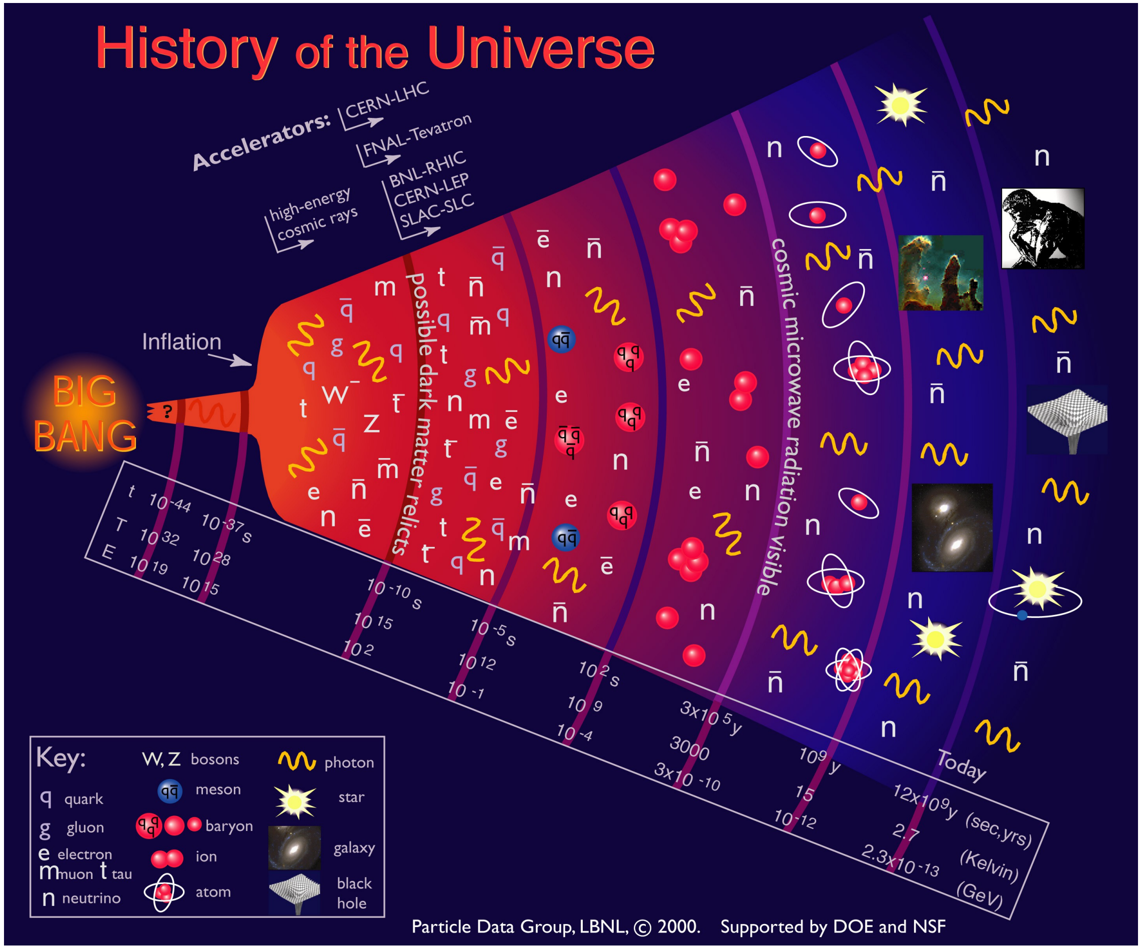
Determining neutrino masses from cosmology

Yvonne Y. Y. Wong
The University of New South Wales
Sydney, Australia

NuFact 2013, Beijing, August 19 – 24, 2013

The cosmic neutrino background...



Embedding the **standard model** in **FLRW cosmology** necessarily leads to a thermal neutrino background (decoupling at T ~ 1 MeV).

Fixed by weak interactions

Present temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma = 1.95\,\mathrm{K}$$

Number density per flavour:

$$n_\nu = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T_\nu^3 = 112\ \mathrm{cm}^{-3}$$

The cosmic neutrino background: energy density...

The present-day neutrino energy density depends on whether the neutrinos are relativistic or nonrelativistic.

