# Neutrinos in cosmology

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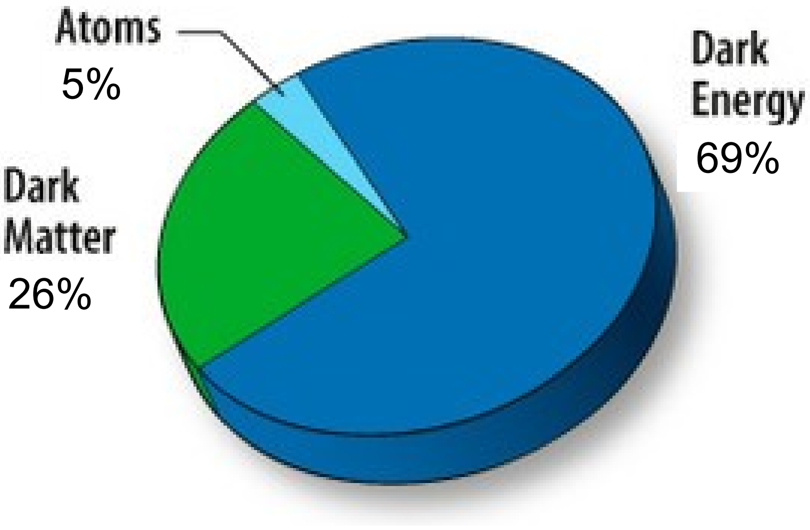
# The concordance flat ΛCDM model...

The simplest model consistent with **present observations**.

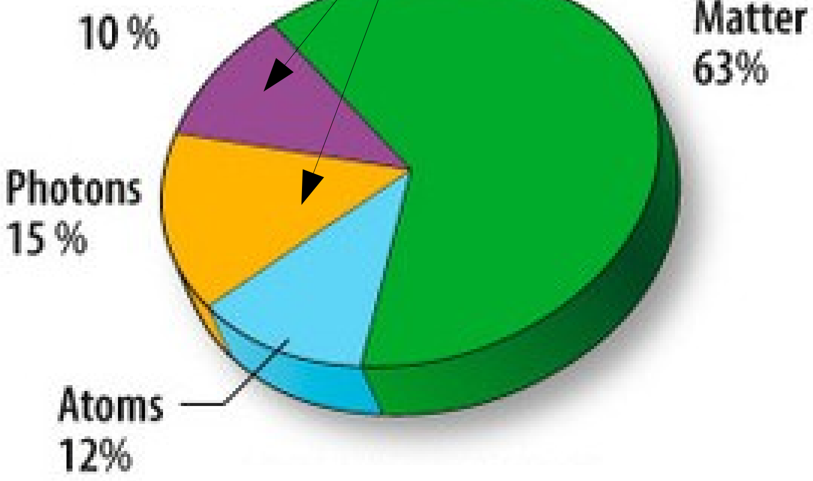
Min. value from $\sum m_\nu = 0.06\,\mathrm{eV}$ oscillations experiments

(Nearly) Massless Neutrinos (3 families)

$\nu$-to-$\gamma$ energy density ratio fixed by SM physics



Composition today



13.4 billion years ago
(at photon decoupling)

Plus flat spatial geometry+initial conditions from single-field inflation

# The neutrino sector beyond ΛCDM...

There are many ways in which the neutrino sector might be more complex than is implied by the standard picture.

Neutrino dark matter

$$\Omega_{\nu,0} h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}} = ??$$

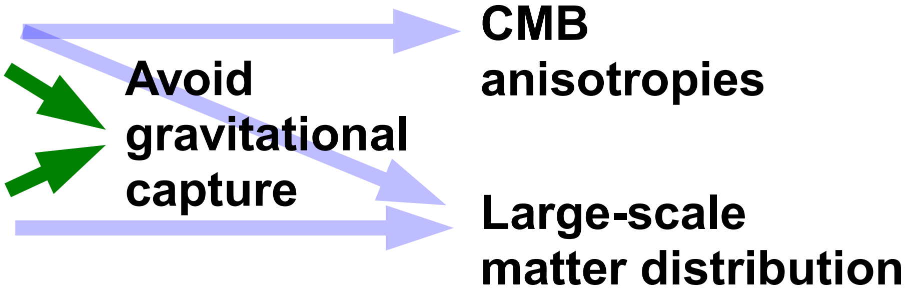
- **Masses** larger than 0.06 eV.
  - No reason to fix at the minimum mass.
  - Laboratory upper limit $\Sigma m_\nu < 7$ eV from β-decay endpoint.
- **More than three flavours**. $N_{\mathrm{eff}} \neq 3 ??$
  - Especially in view of the short baseline sterile neutrino.
- **Free-streaming or not?**
  - Possible new neutrino interactions.

# Masses...

# Free-streaming neutrinos...

For most of the observable history of the universe neutrinos have significant speeds.

- eV-mass neutrinos become nonrelativistic near $\gamma$ decoupling.
- Even when nonrelativistic, neutrinos have large thermal motion.

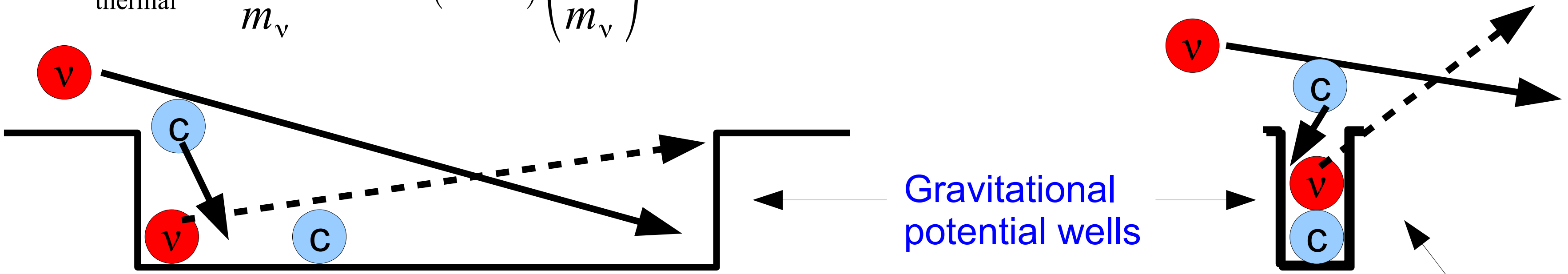


**Avoid gravitational capture**

**CMB anisotropies**

**Large-scale matter distribution**

$$v_{\text{thermal}} = \frac{T_\nu}{m_\nu} \simeq 50.4(1+z)\left(\frac{\text{eV}}{m_\nu}\right)\ \text{km s}^{-1}$$



Non-clustering

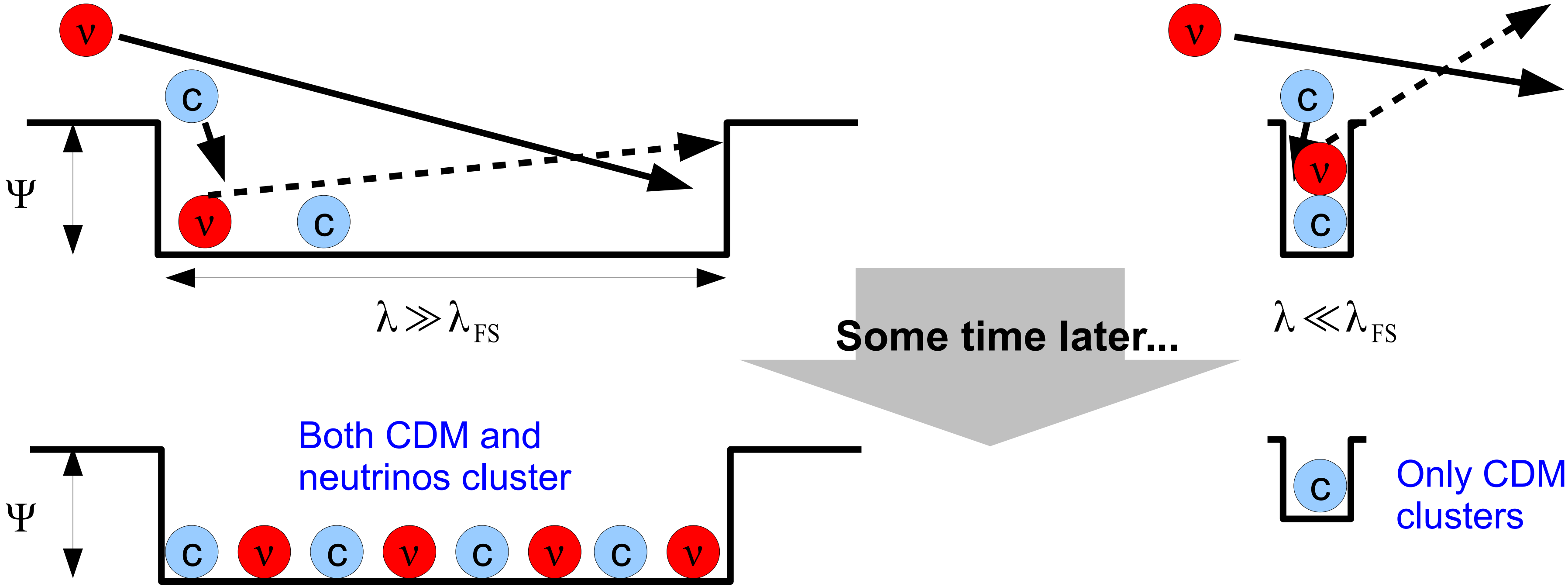
$\lambda \ll \lambda_{\text{FS}}$

$k \gg k_{\text{FS}}$

**Free-streaming scale**:

$$\lambda_{\text{FS}} \equiv \sqrt{\frac{8\pi^2 v_{\text{thermal}}^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\text{eV}}{m_\nu}\right)\ h^{-1}\ \text{Mpc}\,; \quad k_{\text{FS}} \equiv \frac{2\pi}{\lambda_{\text{FS}}}$$

Consider a neutrino and a cold dark matter particle encountering two gravitational potential wells of different sizes in an expanding universe:



