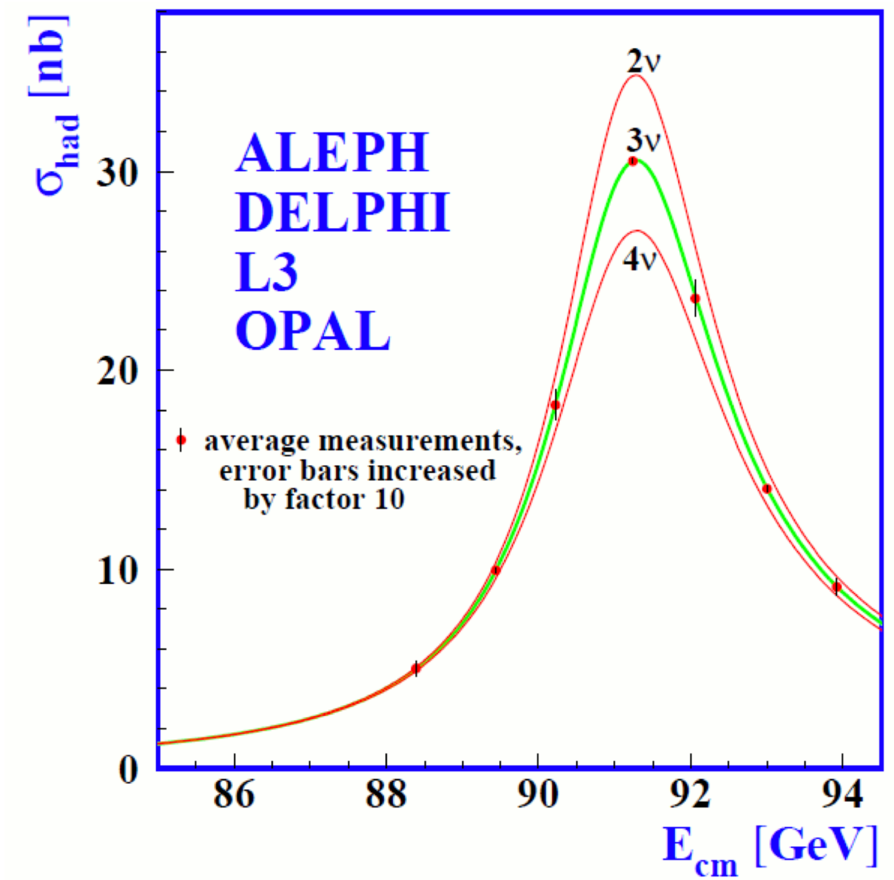
L/E ~ $\mathcal{O}(10^3$ km/GeV)

Well-measured with atmospheric and accelerator neutrinos



The three-flavour picture

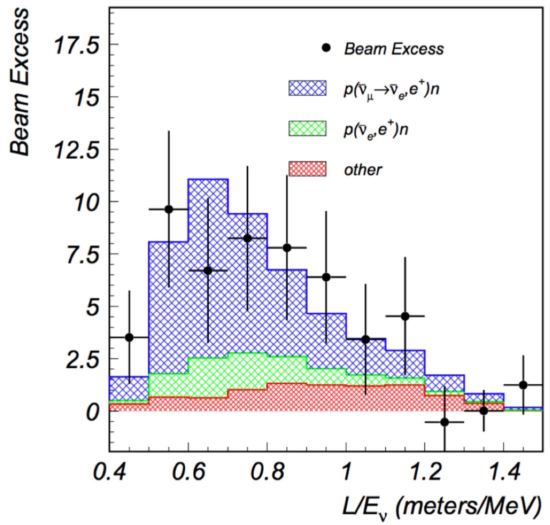
$$\Gamma_Z = \Gamma(Z^0 \to q\bar{q}) + 3\Gamma(Z^0 \to e^+e^-) + N_\nu \Gamma(Z^0 \to \nu\bar{\nu})$$



e^+e^- scattering confirms our suspicions

- $N_\nu = 2.984 \pm 0.008$

So what's the problem?

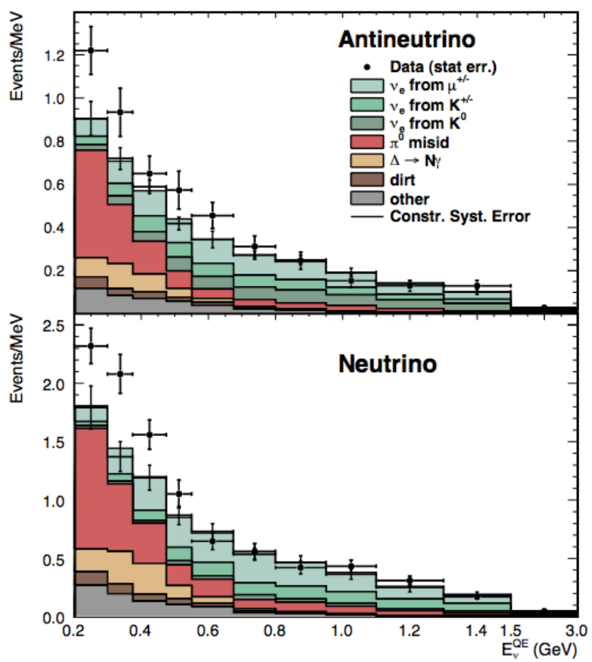


LSND

An antielectron-like excess in a $\bar{\nu}_\mu$ beam

L/E = O(1 km / GeV)

Phys. Rev. **D64**, 112007 (2001)



MiniBooNE

Similar electron- and antielectron-like excesses in ν_μ and $\bar{\nu}_\mu$ beams

L/E = O(1 km / GeV)

Phys. Rev. Lett. **110**, 161801 (2013)

This would require Δm^2 = O(1 eV^2)

- Does not fit with the three-flavour picture

The light, sterile neutrino

e^+e^- scattering tells us this neutrino doesn't couple with the Z boson

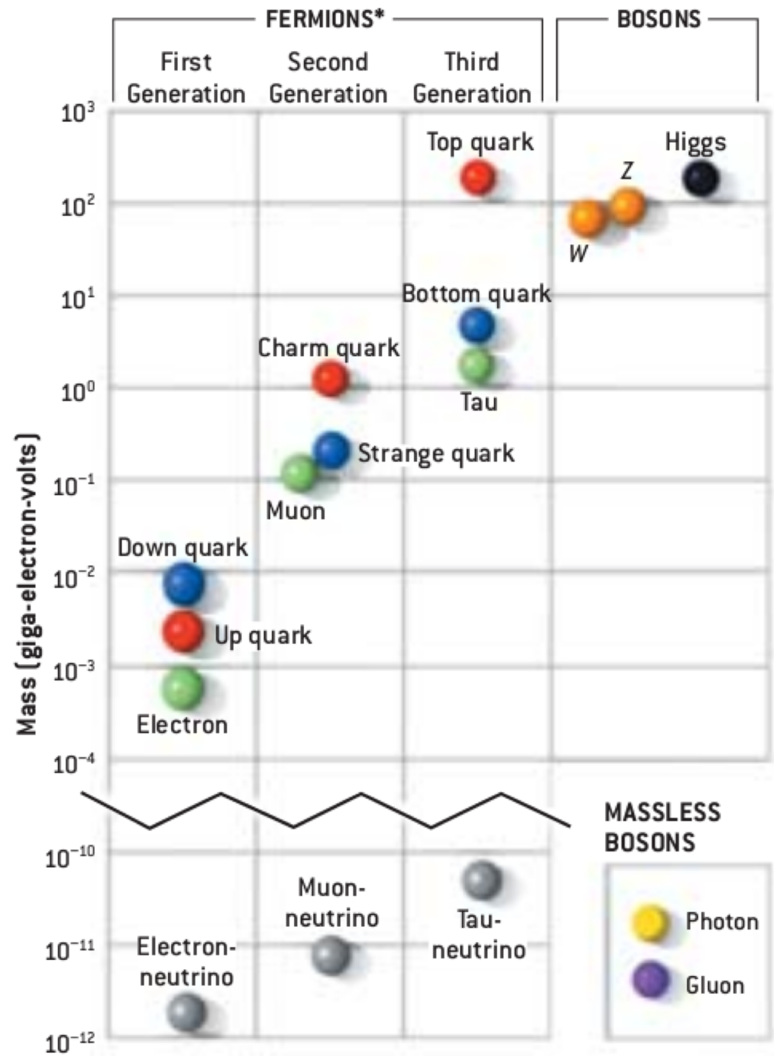
- Sterile – oscillations are the only way we can see it

'Light' means eV rather than keV (or above) scale

- Theorists love heavy sterile neutrinos, e.g. seesaw models with Majorana neutrinos

Sterile neutrinos aren't a crazy idea

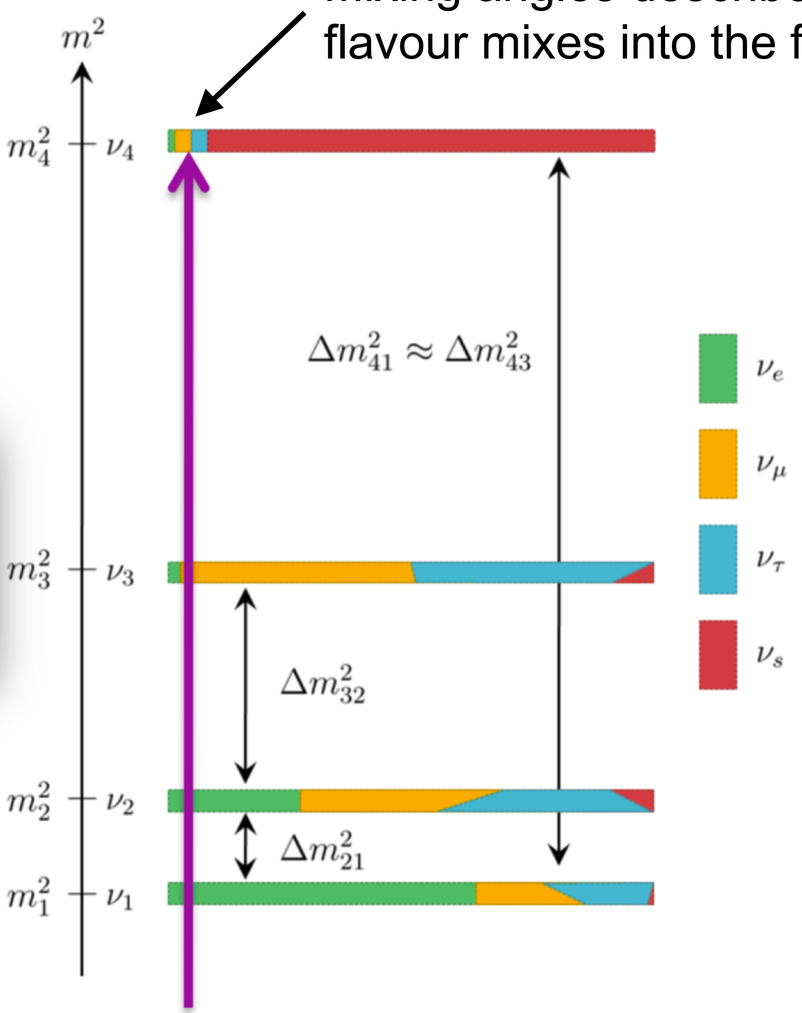
- Neutrinos are light, are the only neutral fermion, and only spin one way
- There's definitely something odd about them, suggesting new physics is involved somewhere



The 3+1 model

Mixing angles describe how much active flavour mixes into the fourth mass state

θ_{14}: electron flavour
θ_{24}: muon flavour
θ_{34}: tau flavour



The standard phenomenological model used to compare data sets

- Just add one new mass eigenstate and one sterile flavour state

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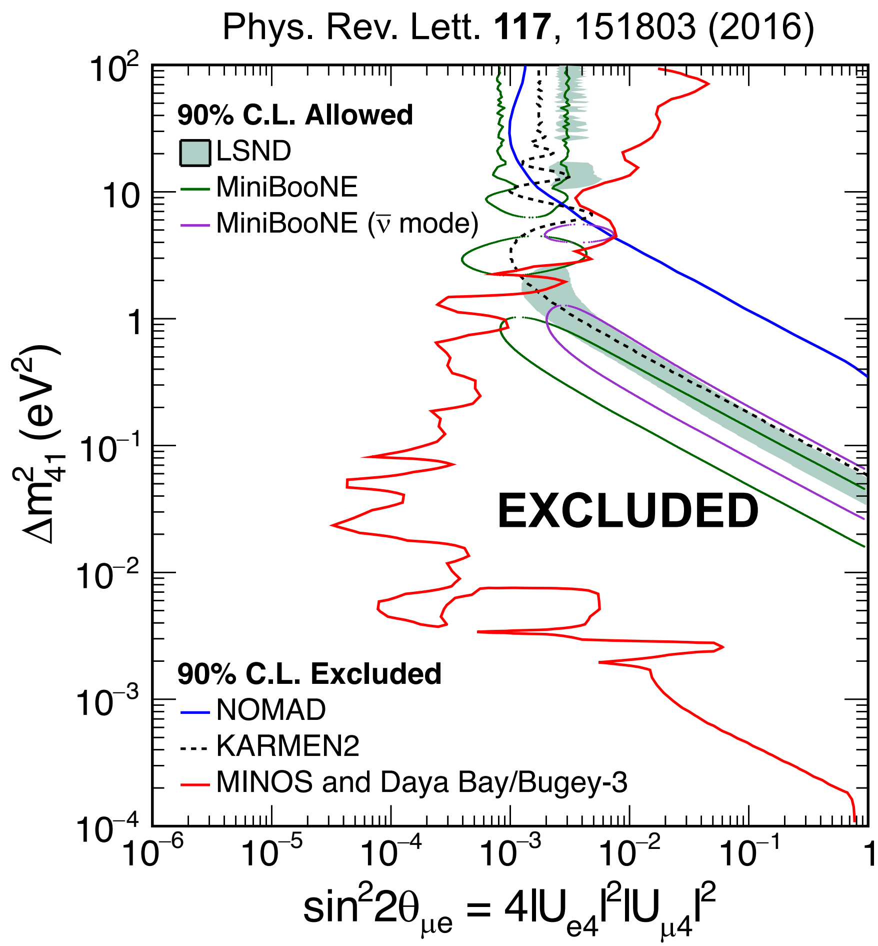
Contention



- LSND and MiniBooNE see sterile neutrinos
- Some gallium and reactor measurements also favour a sterile neutrino
- Other experiments rule out most of their parameter space