- **Relativistic** (m << T):

Photon energy density

$$\rho_\nu = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma \quad \Leftarrow \quad \frac{3\rho_\nu}{\rho_\gamma} \sim 0.68$$

- **Nonrelativistic** (m >> T ~ 10^{-4} eV):

ΛCDM (since Planck)

$$\rho_\nu = m_\nu n_\nu \quad \Rightarrow \quad \Omega_{\nu,0}h^2 = \frac{m_\nu}{94\,\mathrm{eV}} > 0.1\%\,h^2$$

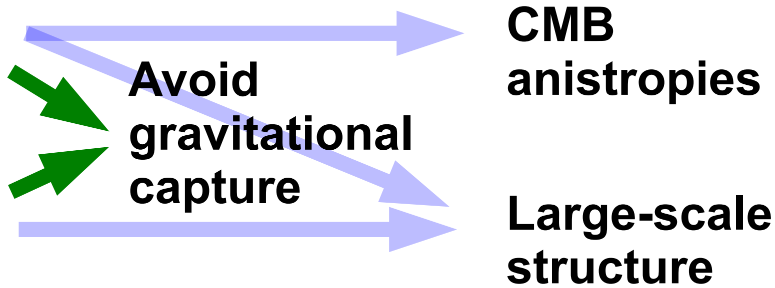
From neutrino oscillations m_ν > 0.05 eV

Neutrino dark matter!

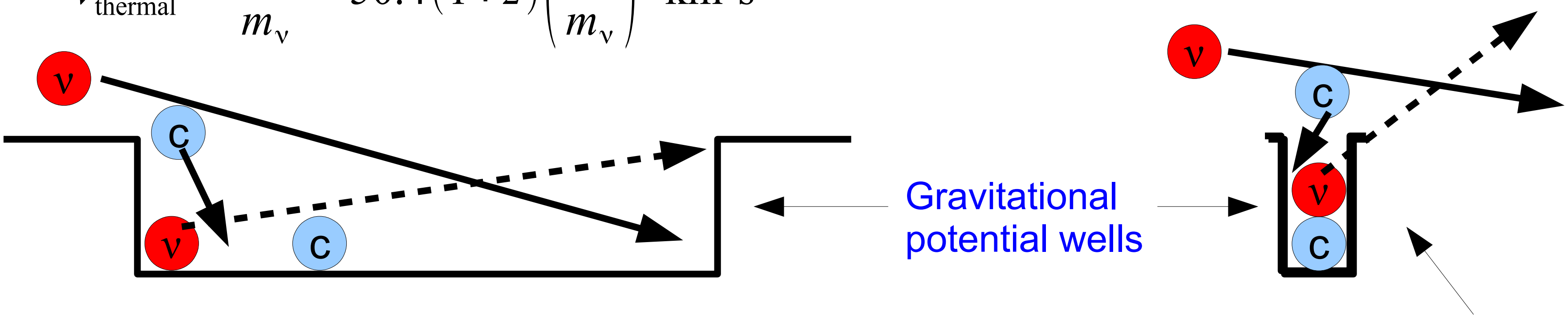
Detecting neutrino masses via free-streaming...