Both CDM and neutrinos cluster

Only CDM clusters

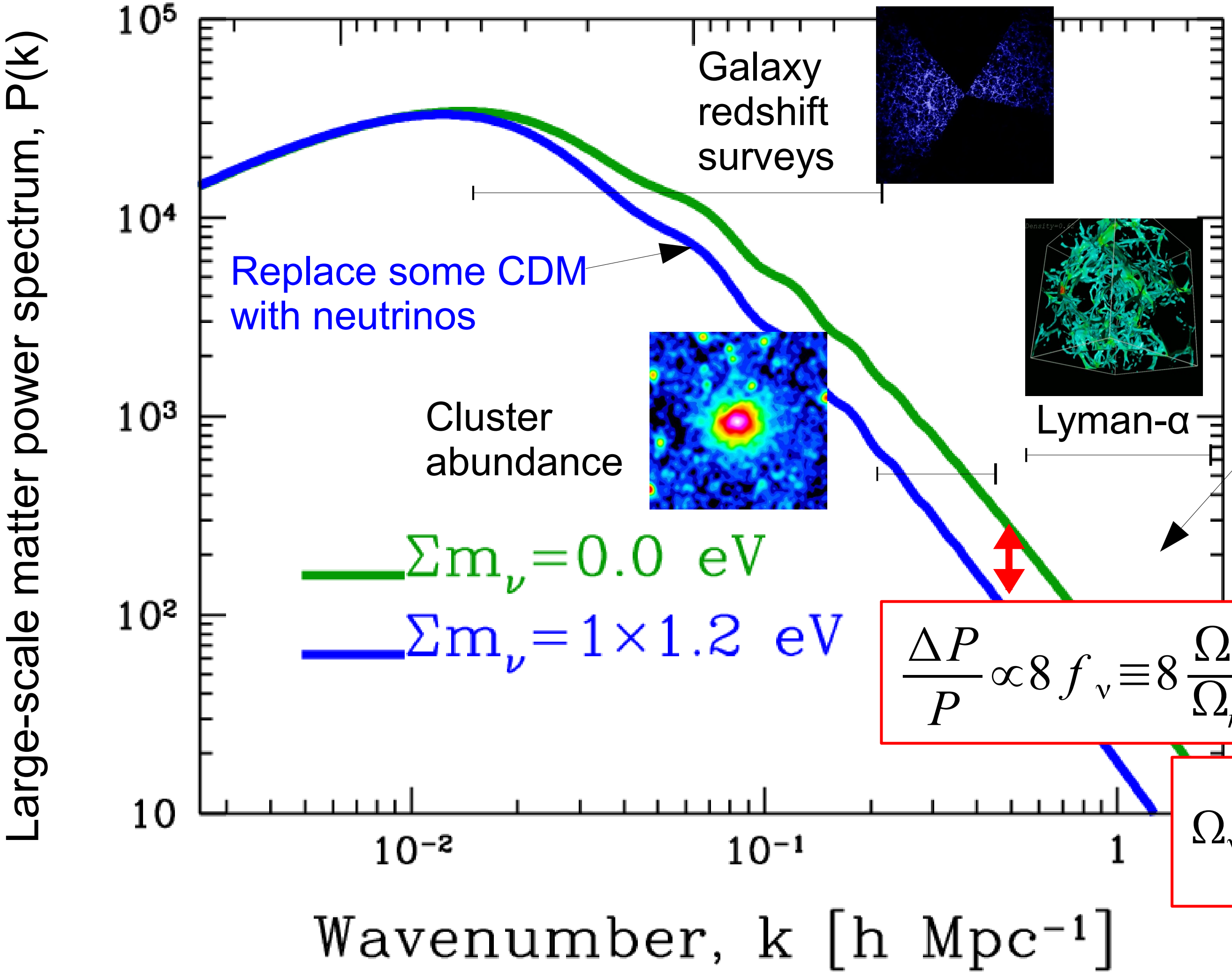
Potential stays the same (during matter domination)

Potential decays

→ **Cosmological neutrino mass measurement** is based on observing this free-streaming induced potential decay at $\lambda << \lambda_{FS}$.

# You've all seen this one...

$$P(k) = \langle |\delta(k)|^2 \rangle$$



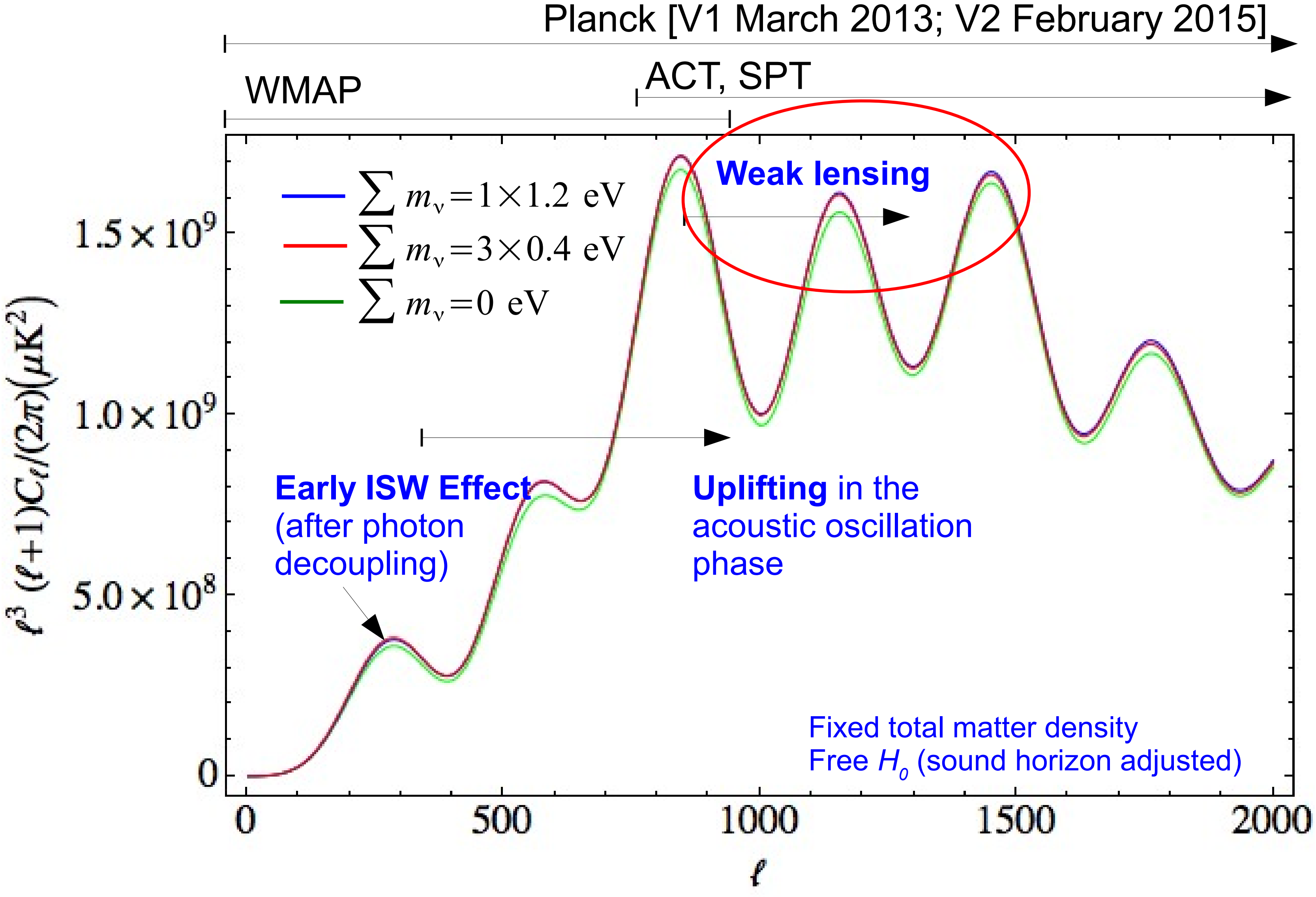
**Small-scale suppression due to potential decay**

$f_\nu$ = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}}$$

# But there are $m_\nu$ signatures in the CMB too...



Planck [V1 March 2013; V2 February 2015]

WMAP

ACT, SPT

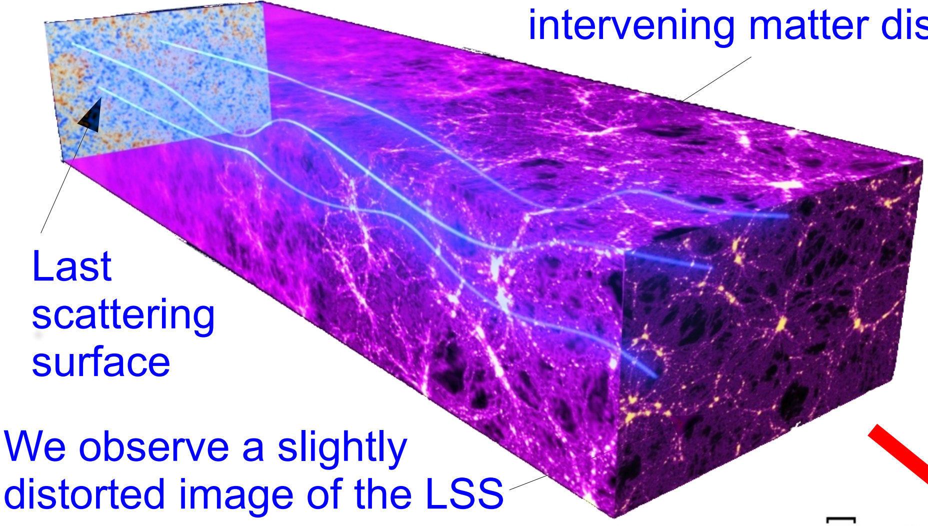
**Weak lensing**

**Early ISW Effect** (after photon decoupling)

**Uplifting** in the acoustic oscillation phase

Fixed total matter density
Free $H_0$ (sound horizon adjusted)

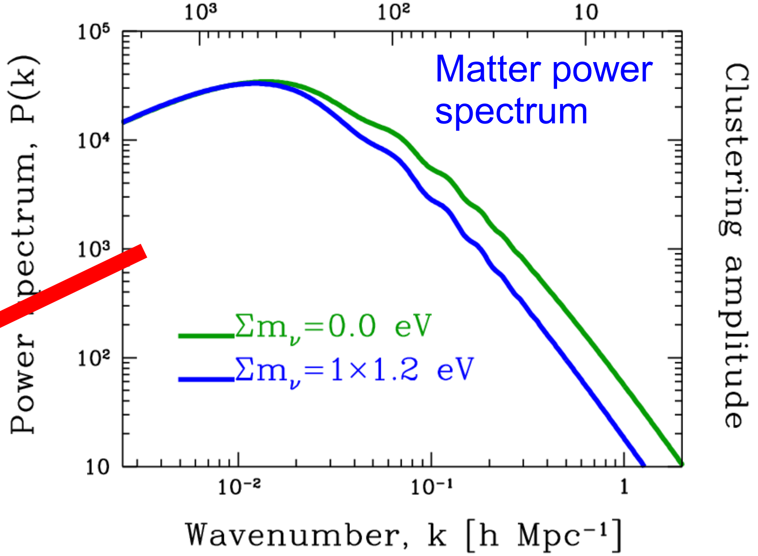
# Weak gravitational lensing...



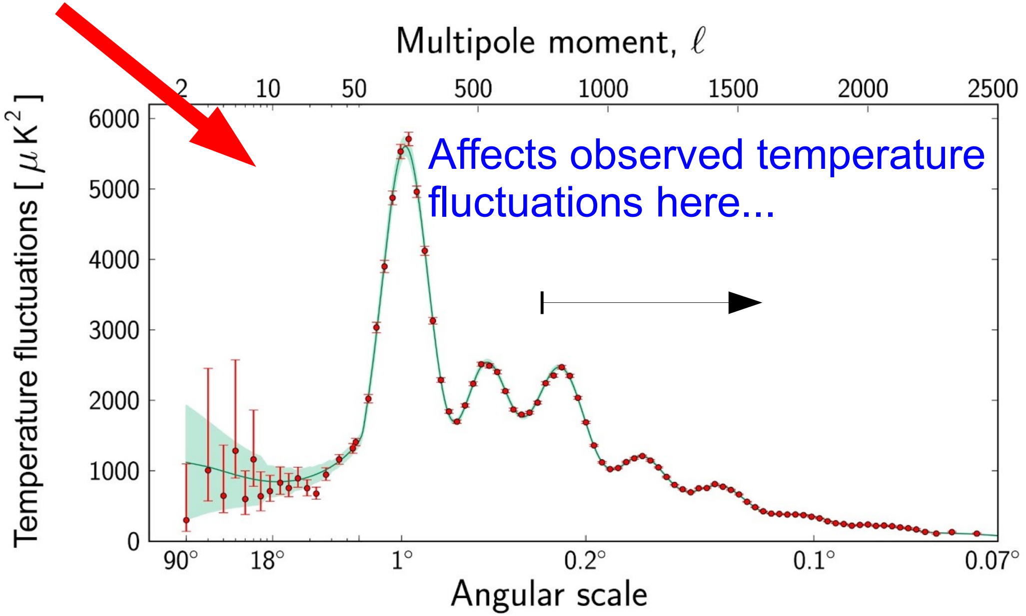
CMB photons **deflected** by intervening matter distribution

Last scattering surface

We observe a slightly distorted image of the LSS

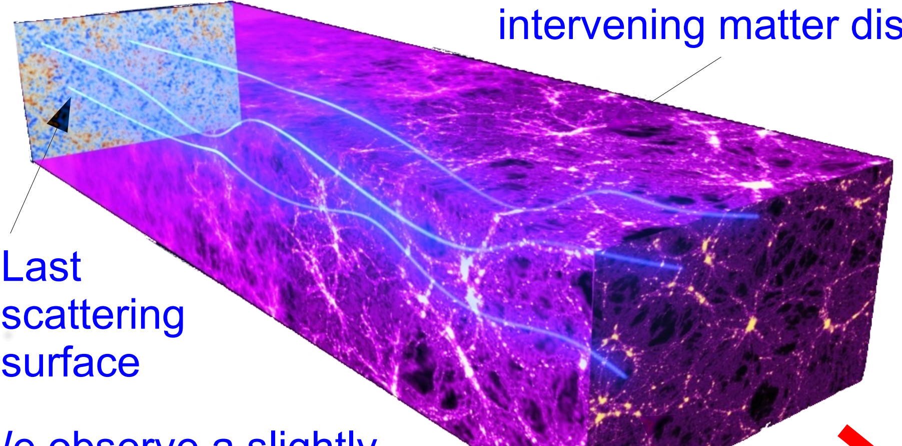


Matter power spectrum



Affects observed temperature fluctuations here...