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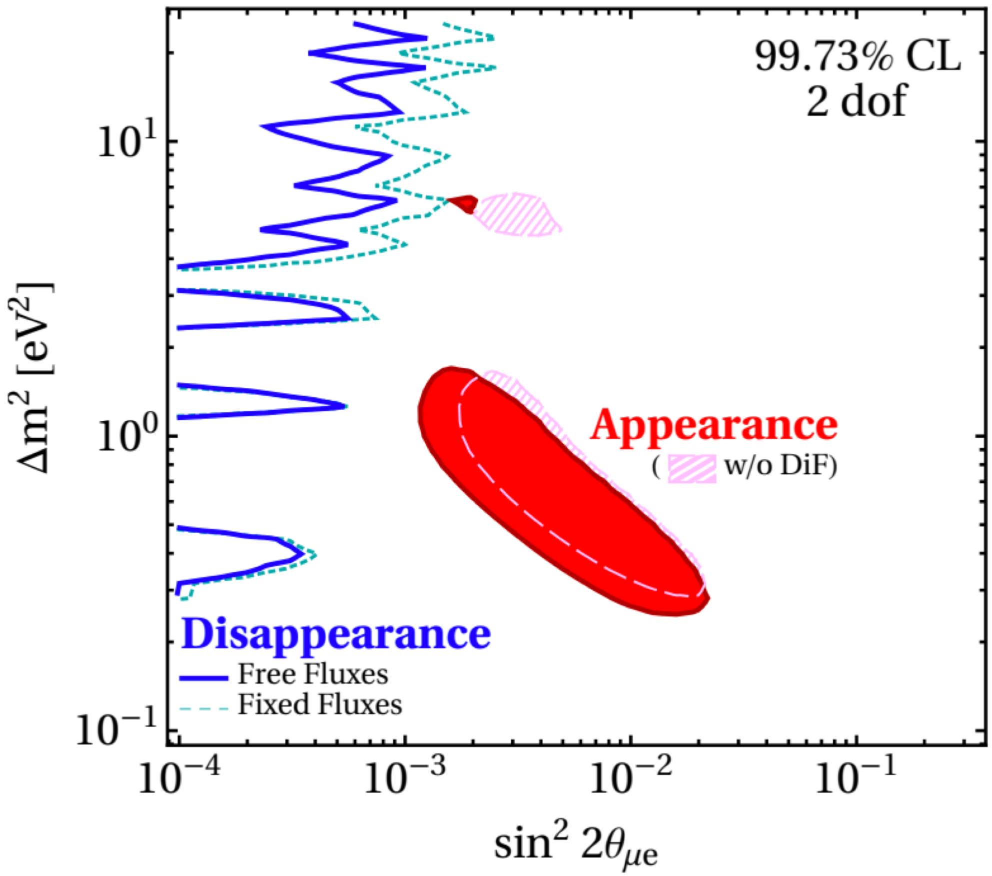
The 3+1 model

M. Dentler *et al.*, arXiv:1803.10661



The standard phenomenological model used to compare data sets

- Just add one new mass eigenstate and one sterile flavour state

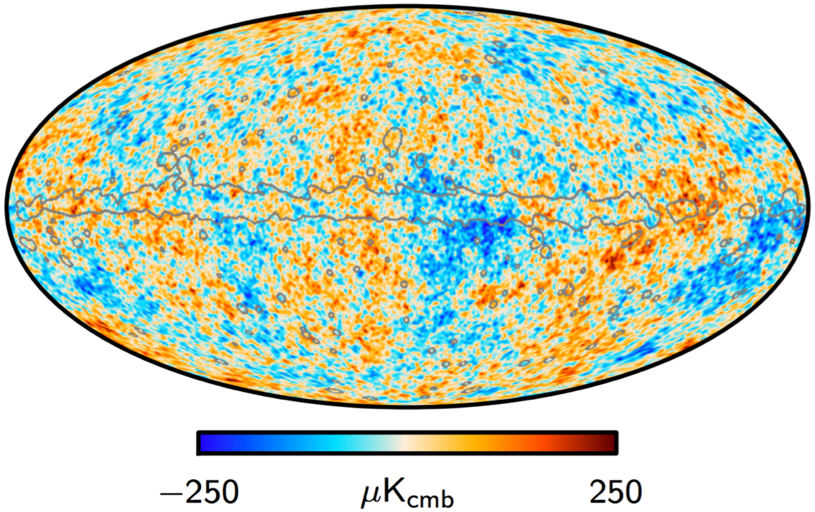
Not possible to explain all data using this model

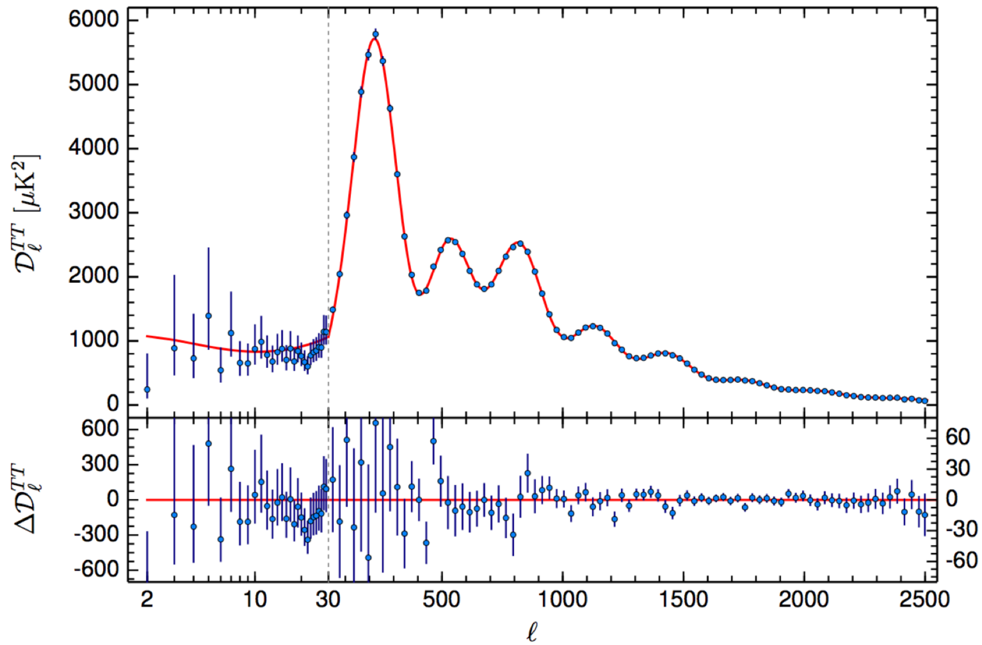
Can of course move to 3+2, 3+3 models…

- Still hard to reconcile all data
- But you can always keep adding parameters

Cosmic Microwave Background

Planck: A&A **594**, A11 (2016)

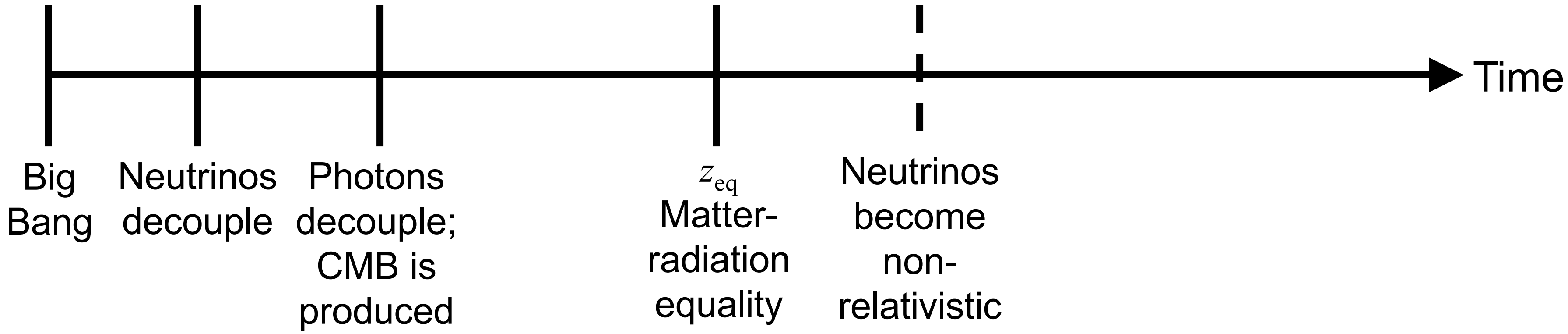




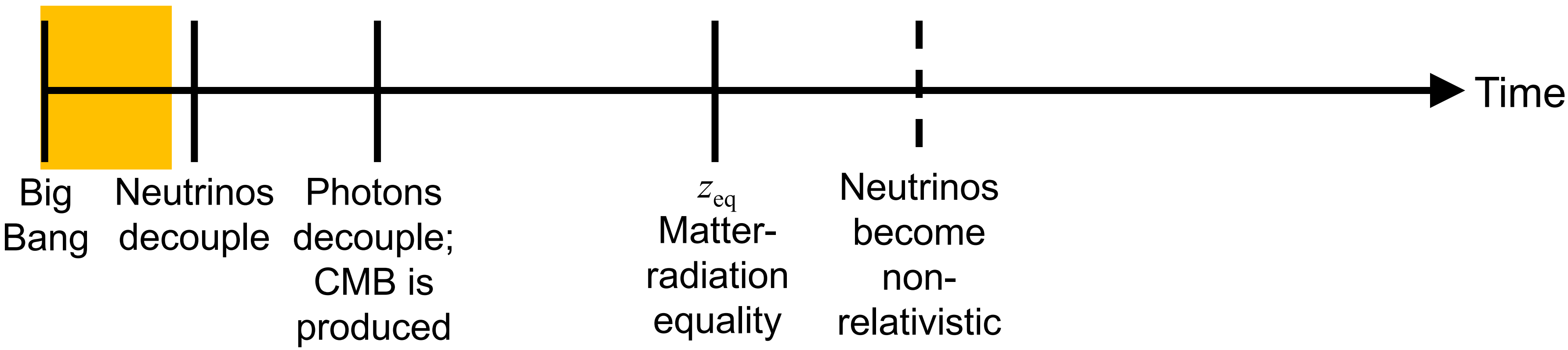
Cosmic Microwave Background provides another constraint on the existence of sterile neutrinos

- Specifically the power spectrum – angular size of fluctuations
- Not usually compared directly to the particle physics constraints

Cosmology


Time
Big Bang
Neutrinos decouple
Photons decouple; CMB is produced
z_{eq}
Matter-radiation equality
Neutrinos become non-relativistic

Neutrino sea



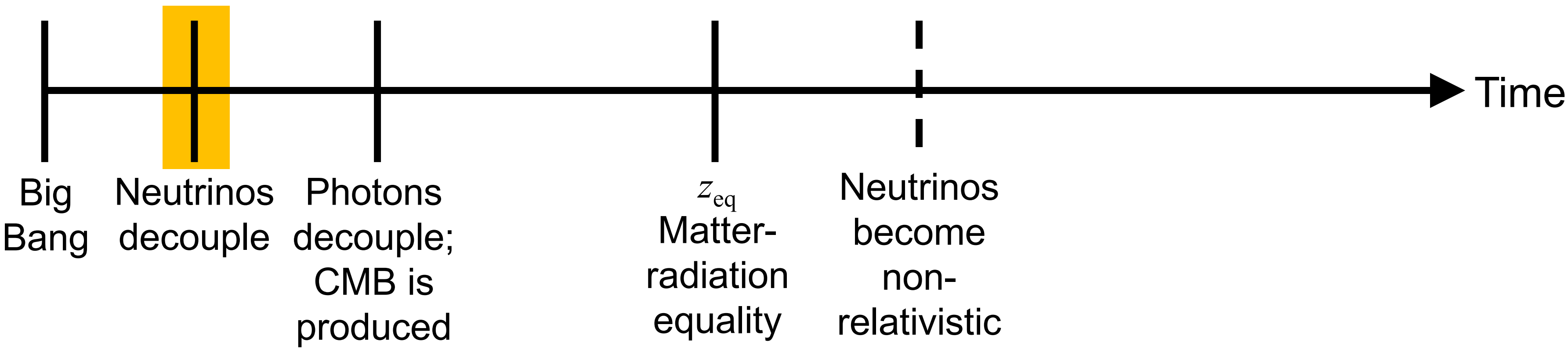
Frequent weak interactions in the early universe

- $\nu_{e,\mu,\tau}$ kept in thermal equilibrium
- Momentum spectrum has a Fermi-Dirac form:

$$f_{\text{eq}}(p,T) = \frac{1}{e^{\frac{(p-\mu_\nu)}{T}} + 1}$$

- (μ_ν is a chemical potential, only exists if there is a neutrino-antineutrino asymmetry)
- With this function and some statistical mechanics, various properties of the neutrino sea can be calculated

Neutrino decoupling



T ~ 1 MeV

- Neutrinos decouple, but are still relativistic (i.e. radiation)
- Slightly flavour-dependent since there are more electrons around than muons or taus
- Fermi-Dirac distribution is frozen in, and then redshifts

N_{eff} is the number of relativistic degrees of freedom in this radiation sea

A short time later $T < m_e$ and e^+e^- pairs annihilate to photons

- This increases the temperature of the CMB
- The neutrino-electron interactions produce percent-level fluctuations to the high-energy part of the neutrino momentum distribution
- Increases N_{eff} from 3 to 3.046

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The expanding universe

Friedman equation

- a is the size of the universe
- ρ is the energy density
- p is the radiation pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

$$\rho = \underbrace{\rho_\gamma + \rho_\nu}_{\rho_r} + \rho_{\mathrm{CDM}} + \rho_{\mathrm{b}} + \rho_\Lambda$$

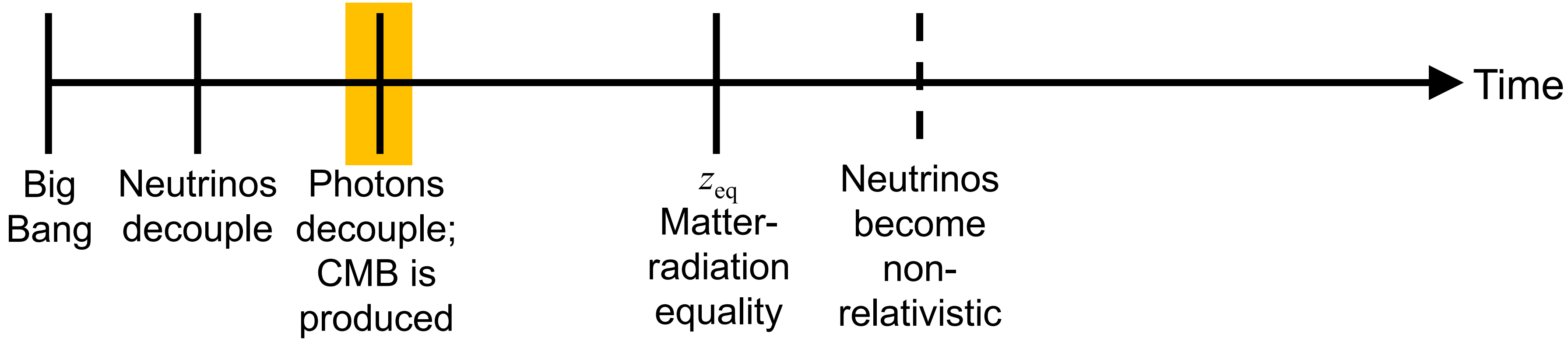
ρ_r: radiation energy density (before neutrinos become non-relativistic)

$$\rho_r = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right]\rho_\gamma$$