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

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



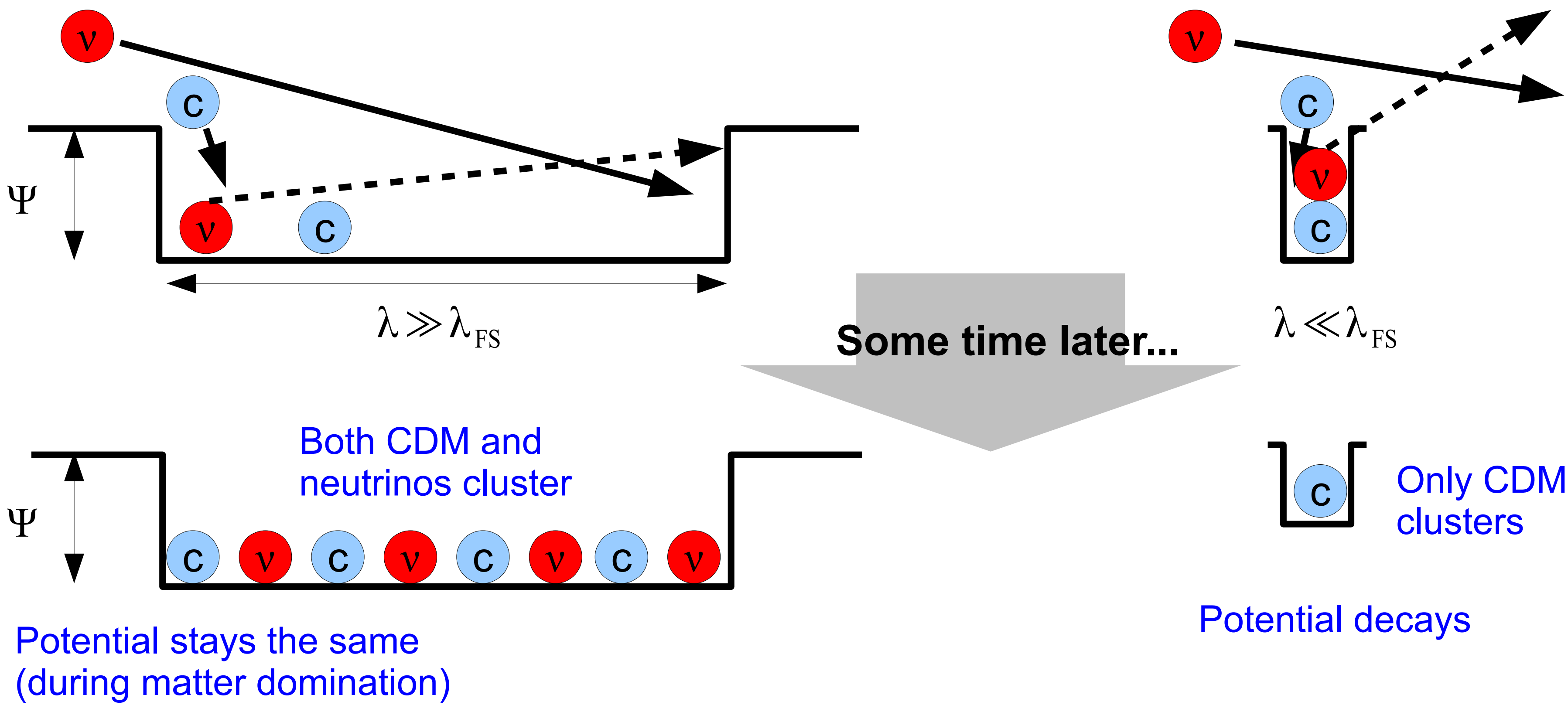
$$v_{\text{thermal}} = \frac{T_\nu}{m_\nu} \simeq 50.4(1+z)\left(\frac{\text{eV}}{m_\nu}\right) \text{ km s}^{-1}$$