# Weak gravitational lensing...



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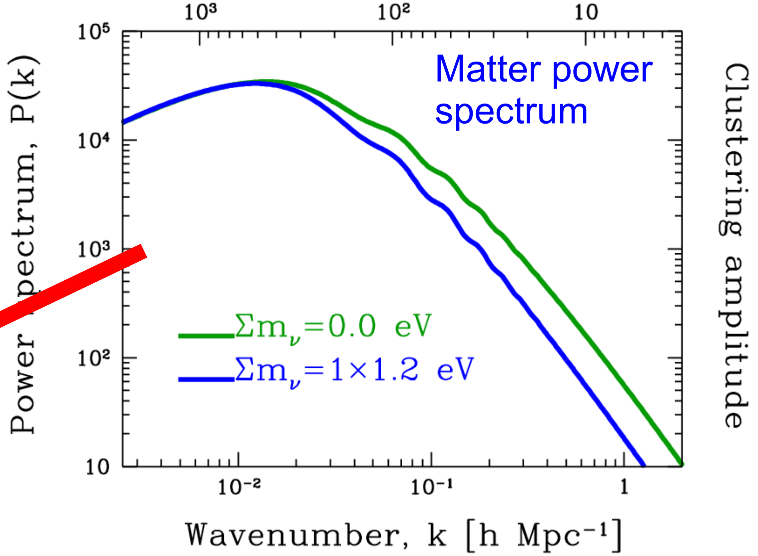
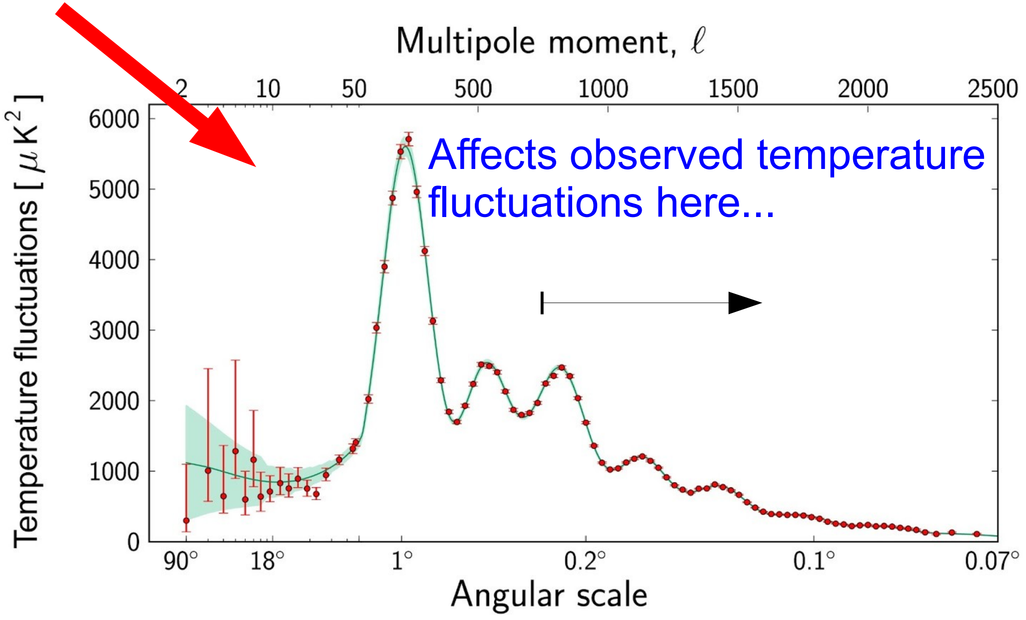




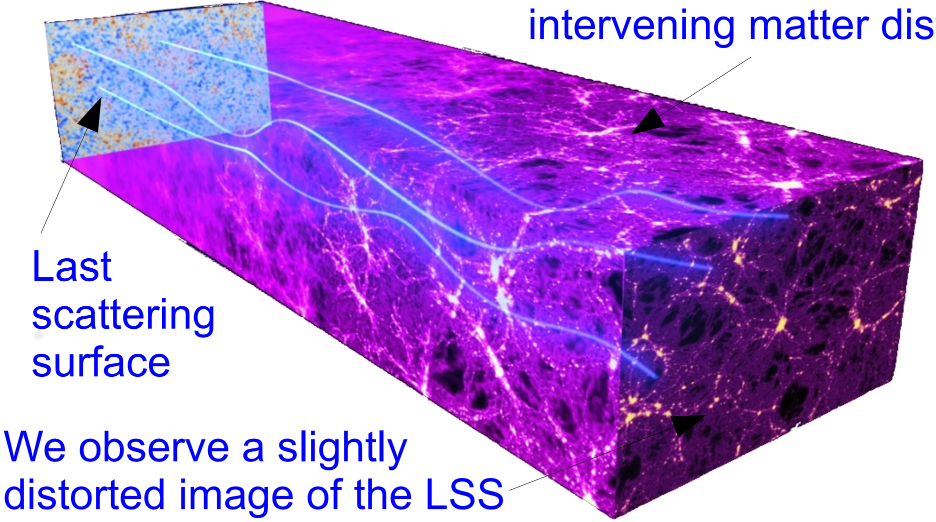
Affects observed temperature fluctuations here...

Planck TT+TE+EE+lowP

$$\sum m_\nu < 0.49 \text{ eV} \quad (95\% \text{C.L.})$$

... largely because of this lensed TT signal. Ade et al. 1502.01589

# Weak lensing: lensing potential power spectrum...



CMB photons **deflected** by intervening matter distribution

Last scattering surface

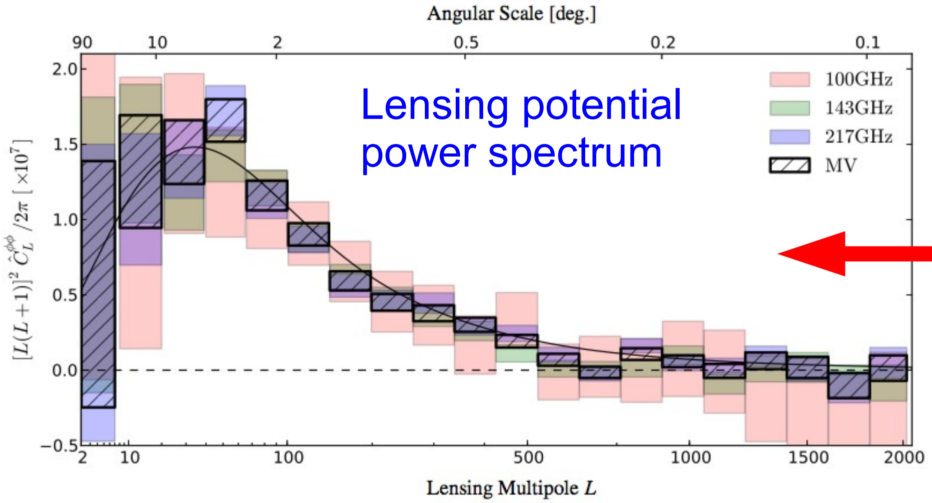
We observe a slightly distorted image of the LSS

Can also try to **reconstruct the intervening matter distribution**.

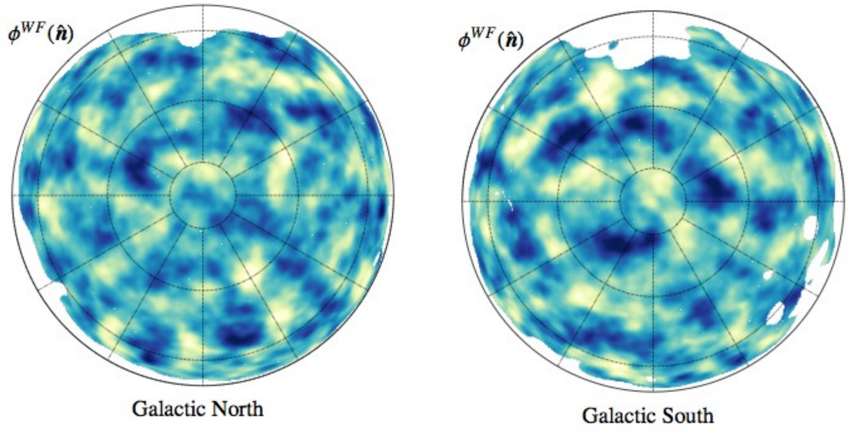
Use **4-point correlation** of observed map to infer the unlensed image.