Can relate the neutrino energy density to the photon energy density

- Then measure the photon properties from the CMB
- And your remaining free parameter is N_{eff}

Birth of the Cosmic Microwave Background



Photons decouple and the CMB is produced

- Fluctuations are frozen in

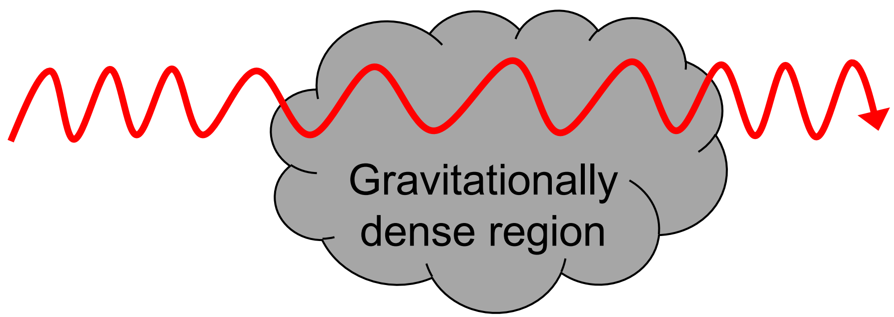
An increase in N_{eff}, or neutrino mass, can change when this happens

- Changes the size of the fluctuations on the sky

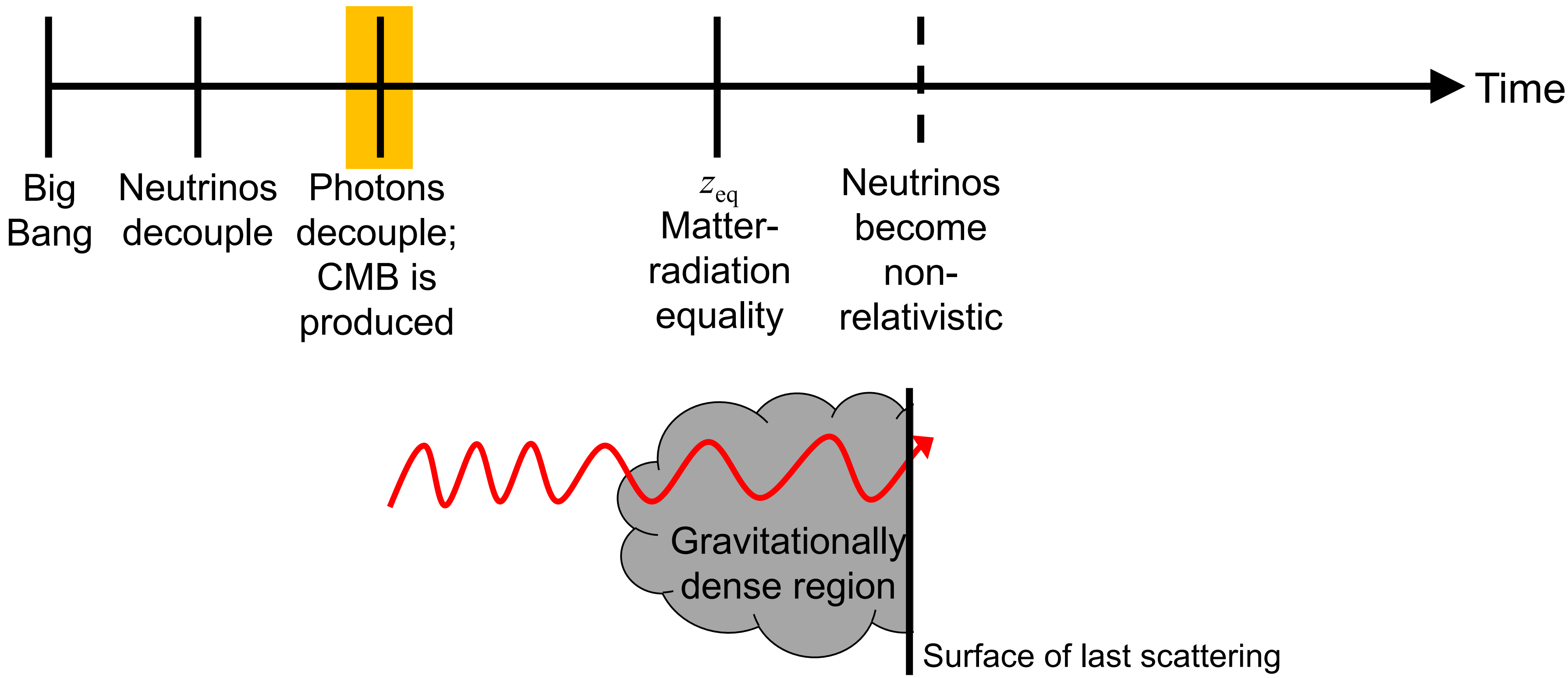
Sachs-Wolfe effect

Photon is red-shifted on the way in, blue shifted on the way out

- The end result is uninteresting: a photon with the same wavelength as it started
- But there are situations where the end result is more interesting…



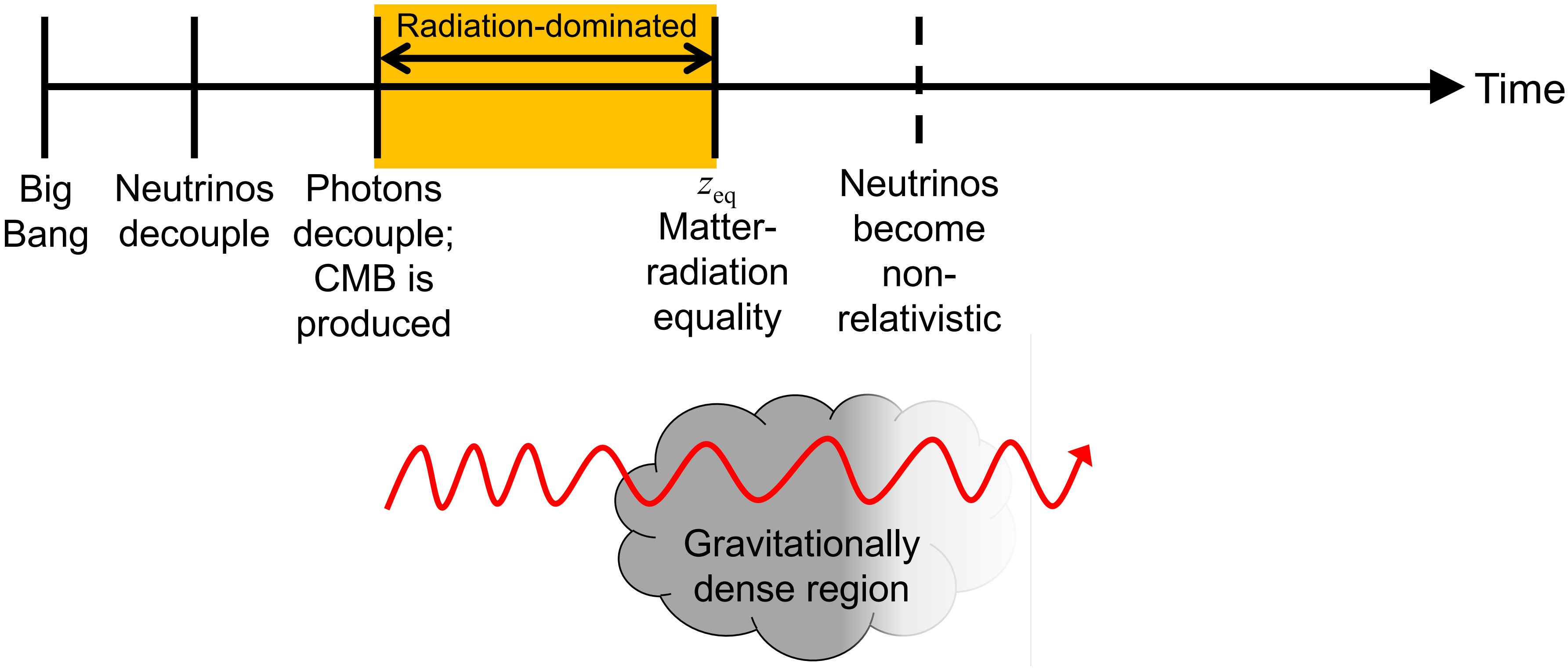
Sachs-Wolfe effect



Gravitational fluctuations at moment the CMB is produced

- Red / blue shift is frozen in

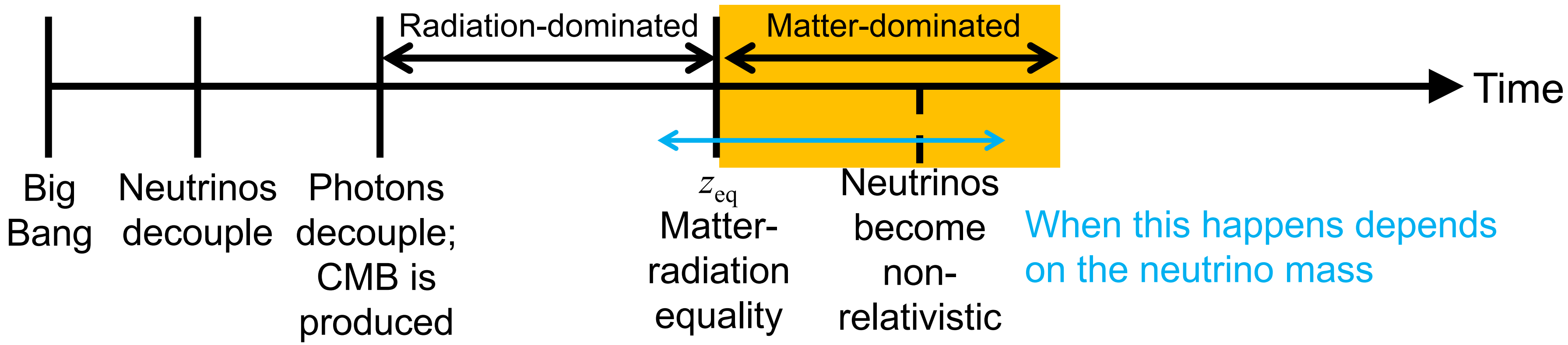
Early-time integrated Sachs-Wolfe effect



Radiation modifies the regional gravitational perturbation as the photon passes through

- The photon gains an overall redshift or blueshift
- Neutrinos with masses below 1 eV are radiation at this point

Matter-dominated universe



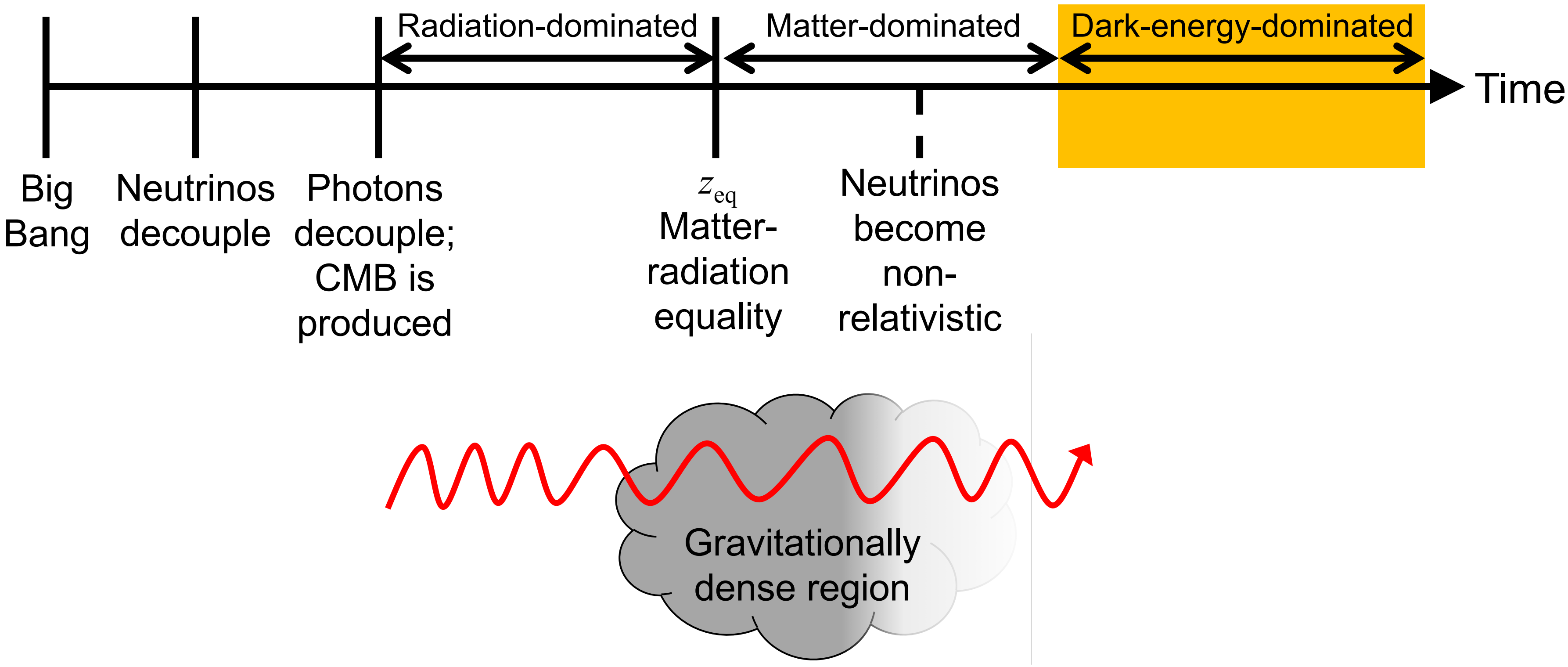
Gravitational perturbations are fairly constant

- No integrated Sachs-Wolfe effect

The presence of more or less non-relativistic matter (neutrinos) affects how much the universe has expanded since the CMB was produced