Non-clustering
$\lambda \ll \lambda_{\text{FS}}$
$k \gg k_{\text{FS}}$

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

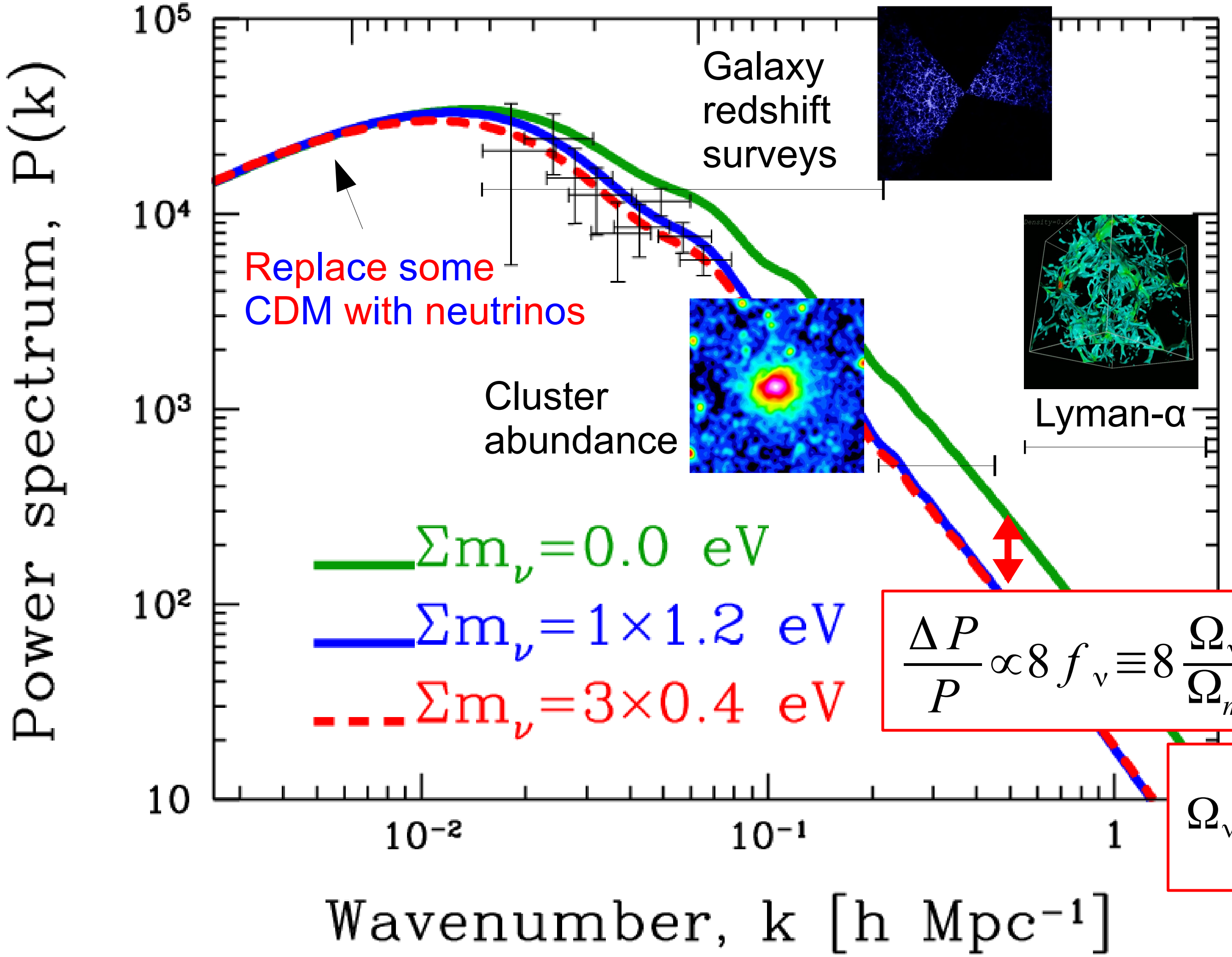
Consider a neutrino and a cold dark matter particle encountering two gravitational potential wells of different sizes in an expanding universe:



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

Large-scale matter distribution...