→ Reconstruct deflection angle

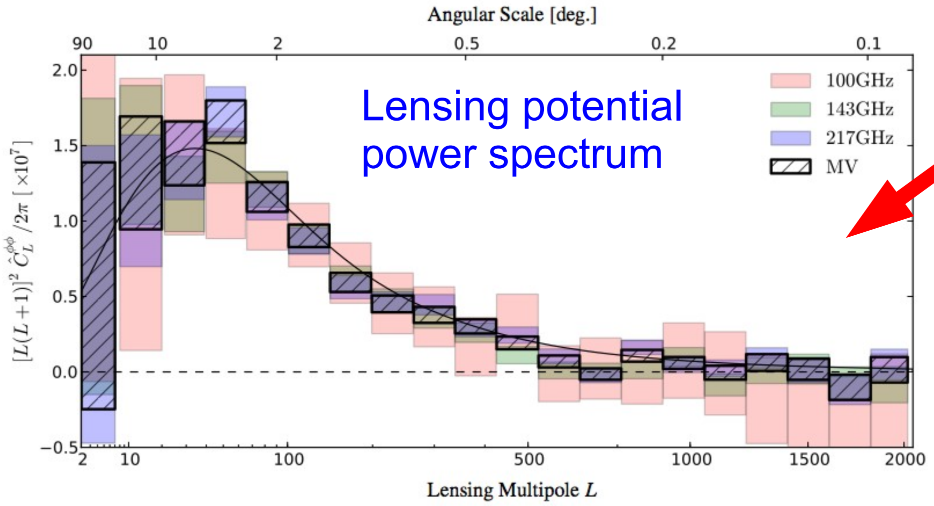
→ Construct lensing potential map



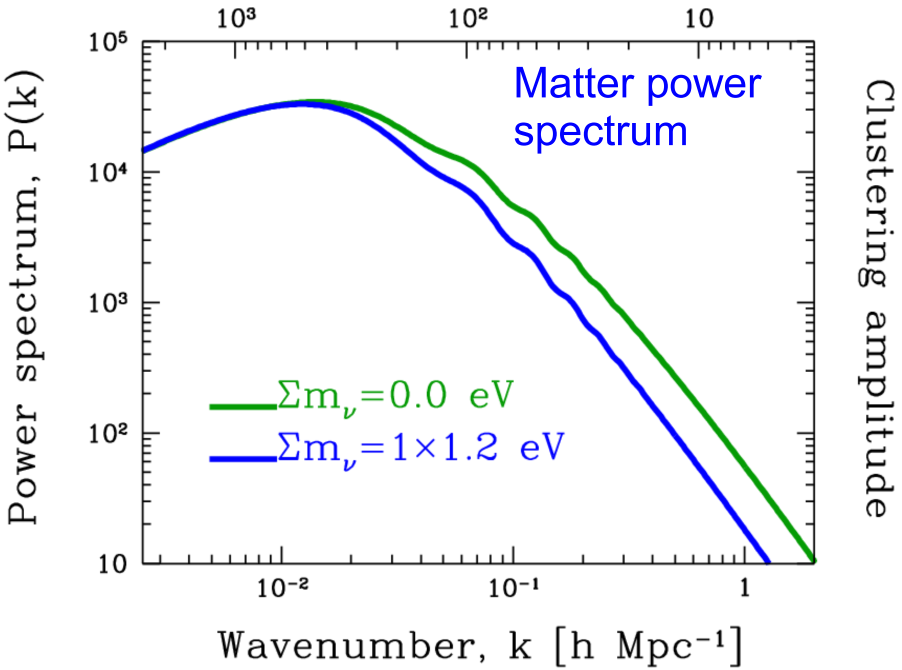
Lensing potential power spectrum



# Weak lensing: lensing potential power spectrum...



This is essentially this integrated along the line-of-sight (with some geometric factors folded in).



Planck TT+TE+EE+lowP+lensing

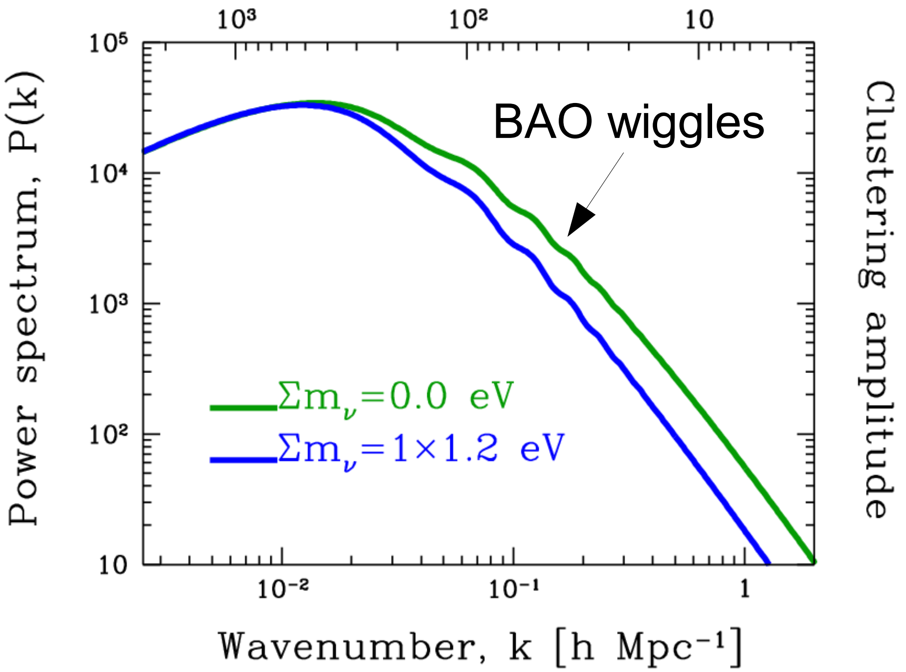
$$\sum m_\nu < 0.59\ \text{eV}\ \ (95\%\,\text{C.L.})$$

Not as good as the no-lensing bound, because of “slight” incompatibility of the lensing amplitude inferred from lensed TT and the lensing potential power spectrum.

# Adding low-redshift, non-CMB data...

**Two types: geometry vs shape**

- **Geometric** (not directly sensitive to neutrino mass):
  - Type Ia supernova
  - Baryon acoustic oscillations ("wiggles") [least prone to nonlinearity issues]



- **Shape** (directly sensitive to neutrino mass):
  - Galaxy power spectrum
  - Cluster abundance
  - Lyman alpha forest

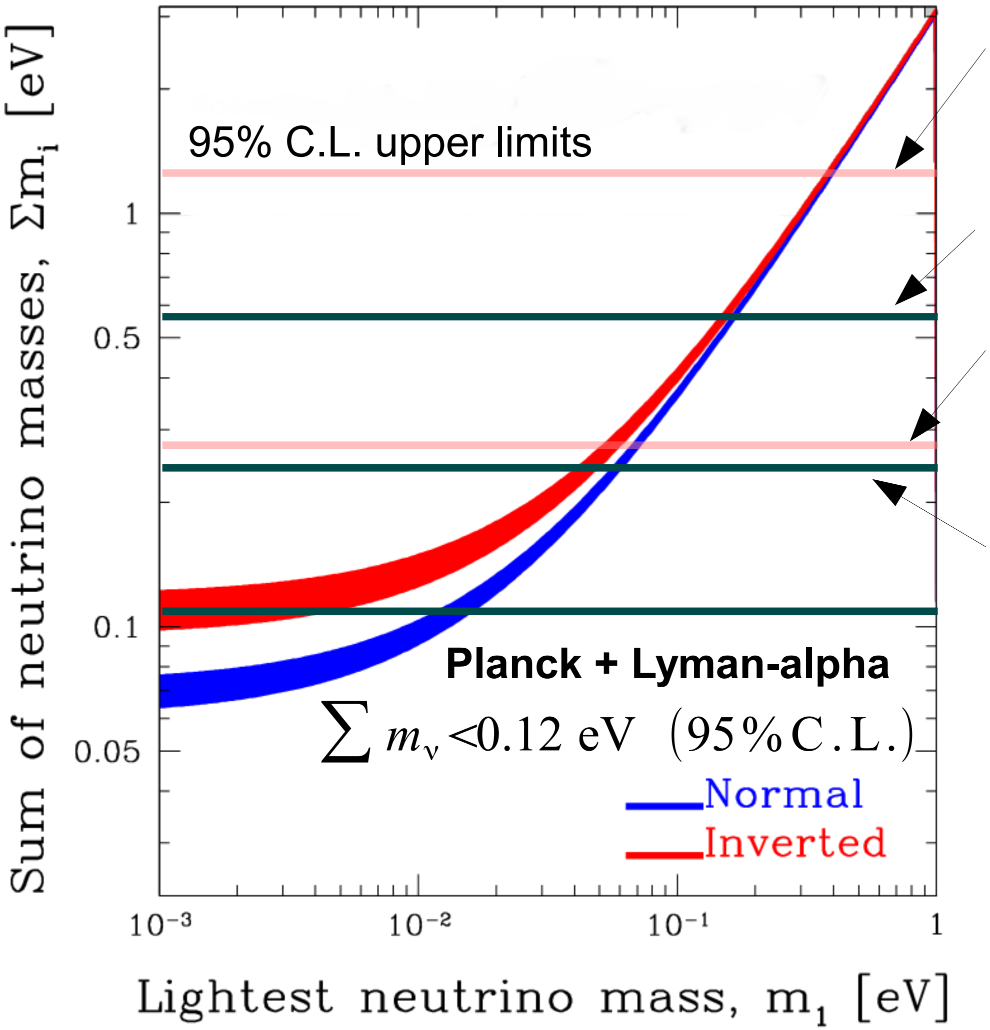
Planck **+BAO** $\sum m_\nu < 0.23\ \mathrm{eV}\quad (95\%\,C.L.)$

Planck+**Lyα** $\sum m_\nu < 0.12\ \mathrm{eV}\quad (95\%\,C.L.)$

Palanque-Delabrouille et al. 2015

# Pre- vs Post-Planck constraints...

ΛCDM+neutrino mass (7 parameters)



95% C.L. upper limits

WMAP9 + ACT

**Planck TT+TE+EE+lowP+lensing**

$$\sum m_\nu < 0.59 \text{ eV} \quad (95\% \text{ C.L.})$$

WMAP7+ matter power spectrum + HST $H_0$

**Planck TT+TE+EE+lowP+lensing**
**+ baryon acoustic oscillations**

$$\sum m_\nu < 0.23 \text{ eV} \quad (95\% \text{ C.L.})$$

**Planck + Lyman-alpha**

$$\sum m_\nu < 0.12 \text{ eV} \quad (95\% \text{ C.L.})$$

Formally similar to the pre-Planck best minimal bound, **but arguably less prone to issues of nonlinearities**.

# The take-home message...

- Formally, the best “Planck party-line” minimal (7-parameter) upper bound on $\Sigma m_\nu$ is still hovering around 0.2—0.3 eV post-Planck2.

- The bound has however become more robust against uncertainties relative to Pre-Planck bounds.
    - Less nonlinearities in BAO than in the matter power spectrum.
    - Does not rely on local measurement of the Hubble parameter...
    - … or on the choice of lightcurve fitters for the Supernova Ia data.

- **Dependence on cosmological model** used for inference?

# What about model dependence?

- I couldn't find anything in the papers accompanying V2...
- However, from V1 (March 2013):

**Planck1 + WP + (ACT ℓ > 1000 + SPT ℓ > 2000) + baryon acoustic oscillations**

ΛCDM+neutrino mass
(7 parameters)

$$\sum m_\nu < 0.25 \text{ eV} \quad (95\,\% \text{ C.L.})$$

Best minimal bound

Dropping assumption
of spatial flatness:

$$\sum m_\nu < 0.32 \text{ eV} \quad (95\,\% \text{ C.L.})$$

→ Some degradation, but still in the same ball park.

# A fourth neutrino??

# It doesn't even have to be a real neutrino...

**Any particle species** that

- decouples while ultra-relativistic and before z ~ $10^6$
- does **not** interact with itself or anything else after decoupling

Smallest relevant
scale enters the horizon

will behave (more or less) like a neutrino as far as the CMB and LSS are concerned.

$$\sum_i \rho_{\nu,i} + \rho_X = N_{\mathrm{eff}}\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right)$$
$$= (3.046 + \Delta N_{\mathrm{eff}})\,\rho_\nu^{(0)}$$

Three SM neutrinos

Neutrino
temperature
per definition

Other non-interacting relativistic
energy densities, e.g., sterile
neutrinos, axions, hidden
photons, etc.

Corrections due to non-instantaneous
decoupling,finite temperature effects,
and flavour oscillations

# Post-Planck2 $N_{\mathrm{eff}}$ ...

Planck-inferred $N_{\mathrm{eff}}$ compatible with 3.046 at better than 2σ.

ΛCDM+$N_{\mathrm{eff}}$ (7 parameters)

$$\begin{aligned}
N_{\mathrm{eff}} &= 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;\\
N_{\mathrm{eff}} &= 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;\\
N_{\mathrm{eff}} &= 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,;\\
N_{\mathrm{eff}} &= 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}\,.
\end{aligned}$$

68% C.I.