- Changes the angular size of the fluctuations
- Depends on the neutrino mass

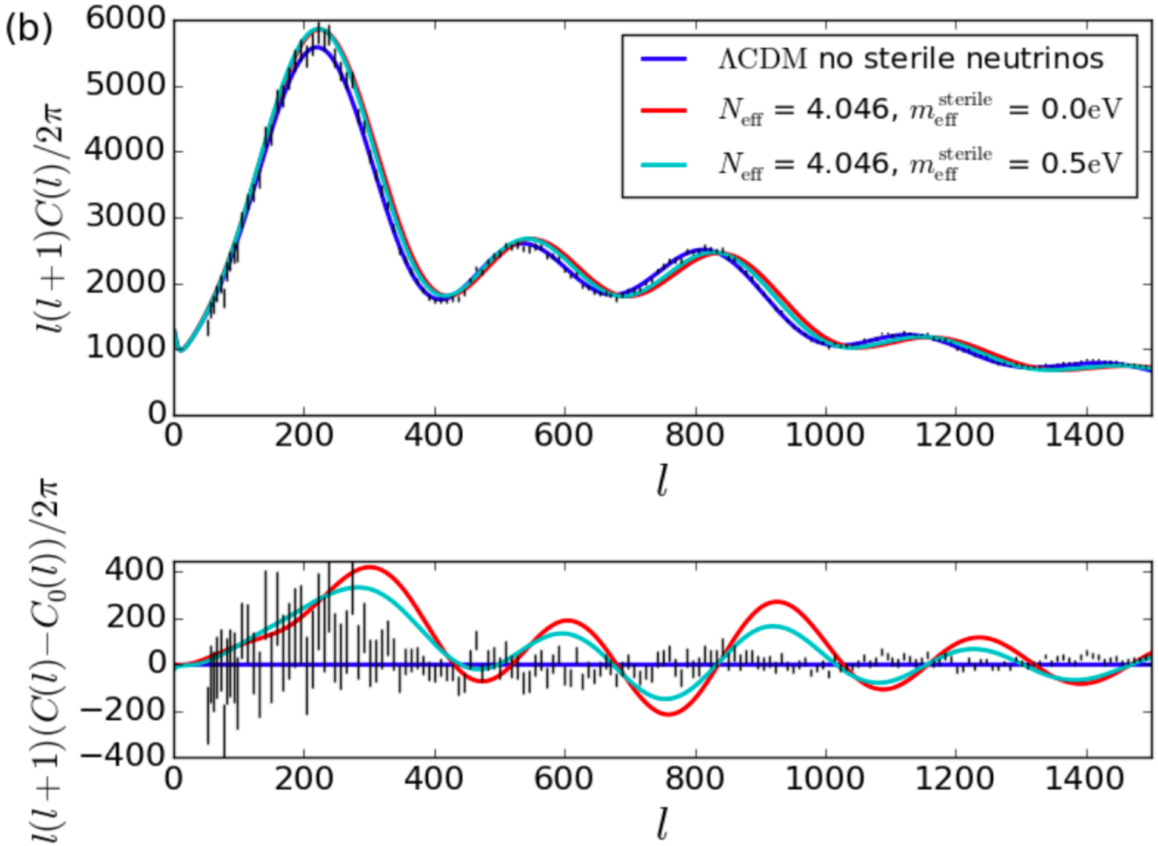
Late-time integrated Sachs-Wolfe effect



Dark energy washes out the gravitationally dense regions (superclusters) as photons pass through

- A redshift or blueshift can be frozen in
- The presence of additional non-relativistic matter (neutrinos) changes the shape of these regions of overdensity

Sterile neutrinos and the CMB



The ways in which neutrinos impact the CMB power spectrum are hugely complicated

- But changes in m_{eff} and N_{eff} alter the positions and amplitudes of the peaks

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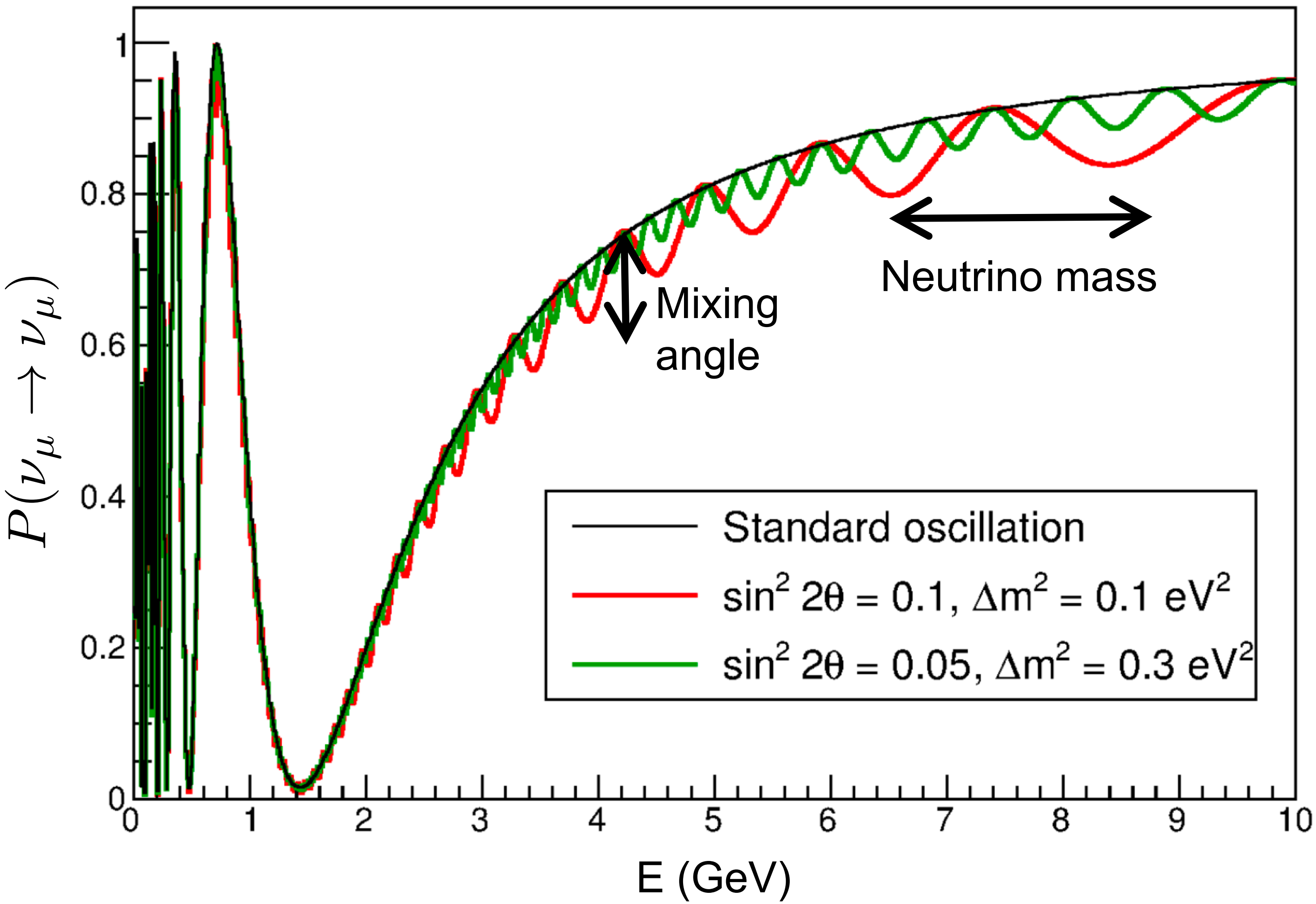
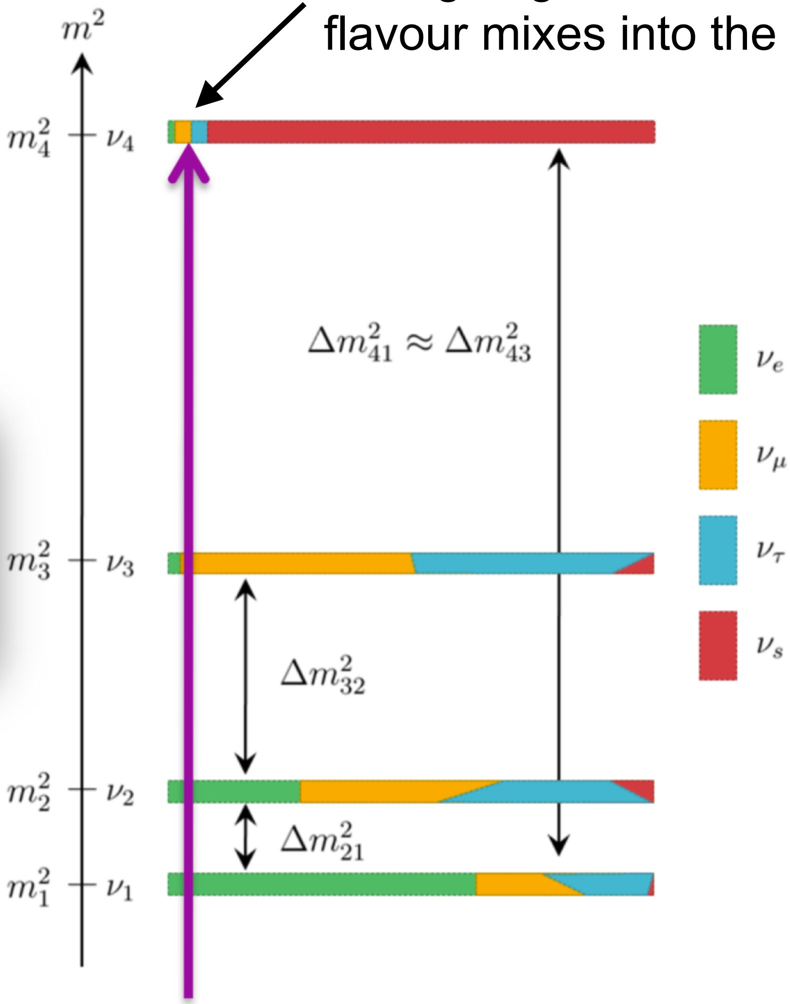
Sterile neutrinos and neutrino oscillations



Relating particle physics to cosmology

Mixing angles describe how much active flavour mixes into the fourth mass state

θ_{14}: electron flavour
θ_{24}: muon flavour
θ_{34}: tau flavour



- Mass splitting relates fairly easily to m_{eff}

$$m_{\text{eff}} = \sum_i m_i$$

- But what about the mixing angles and N_{eff}?

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Decoupling of a sterile neutrino

S. Hannestad *et al.*, Cosmol Astropar. Phys. **2012**, 025 (2012), arXiv:1204.5861

K. Enqvist *et al.*, Nucl. Phys. B **373**, 498 (1992)

Typically work in a 'two-flavour' model

$$\nu_a = \cos\theta_s \nu_1 - \sin\theta_s \nu_2 \quad \text{(active flavour)}$$

$$\nu_s = \sin\theta_s \nu_1 + \cos\theta_s \nu_2 \quad \text{(sterile flavour)}$$

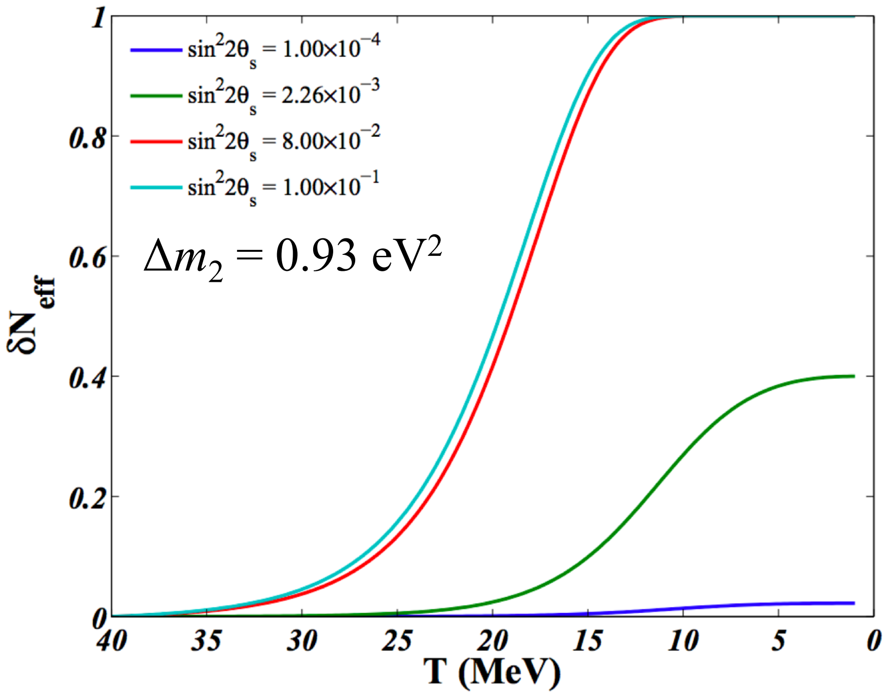
- θ_s is θ_{14}, θ_{24} or θ_{34}, depending on which active flavour we allow to mix into the new mass state

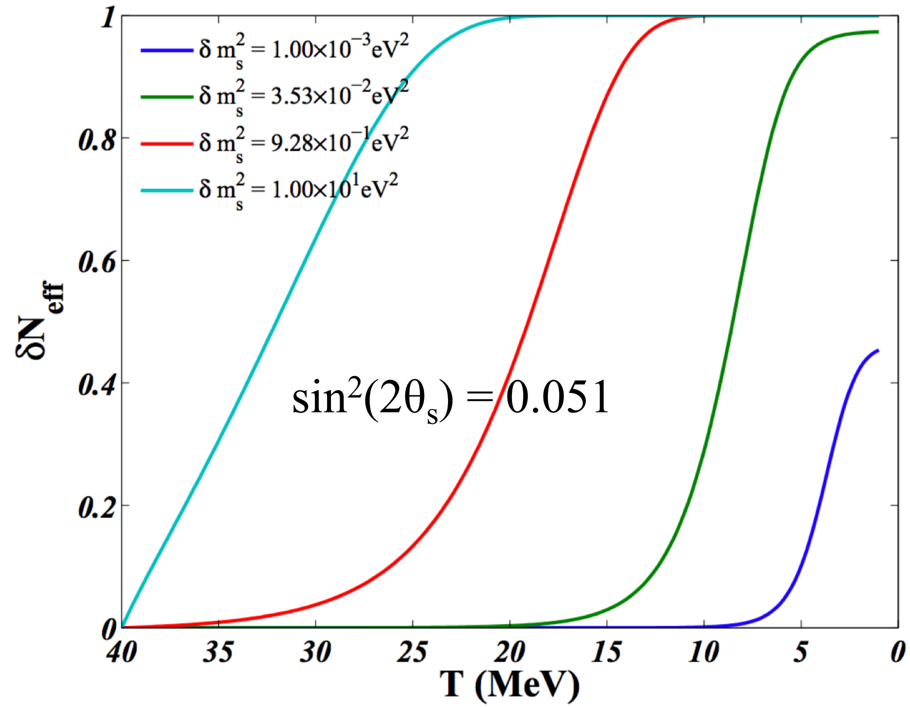
Hannestad and Enqvist papers numerically solve the quantum-kinetic equations