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

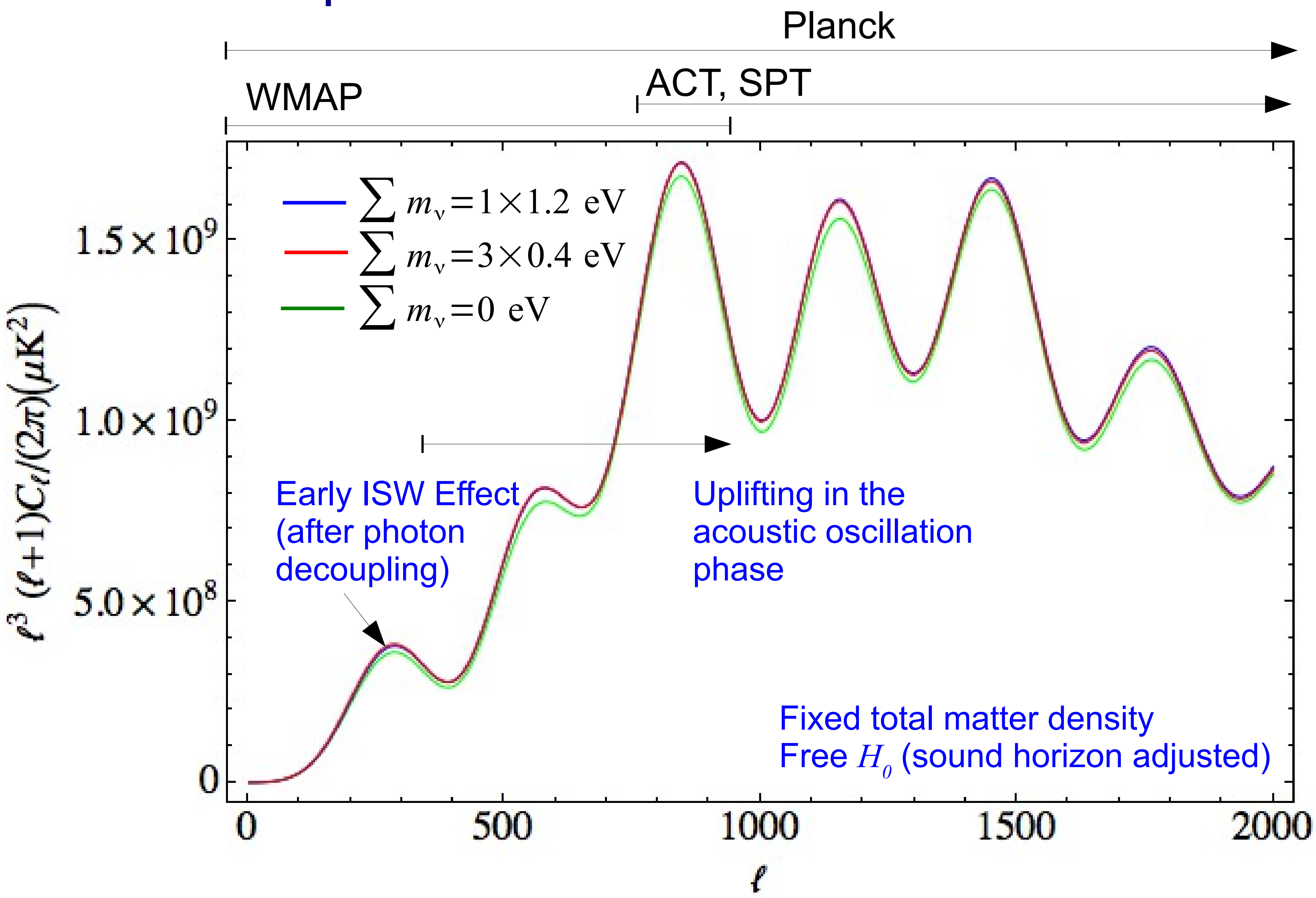


f_ν = Neutrino fraction

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

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

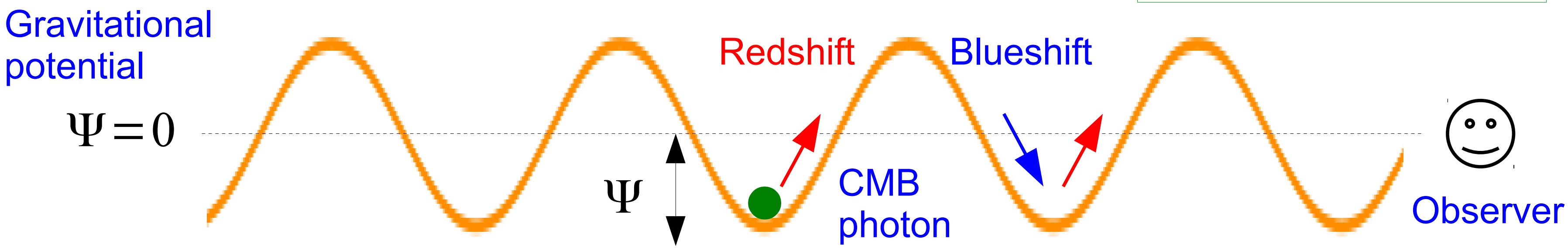
CMB anisotropies...



Sachs-Wolfe effect:

Observed CMB temperature fluctuation

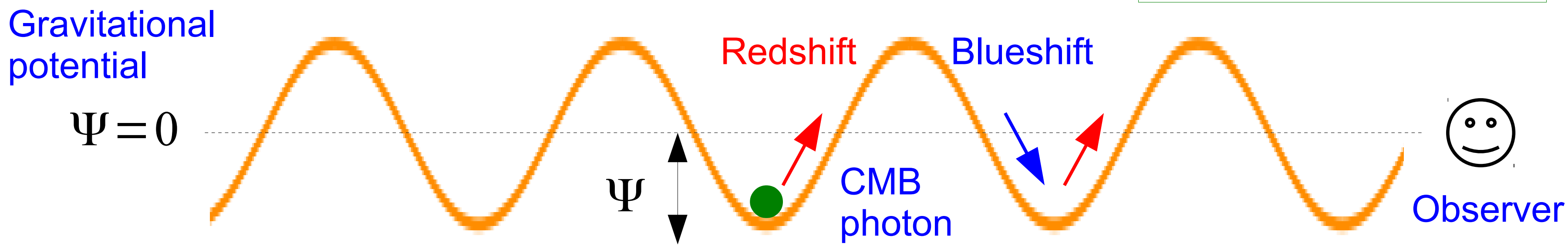
$$\left.\frac{\Delta T}{T}\right|_{\text{observed}} = \left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} + \Psi$$