ΛCDM+neutrino mass+$N_{\mathrm{eff}}$ (8 parameters)

$$\left.\begin{aligned}
N_{\mathrm{eff}} &= 3.2 \pm 0.5\\
\sum m_\nu &< 0.32\ \mathrm{eV}
\end{aligned}\right\} \quad 95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}BAO}.$$

**Looks like the end of the $N_{\mathrm{eff}}$ story...** **But note this...**

# The $N_{eff}$-$H_0$ degeneracy...

A larger $N_{\rm eff}$ does bring the Planck-inferred $H_0$ into better agreement with most direct measurements.

Freedman et al. 2012

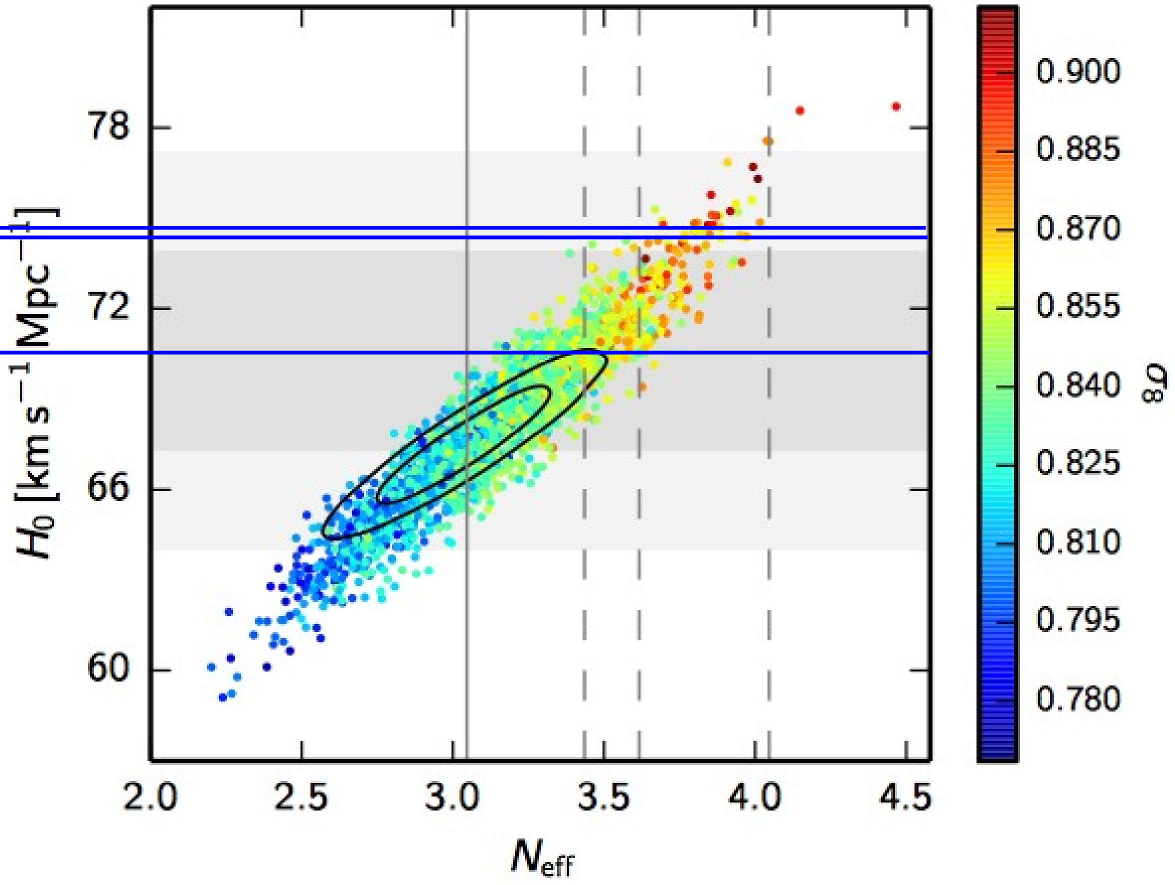
$H_0 = 74.3 \pm 2.6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

$H_0 = 73.9 \pm 2.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Efstathiou 2014

$H_0 = 70.6 \pm 3.3\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Efstathiou 2014



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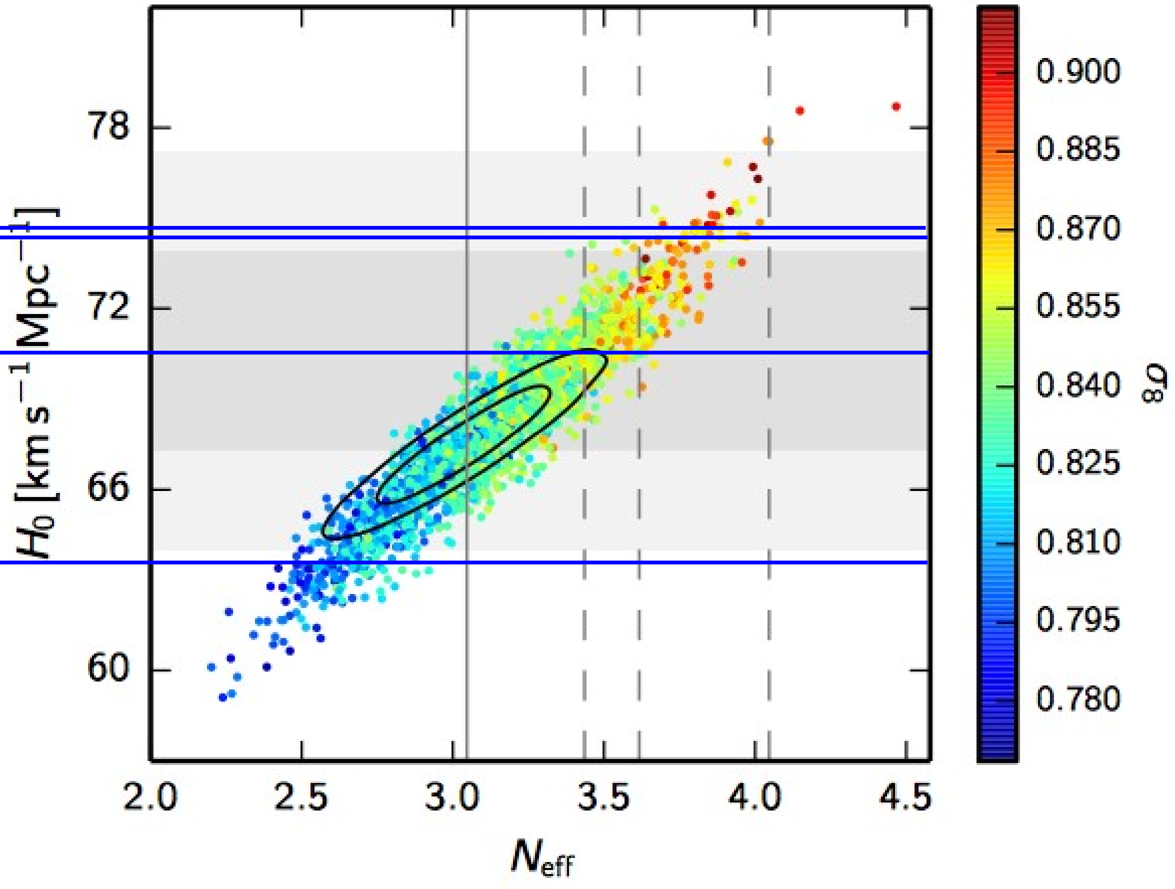
Efstathiou 2014

$H_0 = 70.6 \pm 3.3\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$

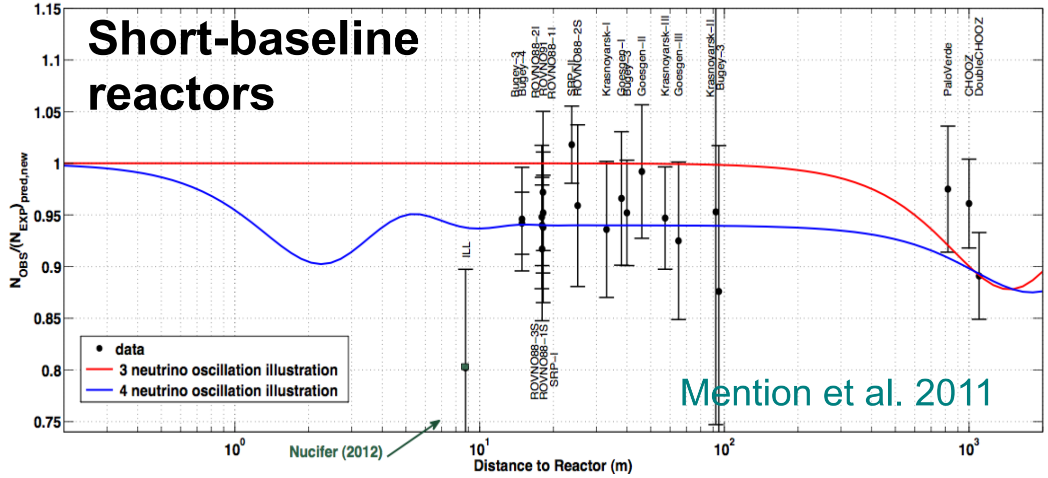
Efstathiou 2014

$H_0 = 63.7 \pm 2.3\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$

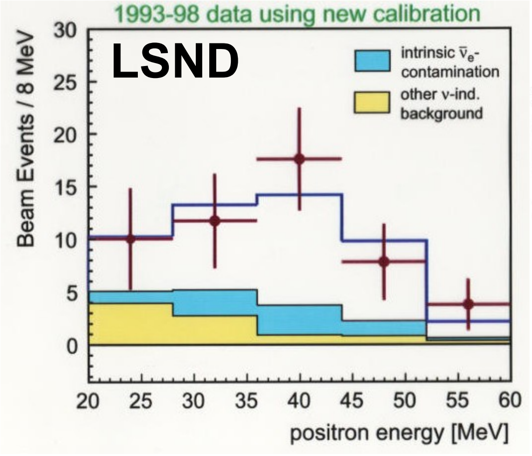
Tammann and Reindl 2013

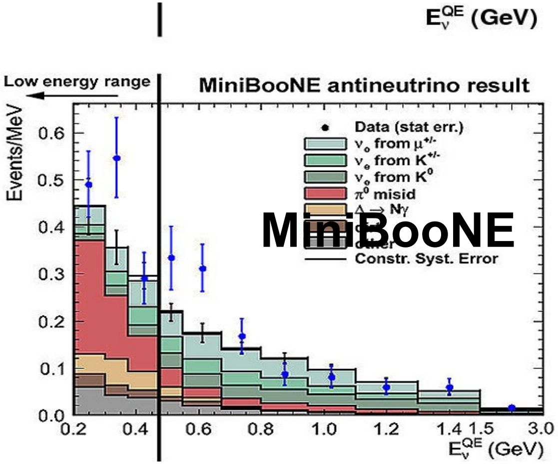


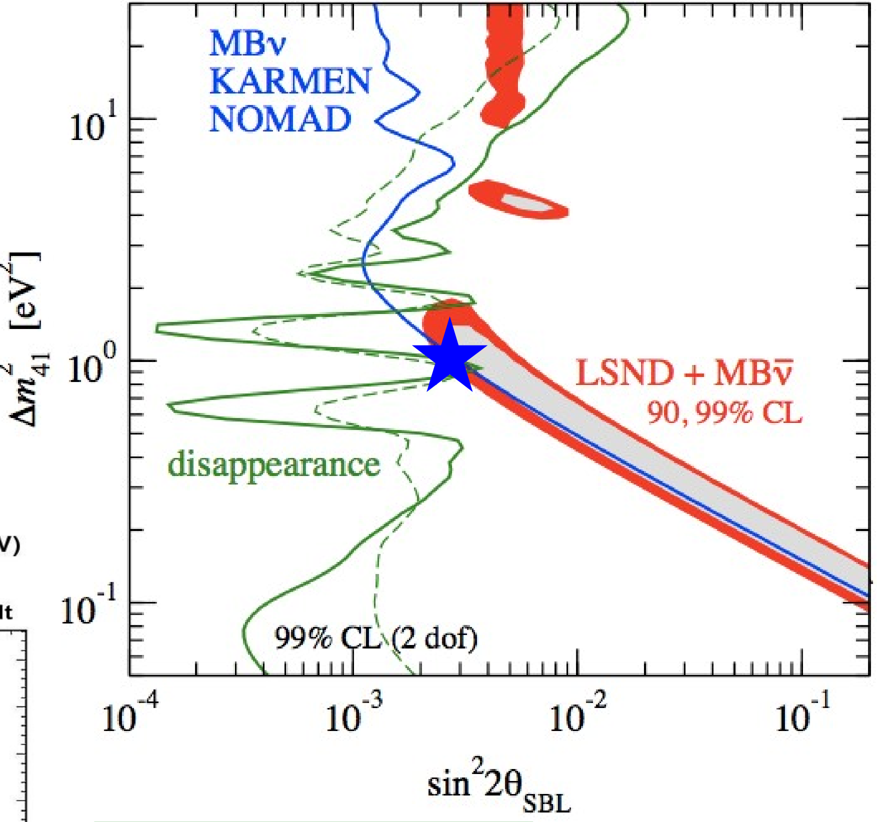
# Implications for the short baseline sterile neutrino...