Define δN_{eff}

- Additional relativistic degrees of freedom, beyond 3.046, introduced by the sterile neutrino
- The size off the mixing angle defines how strongly the sterile state couples to the Fermi-Dirac distribution before decoupling
- For a small mixing angle, the sterile neutrino does not produce an entire extra degree of freedom: $\delta N_{eff} < 1$

Decoupling of a sterile neutrino





Define δN_{eff}

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Graphs from S. Hannestad *et al*., Cosmol Astropar. Phys. **2012**, 025 (2012), arXiv:1204.5861

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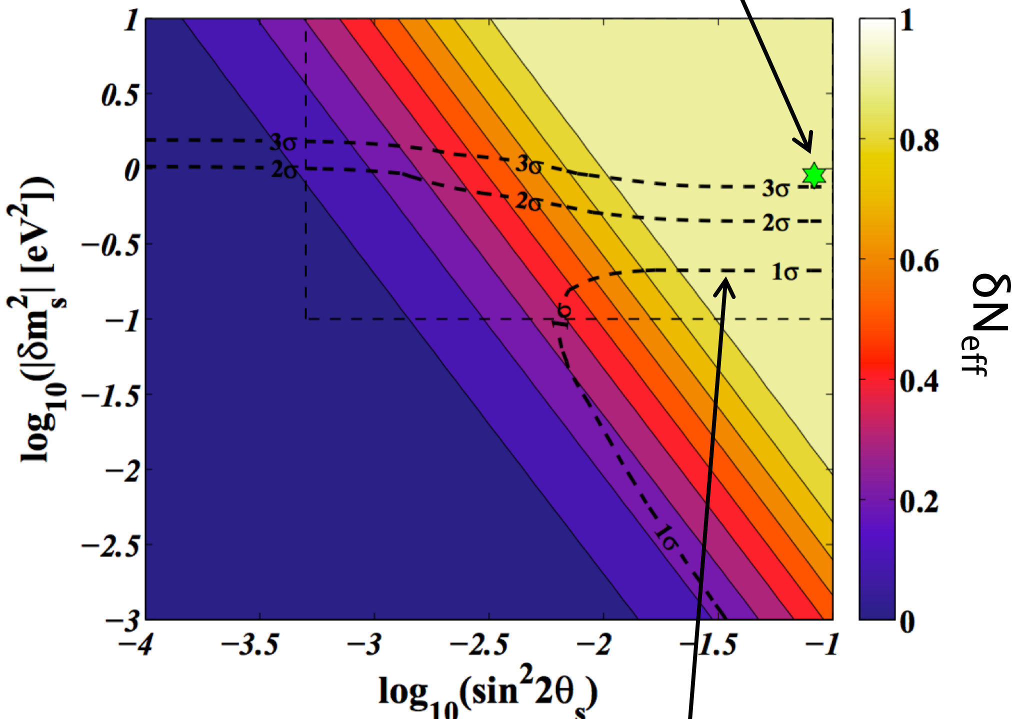
Relating particle physics to cosmology

The Hannestadt *et al.* work allows us to relate our three parameters

- δm^2_s, $\sin^2(2\theta_s)$ and δN_{eff}

Giunti & Laveder 3+1 best fit (Phys Lett B706, 200 (2011))



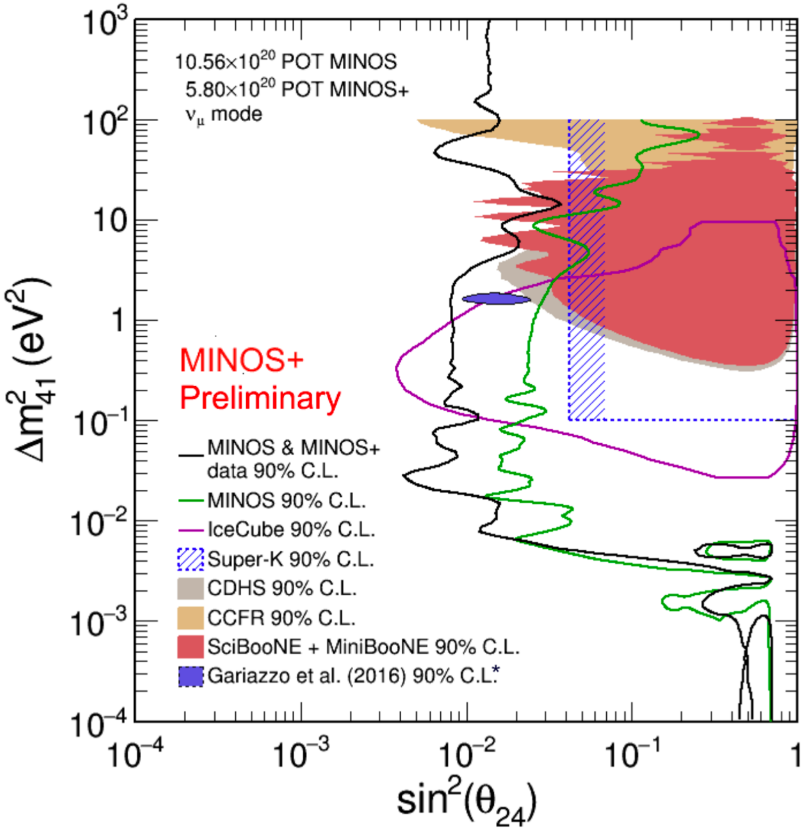
Pre-Plank CMB and large scale structure exlusion region

Graph from S. Hannestad *et al*., Cosmol Astropar. Phys. **2012**, 025 (2012), arXiv:1204.5861

Muon neutrino measurements

MINOS result: Phys. Rev. Lett. **117**, 151803 (2016) (not the most recent)

IceCube result: Phys. Rev. Lett. **117**, 071801 (2016)



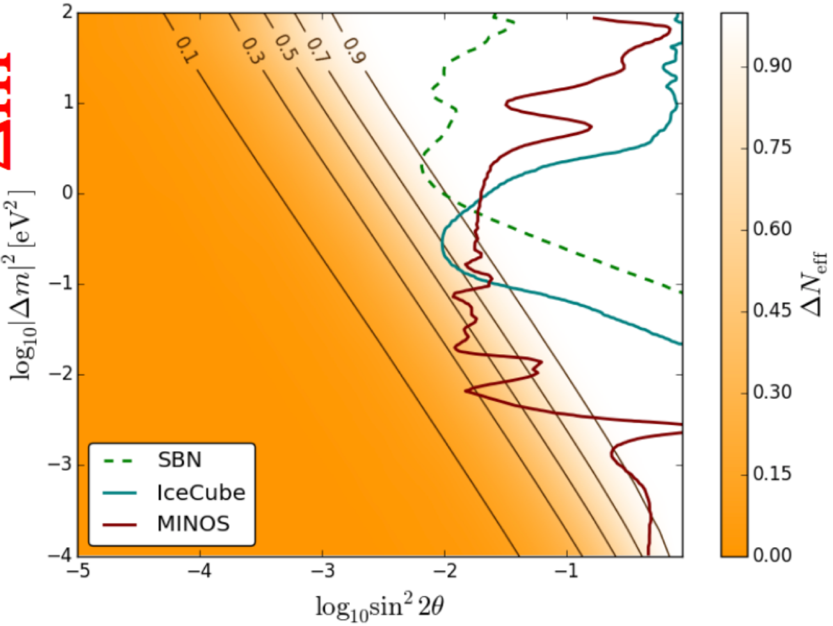
Assume $\theta_{14} = \theta_{34} = 0$, and leave θ_{24} free

- Only muon flavour mixes with the fourth mass state
- Allows comparison with the MINOS and IceCube ν_μ-disappearance limits

Particle physics → cosmology

ΔN_{eff}

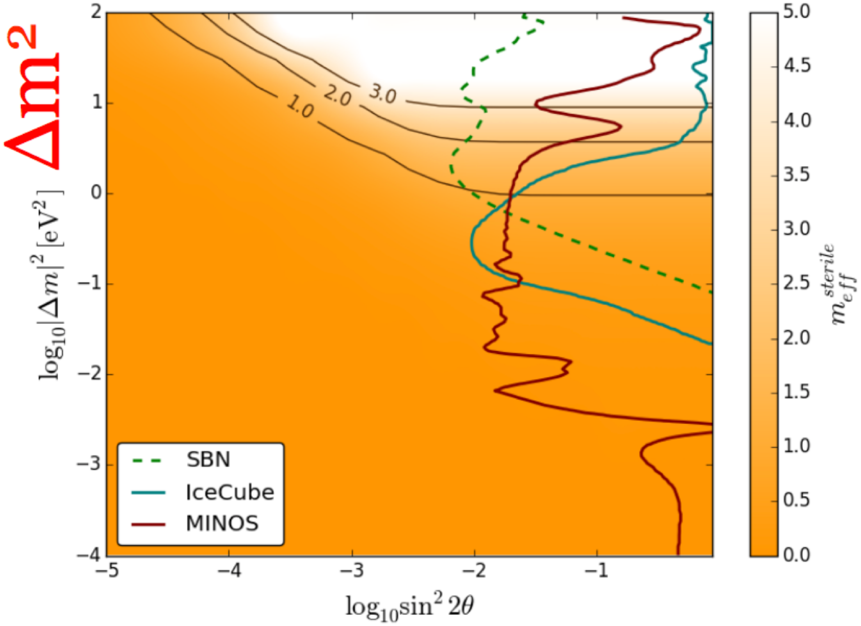
Δm^2



$\sin^2 2\theta$

m_{eff}

Δm^2



$\sin^2 2\theta$

S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

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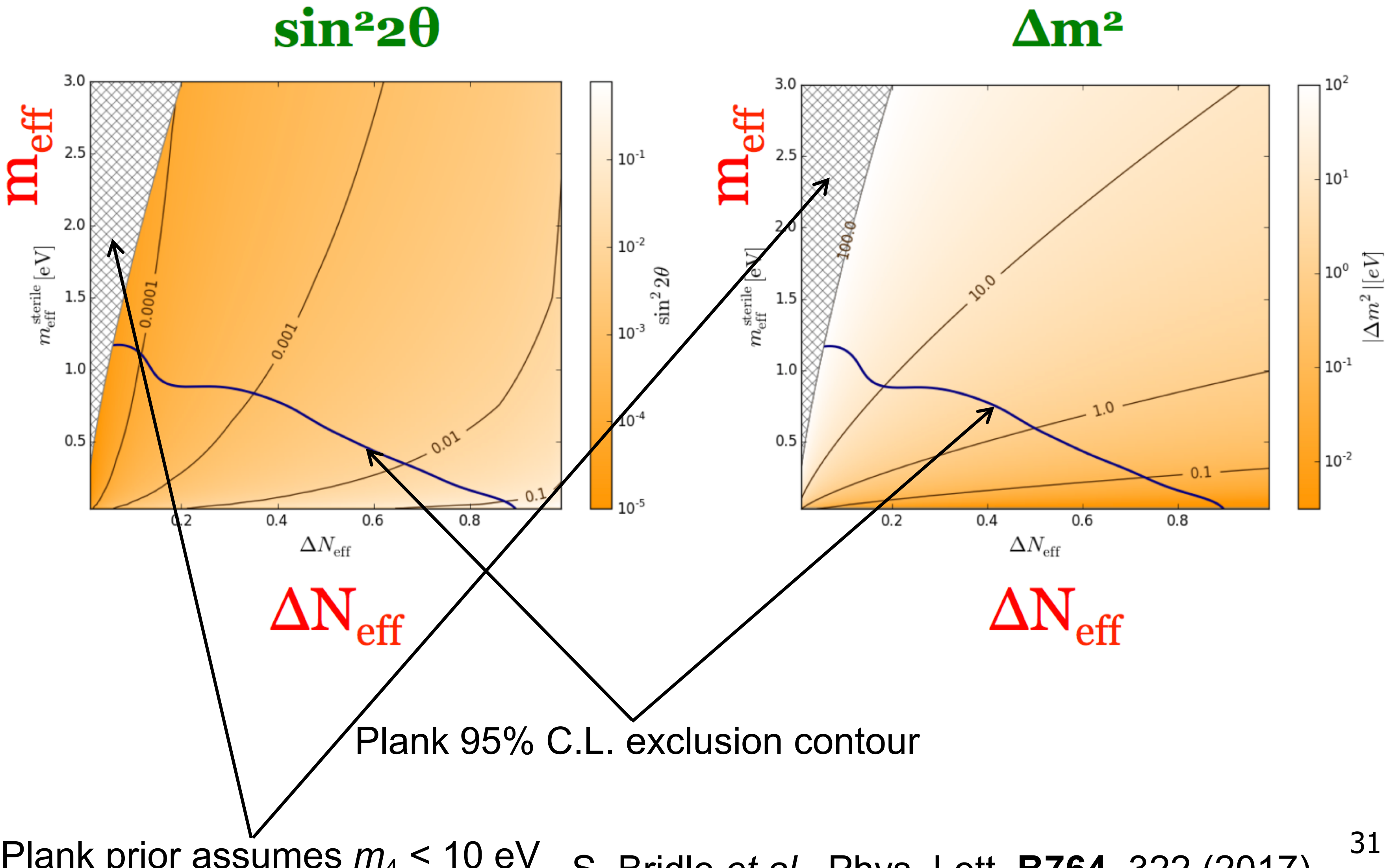
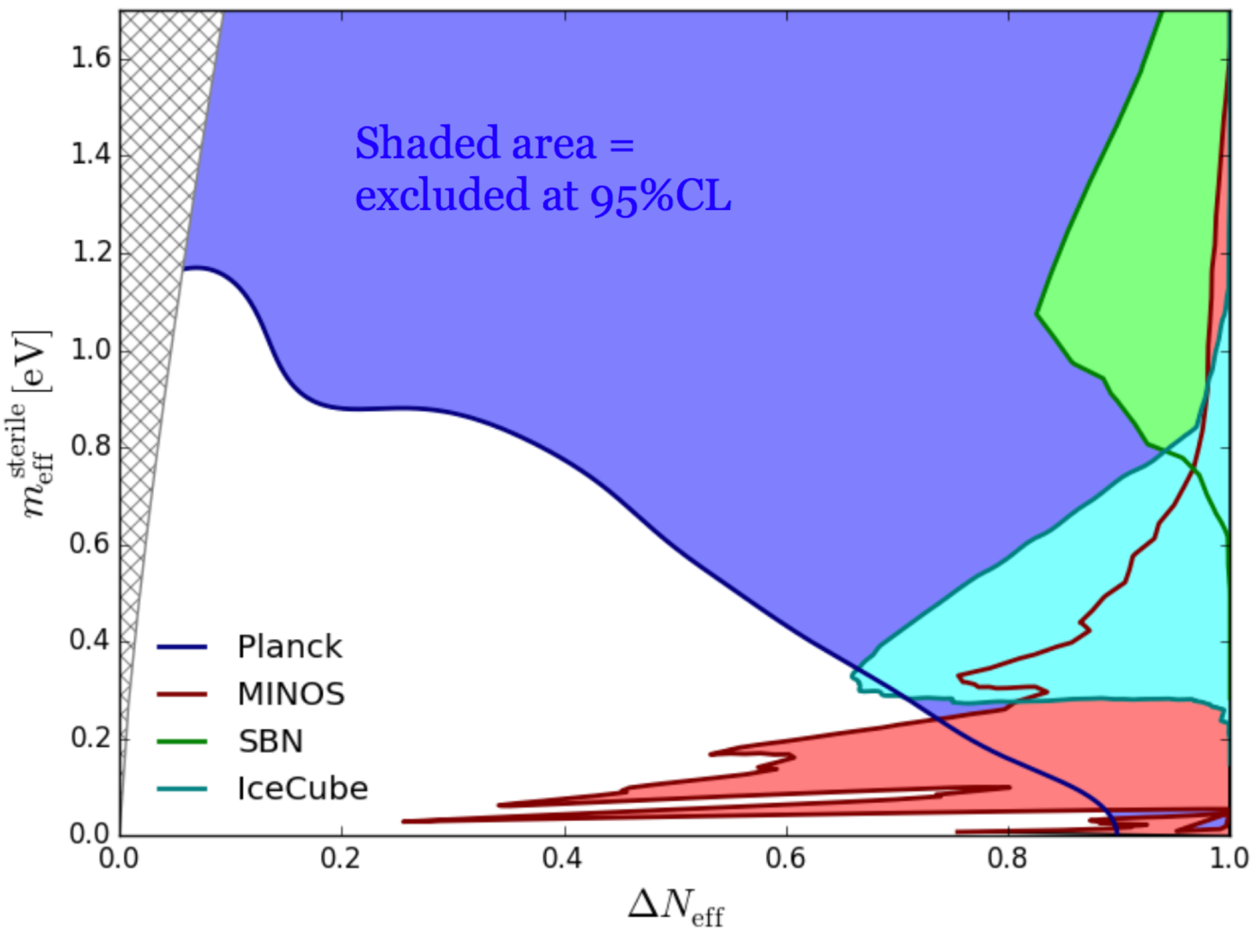
Cosmology → particle physics