Mention et al. 2011







$$\Delta m^2_{SBL} \sim 1 \;\; \mathrm{eV}^2$$
$$\sin^2 2\theta_{SBL} \sim 3\times 10^{-3}$$

Kopp, Maltoni & Schwetz 2011

# Implications for the short baseline sterile neutrino...

Sterile neutrinos can be **produced in the early universe** via a combination of active–sterile neutrino oscillations and scattering, prior to neutrino decoupling (T ~ 1 MeV).

- **Not a necessity**, but depends on the effective $\Delta m^2$ and $\sin^2 2\theta$ in the medium.
- Abundance calculated from the **quantum kinetic equations**.

Sigl & Raffelt 1993
McKellar & Thomson 1994
See also talks by Saviano and Archidiacono

- But in a very very rough way:

$$\Gamma_{\mathrm{prod}} \sim \frac{1}{2}\frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + [(\Delta m^2/2p)\cos 2\theta + V_m]^2 + \Gamma_a^2/4}\,\Gamma_a$$

Sterile production rate

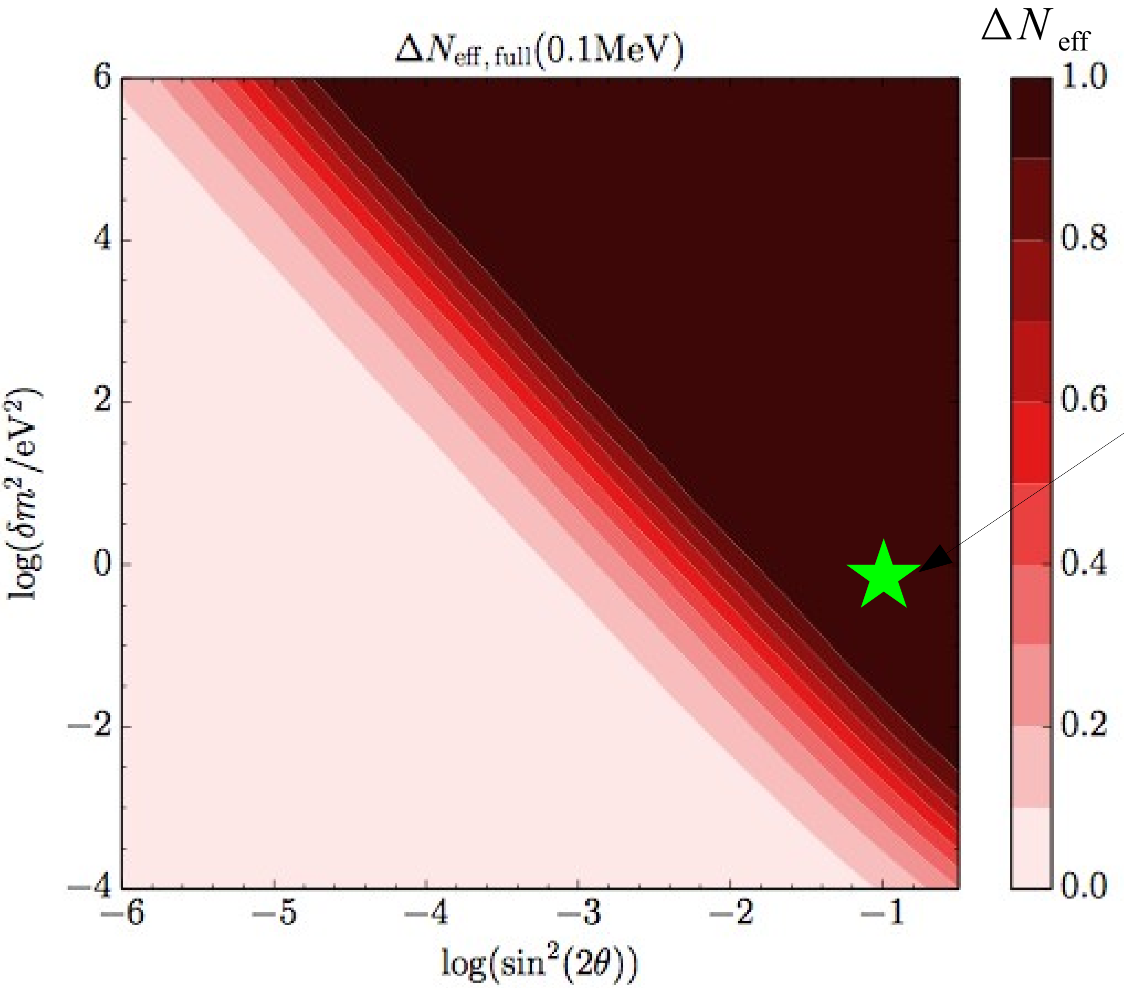
Vacuum mixing parameters

Matter (MSW) effects

Active neutrino scattering rate

# High precision (< 0.1%) evaluation of the QKEs:

Hannestad, Hansen, Tram & Y³W 2015



SBL-preferred

$$m_{\rm SBL} \sim 1 \ \ {\rm eV}$$
$$\Delta N_{\rm eff} \sim 1$$

**Obviously at odds with Planck limits...**

$$\left.\begin{array}{r} N_{\rm eff} = 3.2 \pm 0.5 \\ \sum m_\nu < 0.32 \text{ eV} \end{array}\right\} \quad 95\%$$

Planck TT + lowP + lensing + BAO

also Hannestad, Tamborra & Tram 2012
and older works of Abazajian, Di Bari,
Foot, Kainulainen, etc. from 1990s-early 2000s

# Reconciling the SBL sterile neutrino with cosmology??

The SBL sterile neutrino is problematic for cosmology only because it is produced in abundance in the early universe.

→ If production can be **suppressed**, then there is no conflict... or is there?!?!

**Some possible mechanisms**:

- A large lepton asymmetry ($L \gg B \sim 10^{-10}$)
- Secret sterile neutrino self-interaction 1 (4-fermion) See talk of Saviano
- Secret sterile neutrino self-interaction 2 (massless mediator) See talk of Archidiacono
- A low reheating temperature ($T_R < 10$ MeV)

# Reconciling the SBL sterile... Large lepton asymmetry

L>>B~$10^{-10}$ generates an effective potential, suppressing the effective active-sterile mixing; L ~ $10^{-2}$ will do.

Foot & Volkas 1995

$$\Gamma_{\rm prod} \sim \frac{1}{2}\frac{(\Delta m^2/2p)^2\sin^2 2\theta}{(\Delta m^2/2p)^2\sin^2 2\theta + [(\Delta m^2/2p)\cos 2\theta + V_m]^2 + \Gamma_a^2/4}\Gamma_a$$

Sterile production rate

Vacuum mixing parameters

Matter (MSW) effects

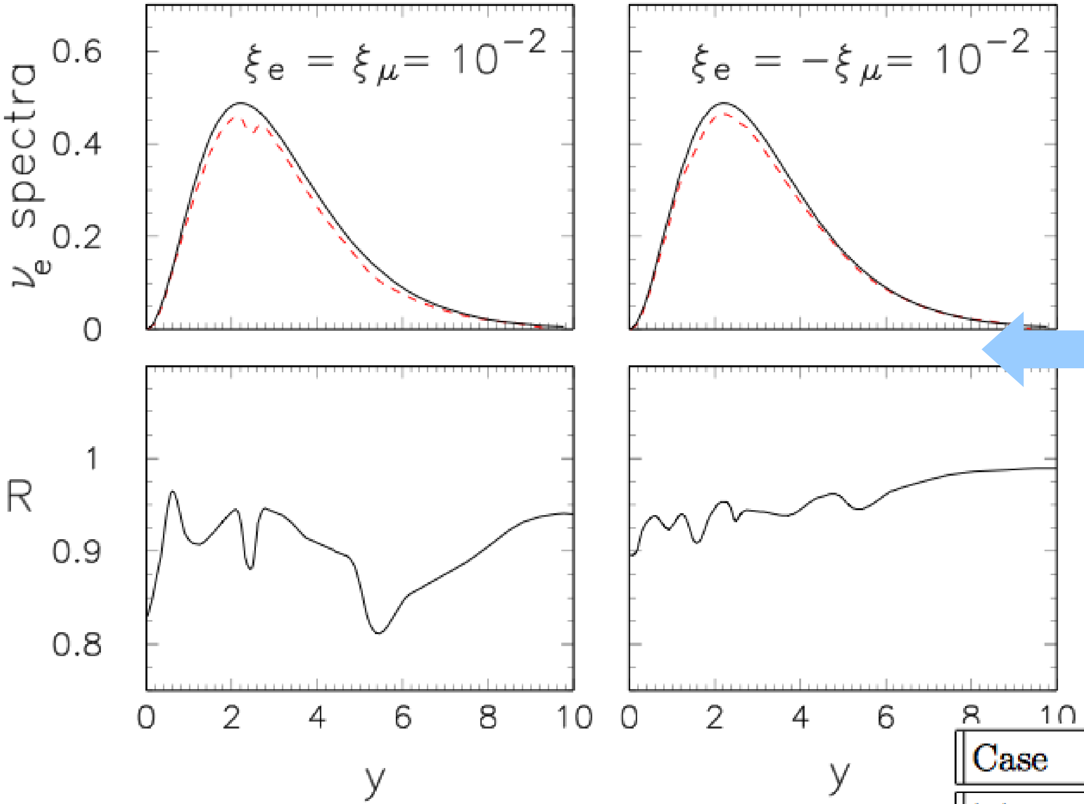
Active neutrino scattering rate

$$= \frac{8\sqrt{2}\,G_F\,p}{3}\left(\frac{\rho_\ell}{M_W^2}+\frac{\rho_{\nu_a}}{M_Z^2}\right) \mp \frac{2\sqrt{2}\,\zeta(3)\,G_F}{\pi^2}T^3 L$$

Finite temperature effects

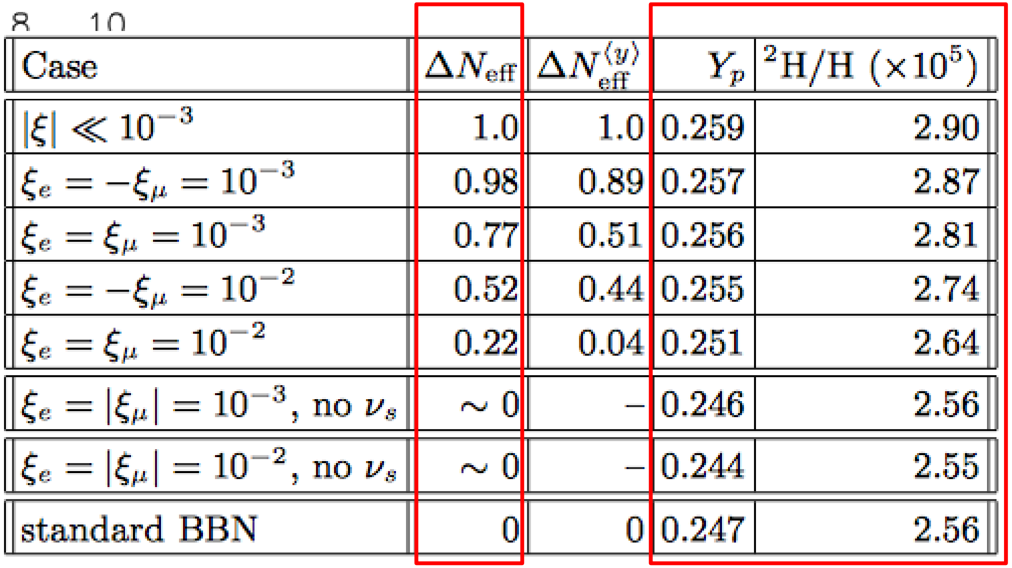
New

**Caveat**: Leads to significant spectral distortion for the (anti)electrons → can be very bad for primordial element abundances. Abazajian, Bell, Fuller & Y$^3$W 2005, Saviano et al. 2013



Saviano et al. 2013

“Rough” numerical estimates of the $\nu_e$ spectrum, and the Helium4 and Deuterium abundances



| Case | $\Delta N_{\rm eff}$ | $\Delta N_{\rm eff}^{\langle y \rangle}$ | $Y_p$ | $^2$H/H $(\times 10^5)$ |
|---|---|---|---|---|
| $\lvert\xi\rvert \ll 10^{-3}$ | 1.0 | 1.0 | 0.259 | 2.90 |
| $\xi_e = -\xi_\mu = 10^{-3}$ | 0.98 | 0.89 | 0.257 | 2.87 |
| $\xi_e = \xi_\mu = 10^{-3}$ | 0.77 | 0.51 | 0.256 | 2.81 |
| $\xi_e = -\xi_\mu = 10^{-2}$ | 0.52 | 0.44 | 0.255 | 2.74 |
| $\xi_e = \xi_\mu = 10^{-2}$ | 0.22 | 0.04 | 0.251 | 2.64 |
| $\xi_e = \lvert\xi_\mu\rvert = 10^{-3}$, no $\nu_s$ | $\sim 0$ | – | 0.246 | 2.56 |
| $\xi_e = \lvert\xi_\mu\rvert = 10^{-2}$, no $\nu_s$ | $\sim 0$ | – | 0.244 | 2.55 |
| standard BBN | 0 | 0 | 0.247 | 2.56 |

**Measurements**

$$Y_p = 0.254 \pm 0.003$$

Izotov et al. 2013

$$^2H/H\,(x\,10^5) = 2.53 \pm 0.04$$

Cooke et al. 2014

# Reconciling the SBL sterile... Sterile self -interaction 1

Dasgupta & Kopp 2014
Hannestad, Hansen & Tram 2014

... mediated by X, with $T_\nu \ll M_X \ll M_Z$.

$$\Gamma_{\mathrm{prod}} \sim \frac{1}{2}\frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + [(\Delta m^2/2p)\cos 2\theta + V_m]^2 + (\Gamma_a + \Gamma_s)^2/4}(\Gamma_a + \Gamma_s)$$

Sterile
production rate

Vacuum mixing
parameters

Matter (MSW)
effects

Active+sterile
scattering rate

$$= \frac{8\sqrt{2} G_F p}{3}\left(\frac{\rho_\ell}{M_W^2} + \frac{\rho_{\nu_a}}{M_Z^2}\right) + \frac{8\sqrt{2} G_X p}{3}\frac{\rho_{\nu_s}}{M_X^2}$$

$$\Gamma_a \sim G_F p T^4$$

$$\Gamma_s \sim G_X p T n_{\nu_s}$$

**Bonus**: If X couples also to DM, can alleviate small-scale problems.

**Caveats**: ...

**Caveats**:

- Spectral distortion for the (anti)electrons again (bad for BBN)
- Flavour equilibration (if secret coupling remains strong after BBN) :

Saviano et al. 2014
see also her talk

$$\begin{array}{ccc} (\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\text{initial}} & \longrightarrow & (\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\text{final}} \\ (1,\quad 1,\quad 1,\quad 0) & & (3/4,\ 3/4,\ 3/4,\ 3/4) \end{array}$$

Effective mass of the sterile neutrino for CMB+LSS

$$m_{\text{eff cosmo}} = \frac{3}{4}\sqrt{\Delta m^2_{\text{SBL}}} \sim 0.8 \ \text{ eV}$$

Bringmann, Hasenkamp,Kersten 2014
Mirizzi et al 2014

**In trouble** with Planck neutrino mass limits again if $M_X$ > 1 MeV...

# The bottom line...

There are some fun games one can play to suppress sterile neutrino production in order to reconcile the SBL sterile neutrino with cosmological observations.

- Beware however that the phenomenology of flavour oscillations + scattering is highly nontrivial.
- There is **no** guaranteed way to make the SBL sterile neutrino completely “safe” for cosmology.

# Free-streaming or not, and its relation to new neutrino interactions

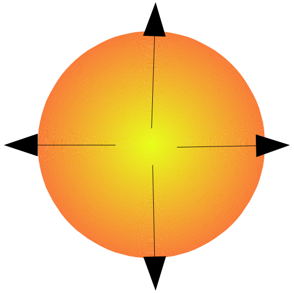
# New neutrino interactions...

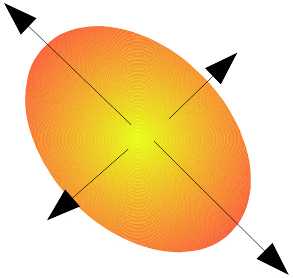
**Standard picture**: neutrino decoupling at T ~ 1 MeV; they frees-stream thereafter.

**A new hidden interactions** can conceivably keep neutrinos in equilibrium at the time of CMB decoupling.

- Interaction can locally isotropise the neutrino fluid.

Isotropic stress
(pressure)





Anisotropic stress

→ Modifies the spacetime metric perturbations

$$ds^2 = a^2(\tau)\left[-(1+\Psi)\,d\tau^2 + (1+\Phi)(dx^2+dy^2+dz^2)\right]$$

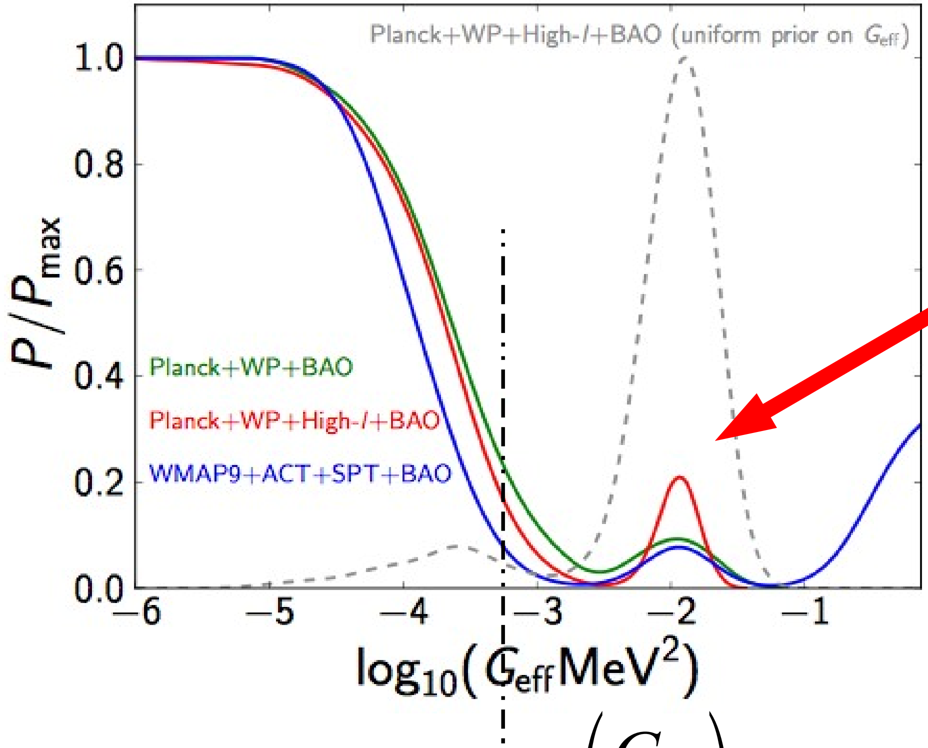
$$k^2(\Phi-\Psi) = 12\pi G a^2(\bar{\rho}+\bar{P})\,\sigma \longleftarrow$$ Anisotropic stress

→ **Observable consequences for the CMB anisotropies**

# e.g. 1: a new 4-fermion self-interaction...

Cyr-Racine & Sigurdson 2014

Delays neutrino “kinetic decoupling”.



“Strongly-coupled mode”

$$\log_{10}\left(\frac{G_X}{G_F}\right)=8.9\pm0.2$$

“Standard mode”

$$\log_{10}\left(\frac{G_X}{G_F}\right)<7.9 \quad (95\,\%)$$

Lowest “kinetic decoupling” temperature of neutrinos is **~ 25 eV**.

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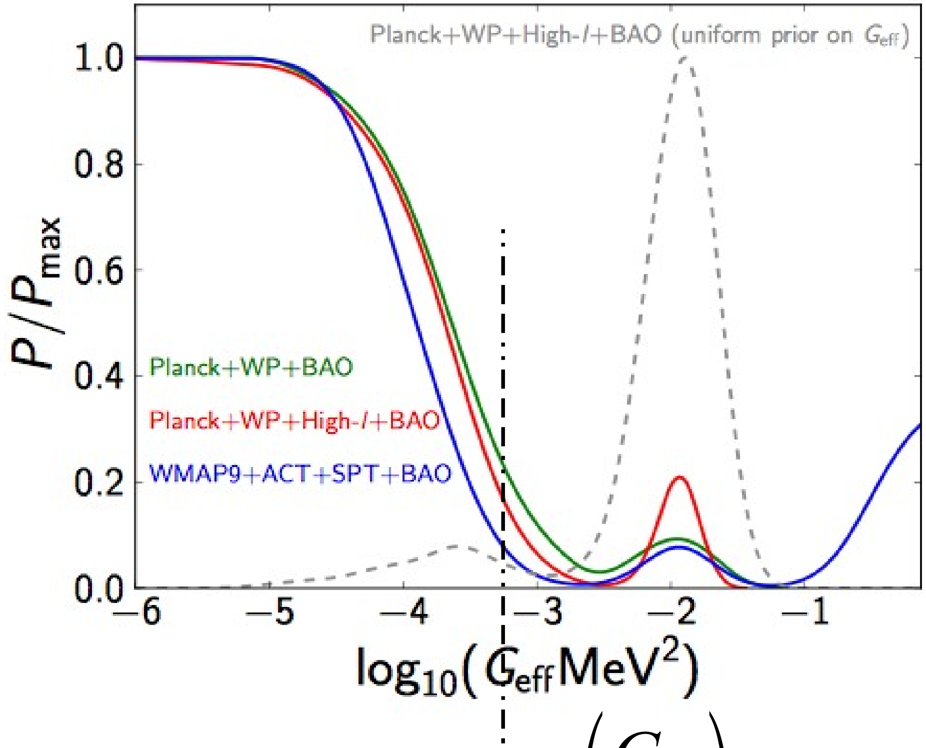