S. Bridle *et al*., Phys. Lett. **B764**, 322 (2017)

Cosmology space



Cosmological limits are weakest at low masses, where MINOS+ becomes stronger

- And remember: new MINOS+ limits now available

S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

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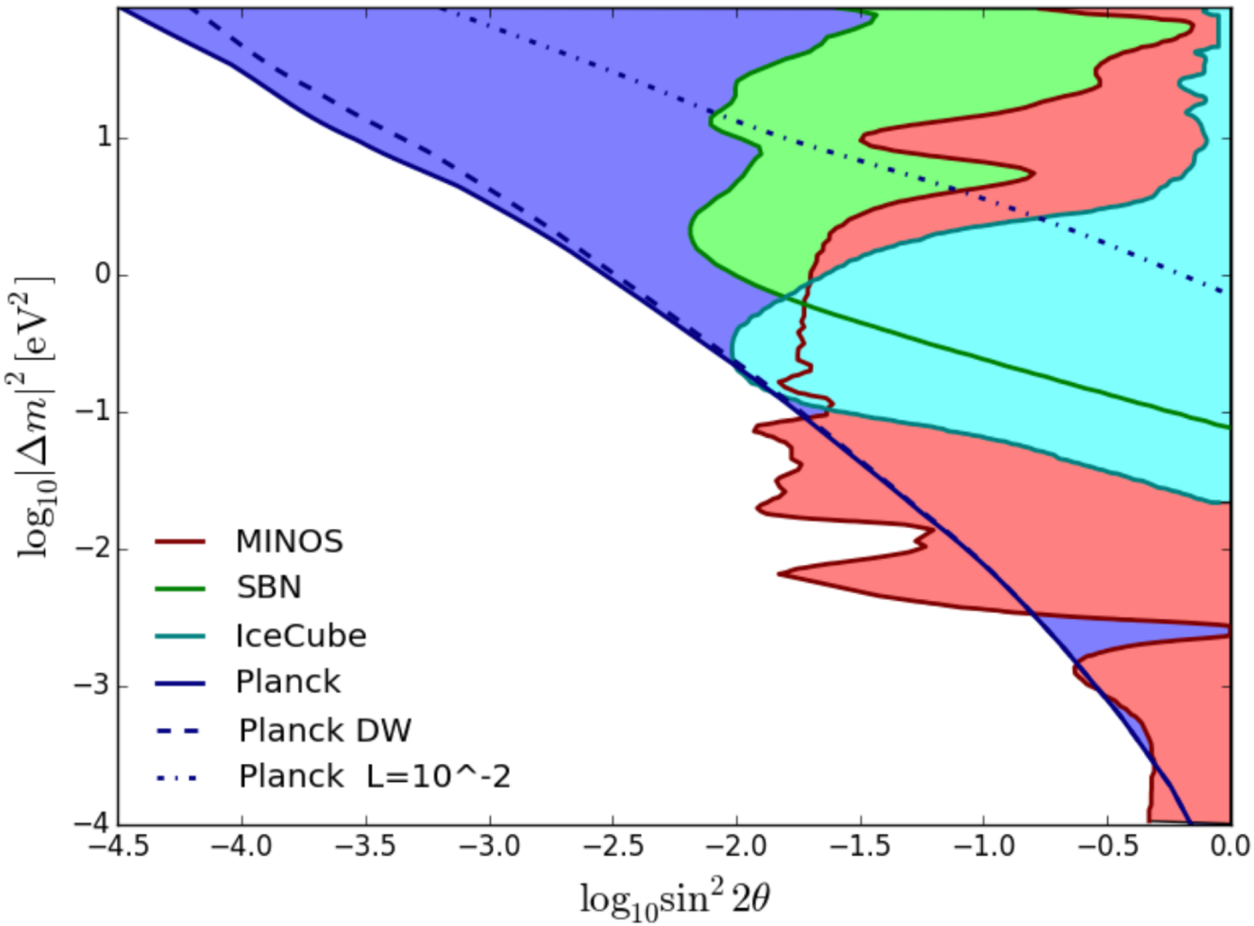
Neutrino physics space

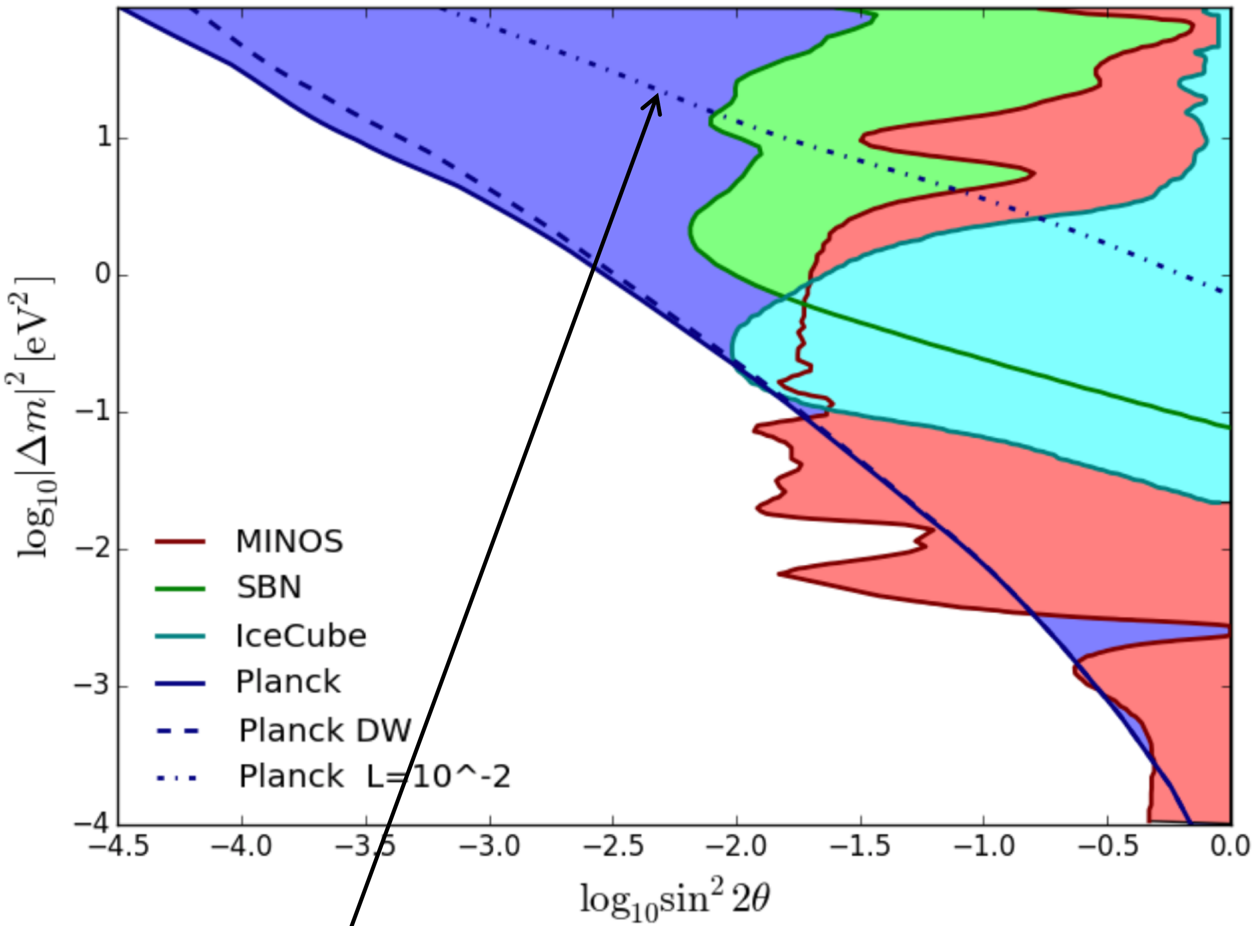


Cosmological limits are weakest at low masses, where MINOS+ becomes stronger

- And remember: new MINOS+ limits now available

S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

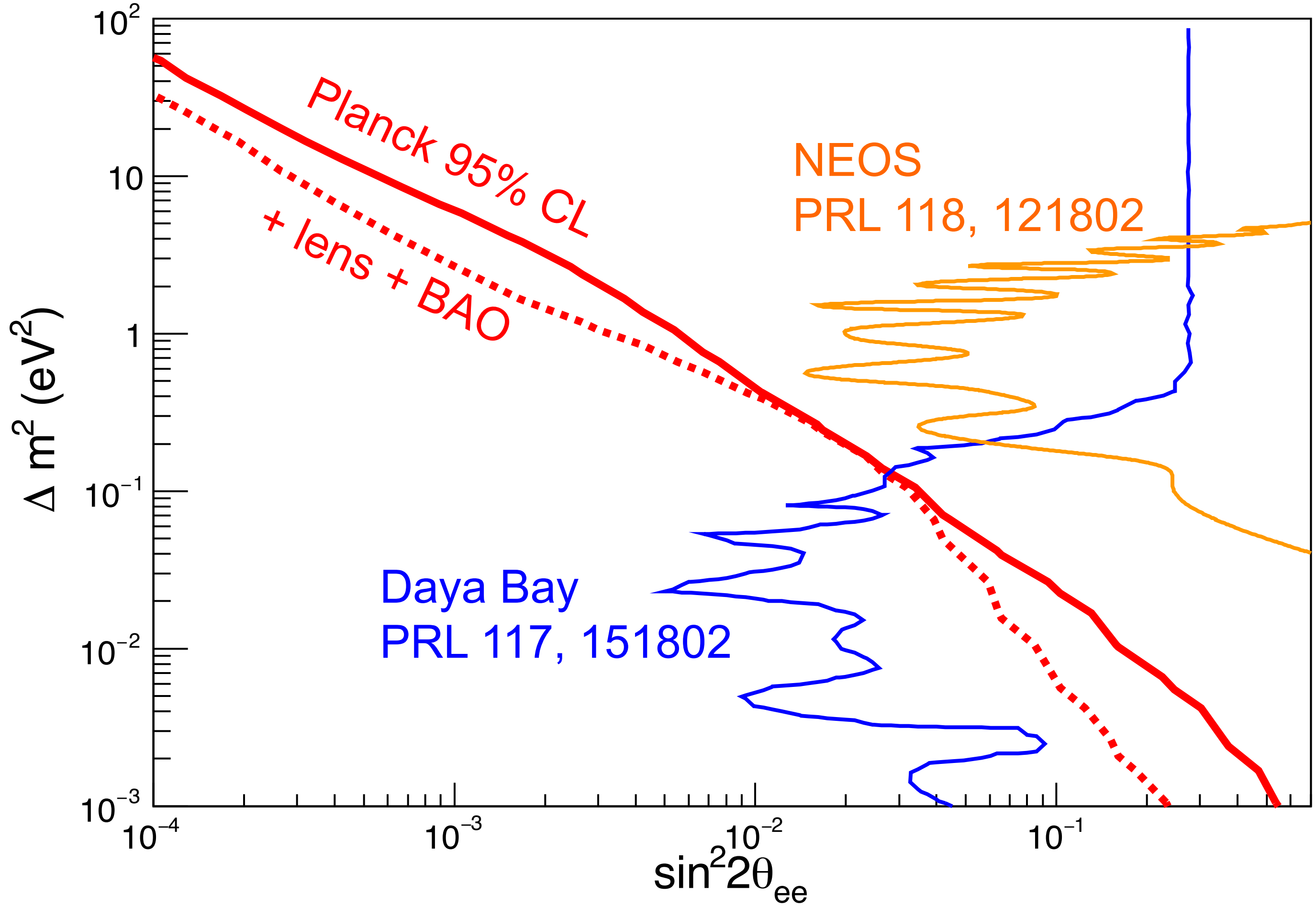
Model dependence



Adding in a neutrino-antineutrino asymmetry at the extreme of possibilities (i.e. a chemical potential)