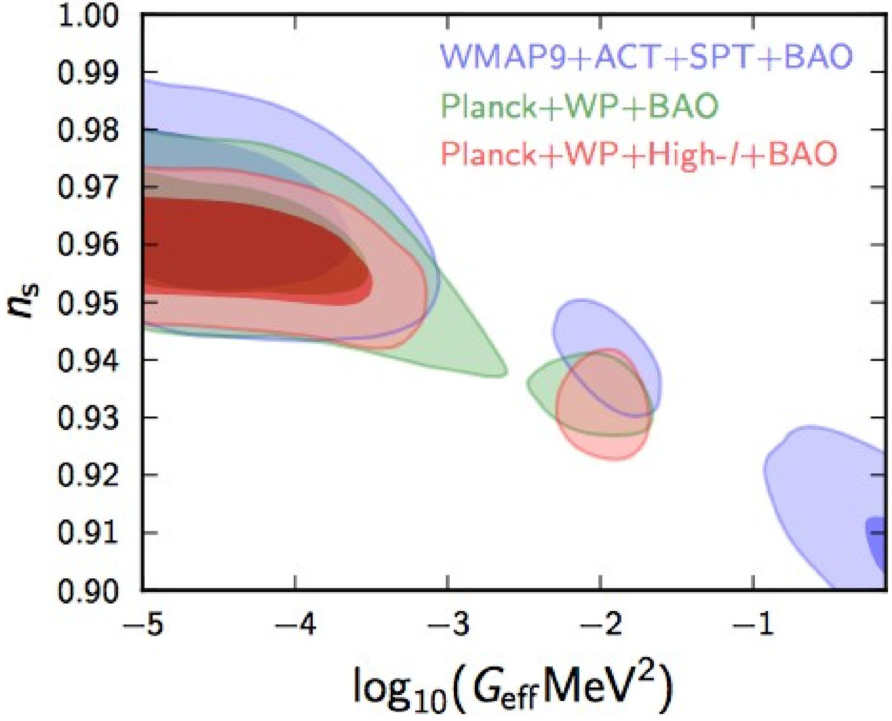

“Standard mode” $\log_{10}\left(\frac{G_X}{G_F}\right) < 7.9 \quad (95\,\%)$

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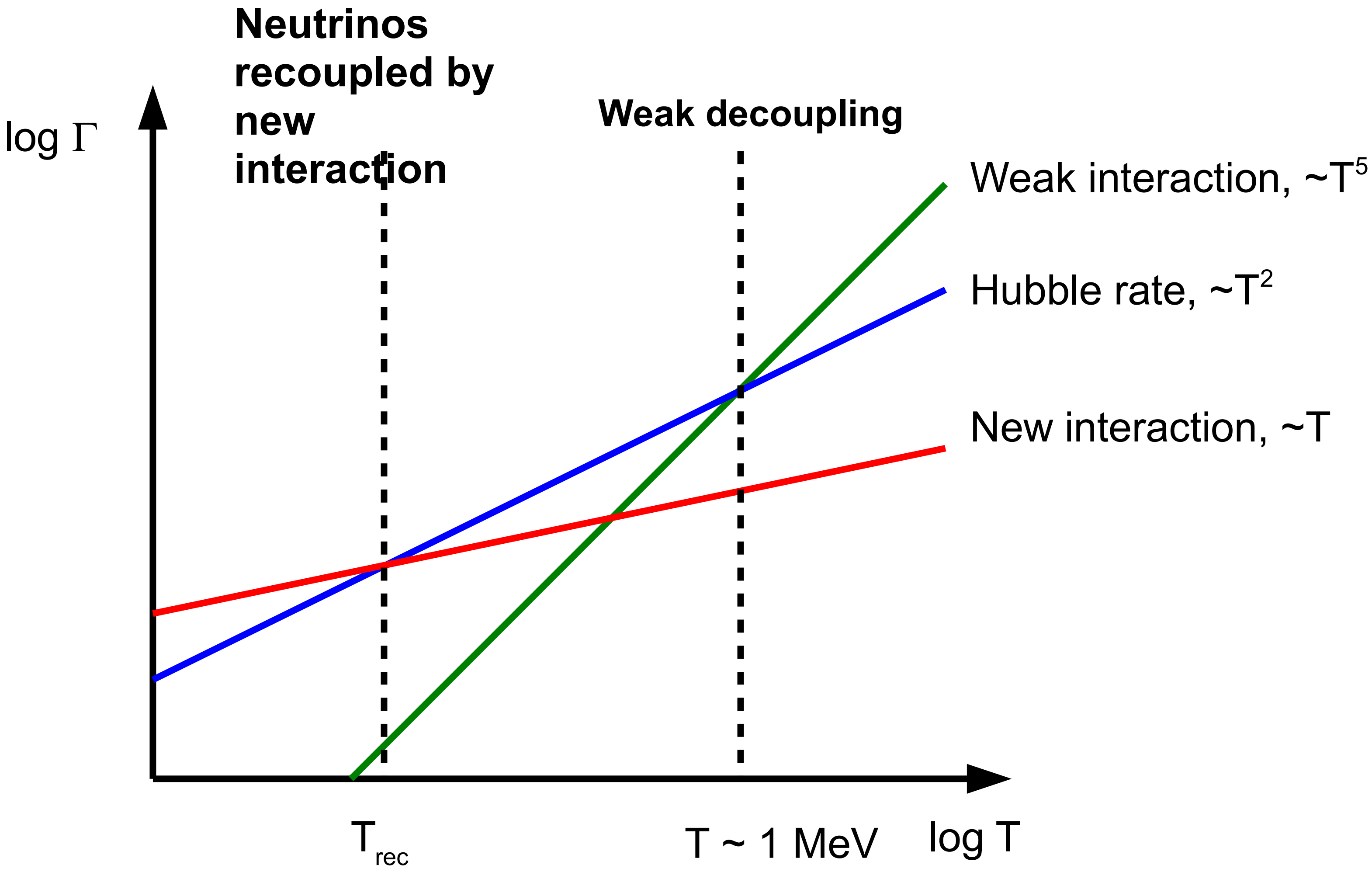
# e.g. 2: self-interaction mediated by a massless scalar...

Forastieri, Lattanzi & Natoli 2015



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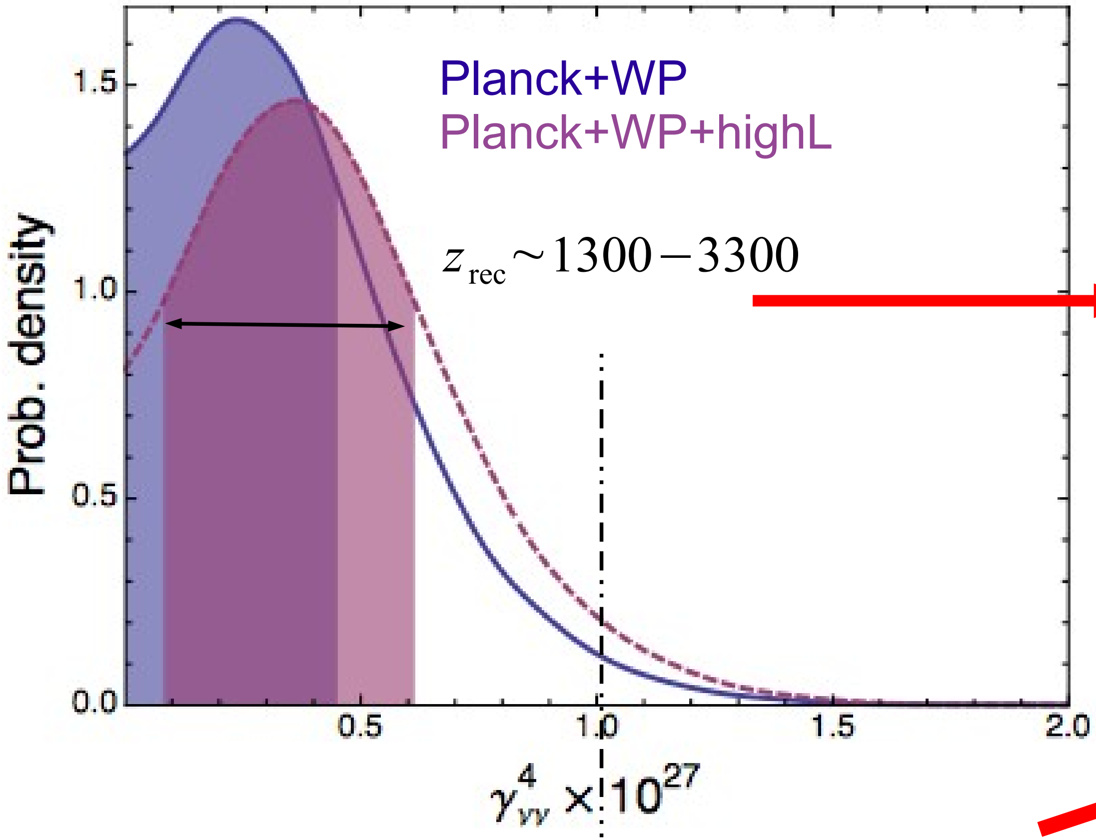

$z_{\rm rec} \sim 1300 - 3300$

A small preference for recoupling shortly before recombination

$z_{\rm rec} < 8500 \quad (95\,\%)$

Highest redshift at which neutrinos could have been recoupled before recombination

# Lots of fun games, but please don't do the following...

It has become fashionable in some quarters to use a sound speed and a viscosity parameter to parameterise neutrino free-streaming vs non-free-streaming behaviours.

$$\dot{\delta}_\nu = \frac{\dot{a}}{a}\left(1 - \boxed{3c_{\rm eff}^2}\right)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - k\left(q_\nu + \frac{2}{3k}\dot{h}\right) ;$$

$$\dot{q}_\nu = \boxed{k\, c_{\rm eff}^2}\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - \frac{\dot{a}}{a}q_\nu - \frac{2}{3}k\pi_\nu ;$$

$$\dot{\pi}_\nu = 3k\, \boxed{c_{\rm vis}^2}\left(\frac{2}{5}q_\nu + \frac{4}{15k}(\dot{h} + 6\dot{\eta})\right) - \frac{3}{5}kF_{\nu,3} ;$$

$$\dot{F}_{\nu,\ell} = \frac{k}{2\ell + 1}\left(\ell F_{\nu,\ell-1} - (\ell + 1)\, F_{\nu,\ell+1}\right), \quad (\ell \geq 3) .$$

- The parameterisation has been shown to be **unphysical**, and has **no interpretation** in terms of particle scattering. Oldengott, Rampf & Y$^3$W 2014; Cyr-Racine & Sigurdson 2014 Sellentin & Durrer 2014
- Claims of robust detection of free-streaming clearly refuted by the two examples.

# Summary...

- **Precision cosmological data** provide strong constraints on the neutrino mass sum.
  - No significant formal improvement between the best pre-Planck, Planck1 and Planck2 upper bounds (at least not for the minimal 7-parameter model).
  - But the **Planck2** bound is arguably more robust against nonlinearities.

- The **fourth neutrino**??
  - No evidence at all. But a 2.5σ discrepancy between Planck and (most) direct measurements of $H_0$ remains.
  - Reconciling the SBL sterile neutrino with cosmology remains difficult.

- **Free-streaming vs interacting neutrinos**.
  - Not as free-streaming as you think; plenty of room for new interactions.