S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

Electron-antineutrino disappearance limits

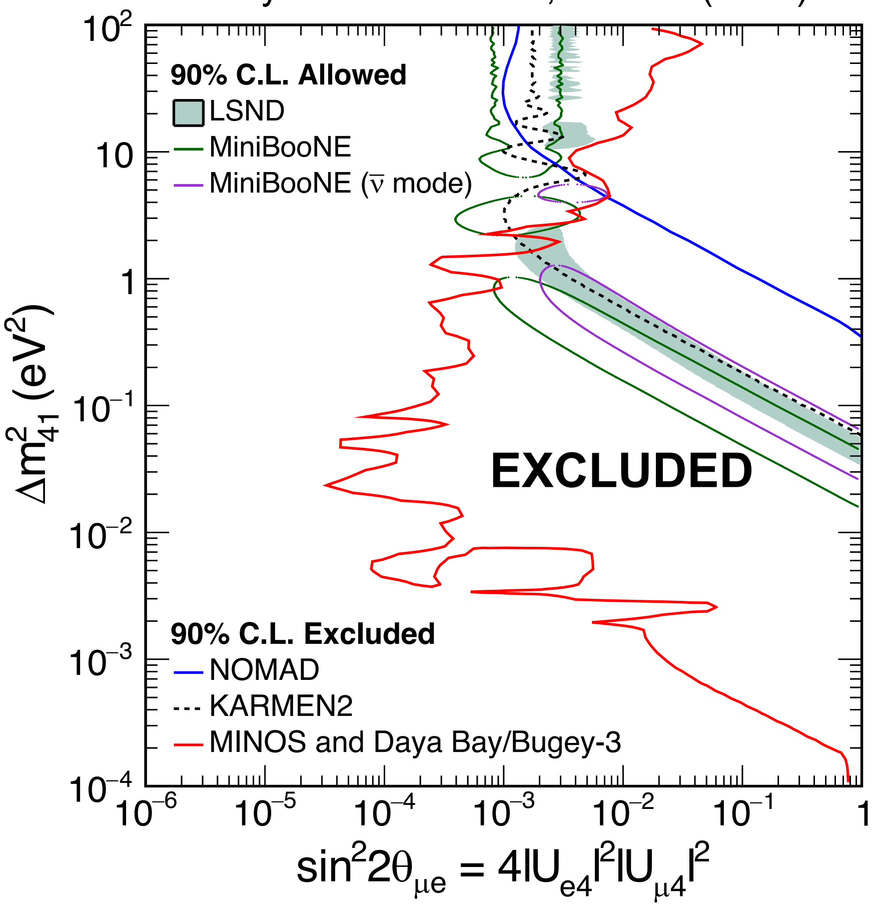


Assume $\theta_{24} = \theta_{34} = 0$, and leave θ_{14} free

- Only electron flavour mixes with the fourth mass state
- Allows comparison with reactor limits

Comparing to appearance results

Phys. Rev. Lett. **117**, 151803 (2016)



The LSND and MiniBooNE hints come from the channel $\nu_\mu \rightarrow \nu_e$ (and the CP conjugate)

This requires both muon and electron flavour to mix with the fourth mass state

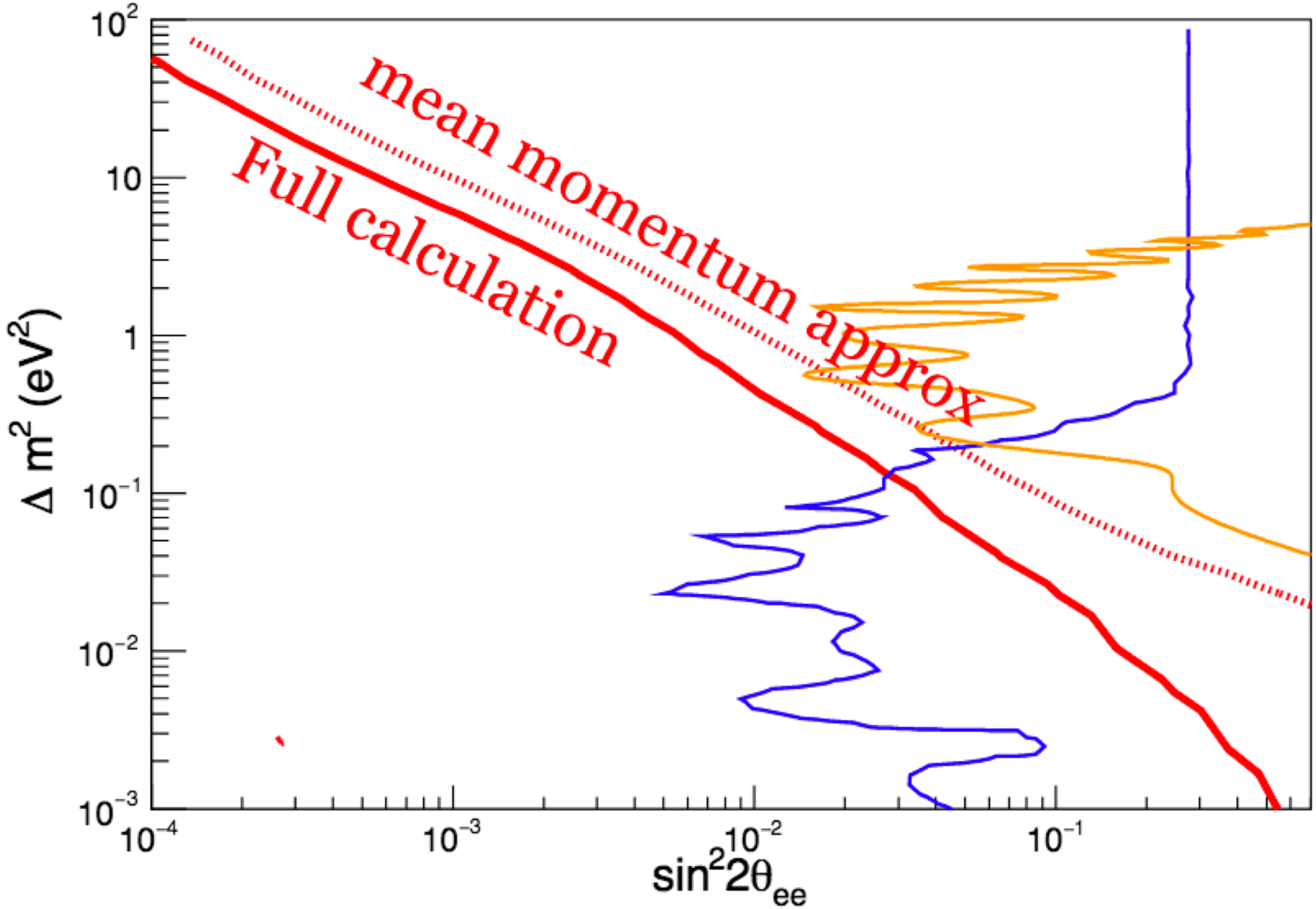
- θ_{24} and θ_{14} must be free parameters

A. Mirizzi *et al*. Phys. Rev. **D86**, 053009 (2012) provides a prescription for decoupling the neutrino sea and calculating δN_{eff}

But requires an approximation

- Instead of a Fermi-Dirac distribution, assume all neutrinos have the mean momentum

Moving to three-flavours



Test this mean-momentum approximation on the electron-neutrino-only case

- Where we can do the exact calculation

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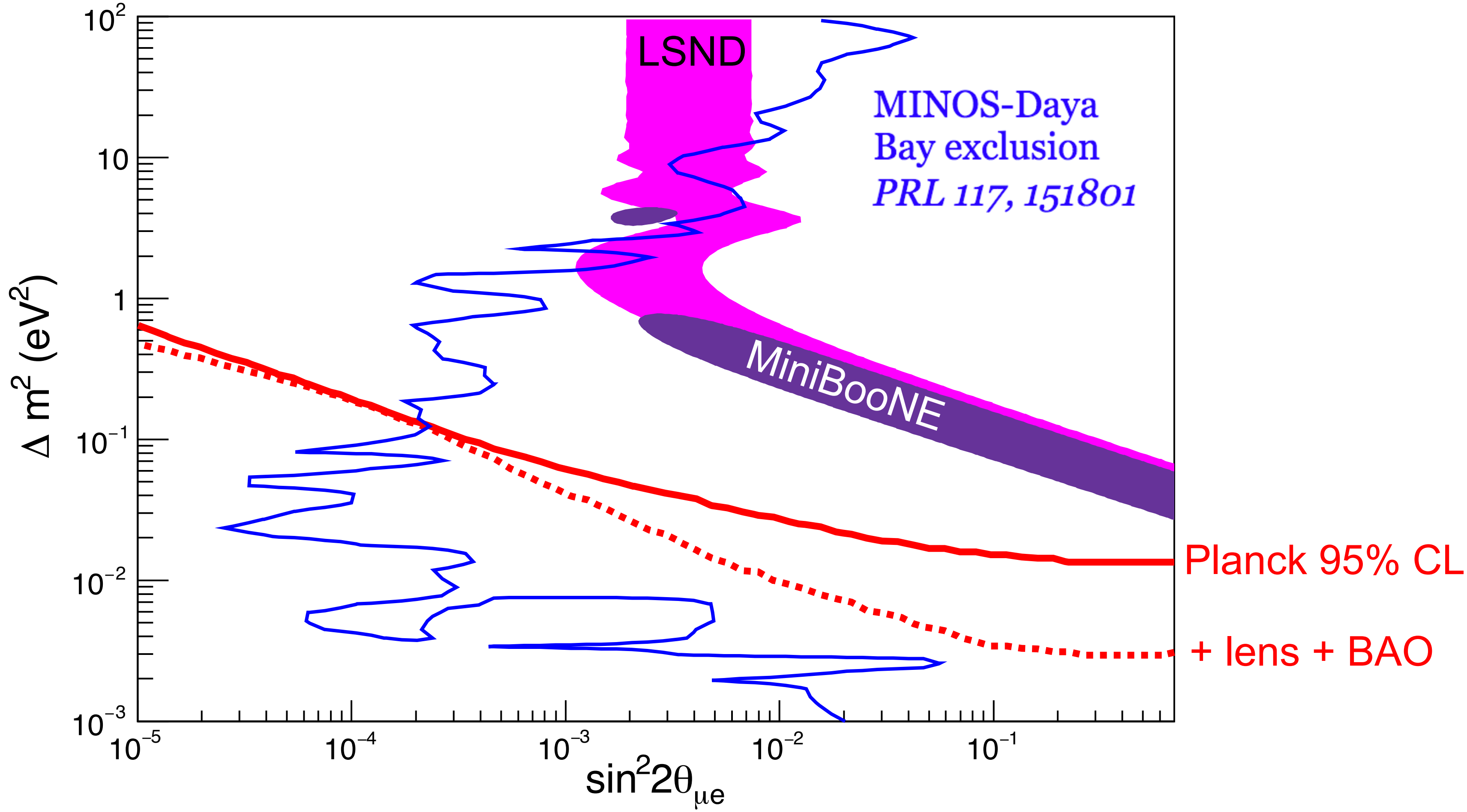
$\nu_\mu \rightarrow \nu_e$ appearance limits



An aside – Sterile neutrinos and 0νββ

- P. Guzowski *et al.*, Phys. Rev. **D92**, 012002 (2015)

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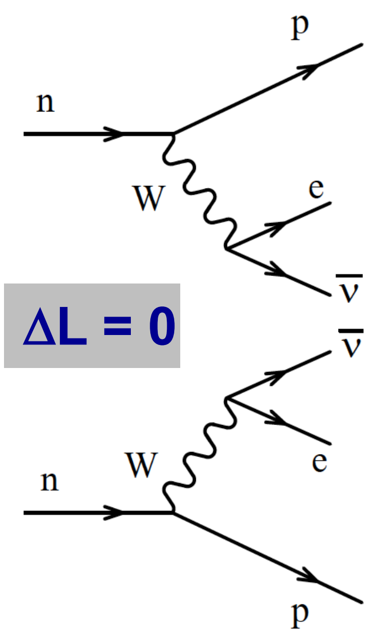
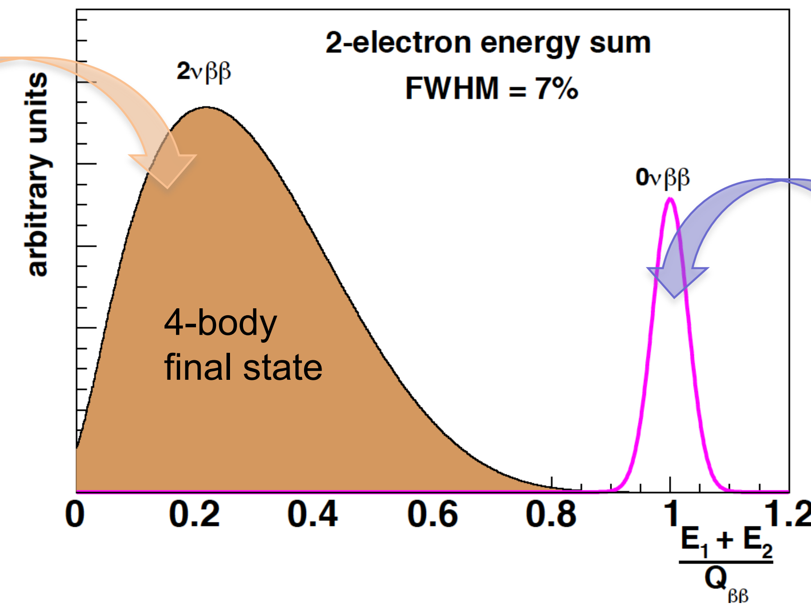
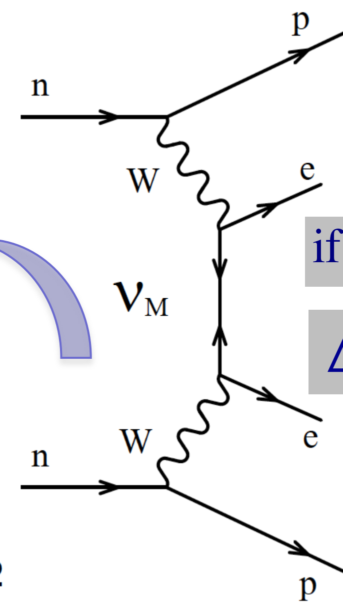
Neutrinoless double beta decay



ΔL = 0





if $m_\nu \neq 0$

ΔL = 2

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^5, Z) \bullet \left| M_{0\nu} \right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

Phase space

Nuclear matrix element

Effective neutrino mass

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The effective neutrino mass

$$|\langle m_{\beta\beta}\rangle|^2 = \left||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3\right|^2$$

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The effective neutrino mass

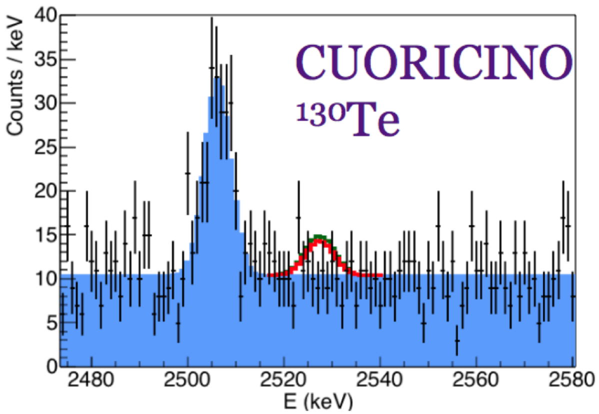
Now add a sterile neutrino:

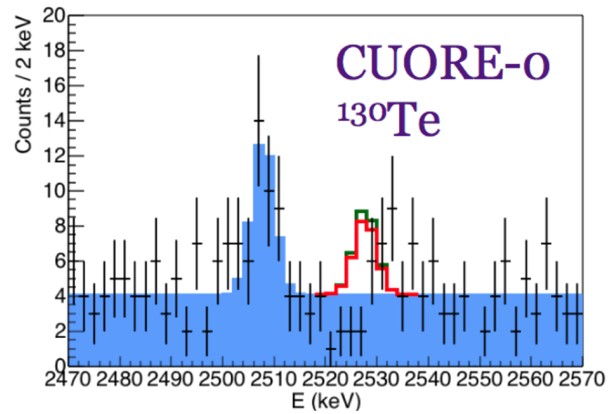
$$|\langle m_{\beta\beta}\rangle|^2 = \Big||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3 + \sin^2\theta_{14} e^{i\alpha_3} m_4\Big|^2$$

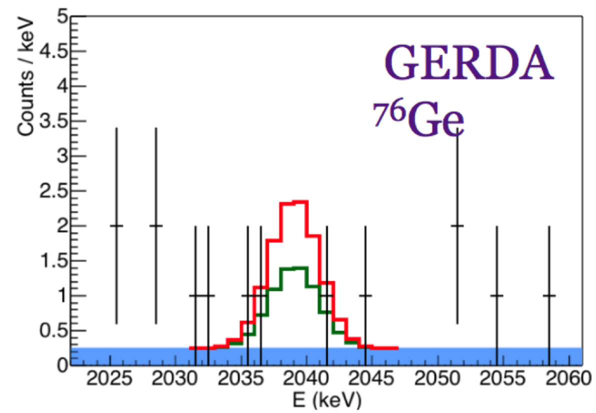
As θ_{14} increases, the effective neutrino mass governing double beta decay increases

- Which would increase the $0\nu\beta\beta$ decay rate

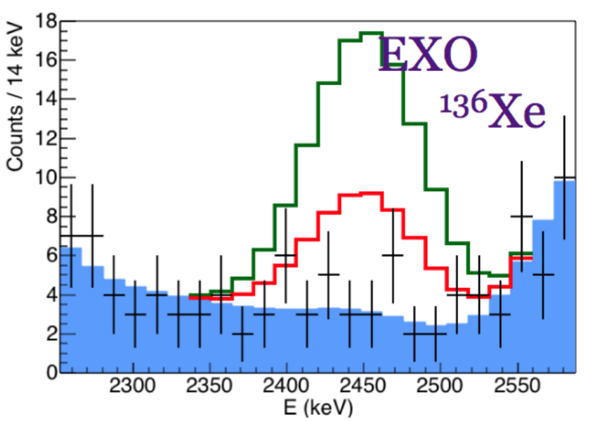
Combine six experiments

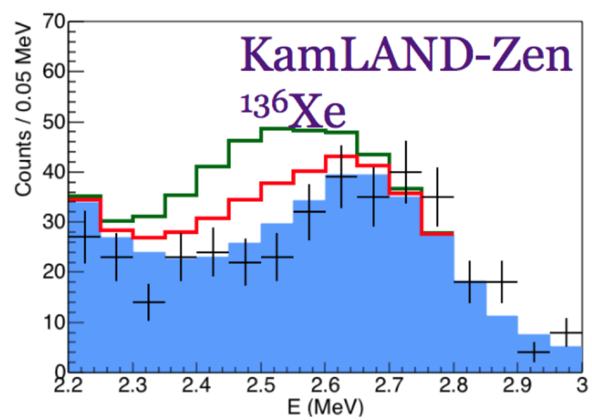


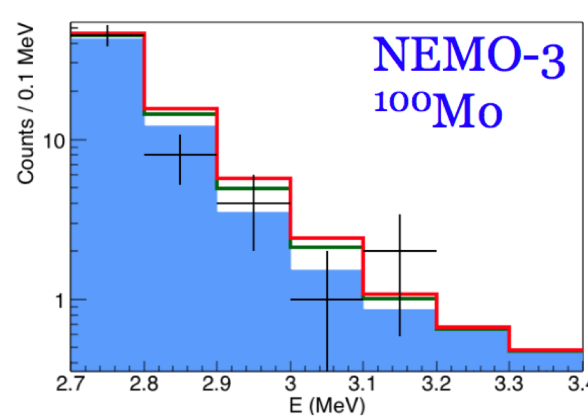




For the *GCM* or *QRPA* NMEs with $m_{\beta\beta}$ = 400 meV

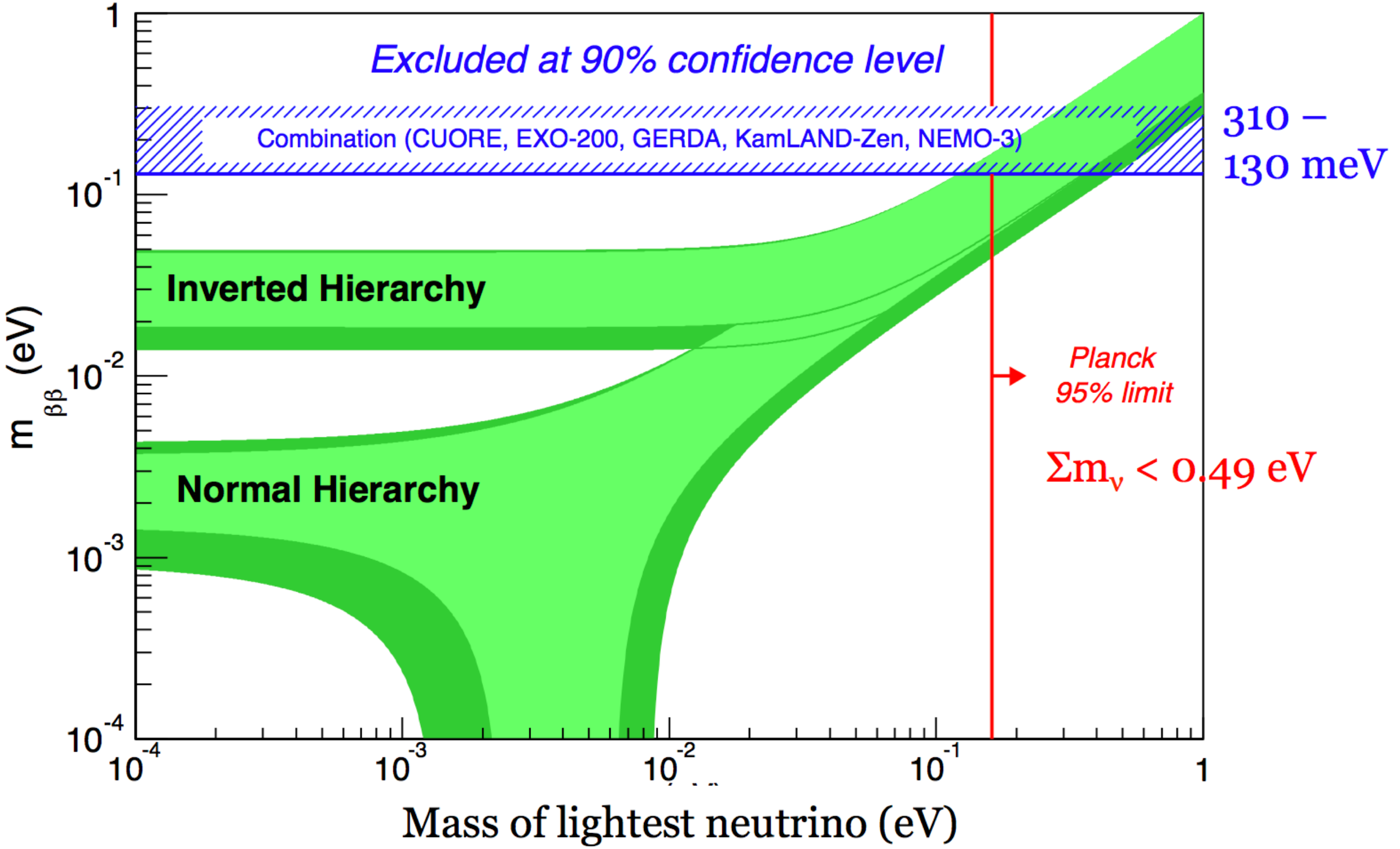






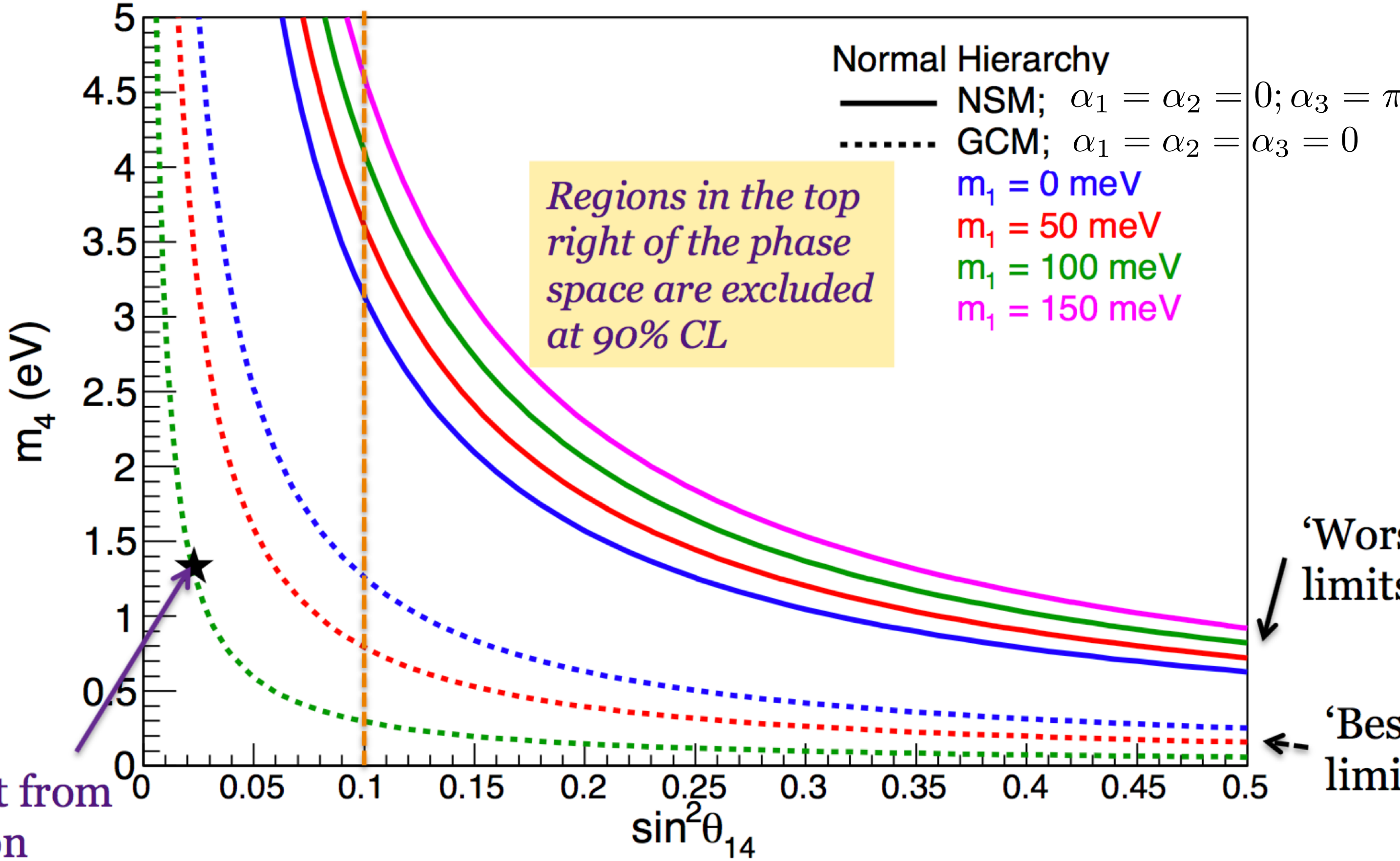
Guzowski, Barnes, Evans, Karagiorgi, McCabe, Söldner-Rembold,
Phys. Rev. D **92**, 012002 (2016)

Exclusion of ‘regular’ 0νββ



Excluding sterile Majorana neutrinos

(approx limit from unitarity constraints in oscillation experiments)



'Worst' case limits

'Best' case limits

Global fit from oscillation experiments
JHEP 05, 050 (2013)

$$\Delta m^2_{41} = 1.78\,\mathrm{eV}^2, \ \ \sin^2(2\theta_{14}) = 0.09$$

P. Guzowski *et al.*,
Phys. Rev. D **92**, 012002 (2016)

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Summary

Cosmological and particle physics searches for sterile neutrinos can be compared in the same parameter space

- Cosmological limits are strongest at mass splittings above ~0.1 eV^2 but are model-dependent
- MINOS+ limits are stronger at the lower mass splittings
- S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

If the neutrino is a Majorana particle, a sterile neutrino would impact $0\nu\beta\beta$ decay rates

- Increasing the effective neutrino mass in a way that is dependent on θ_{14}
- The non-observation of $0\nu\beta\beta$ can be used to place limits on sterile neutrino parameter space, assuming neutrinos are Majorana particles
- P. Guzowski *et al.*, Phys. Rev. **D92**, 012002 (2015)