Sachs-Wolfe effect:

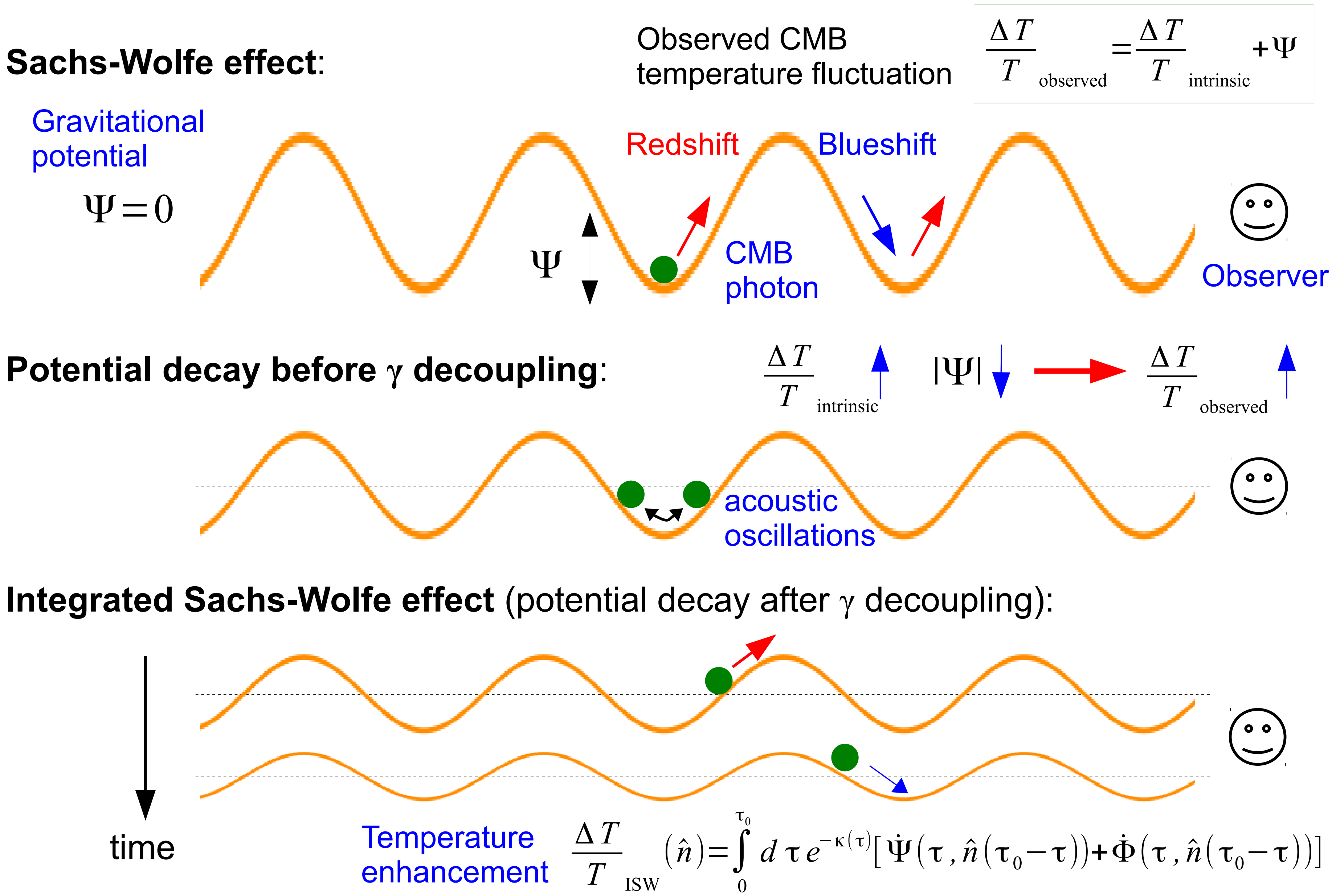
Observed CMB temperature fluctuation

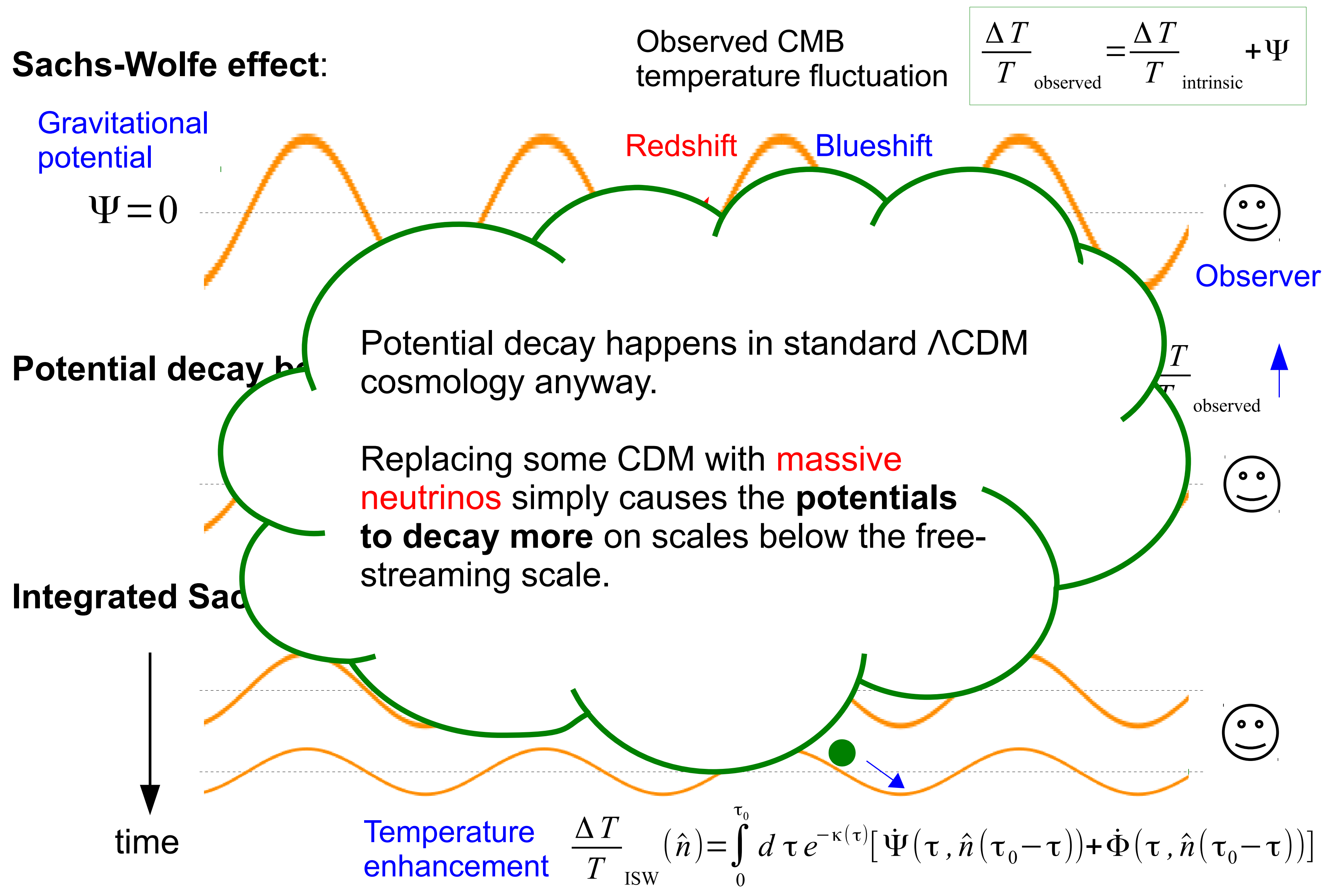
$$\left.\frac{\Delta T}{T}\right|_{\text{observed}} = \left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} + \Psi$$



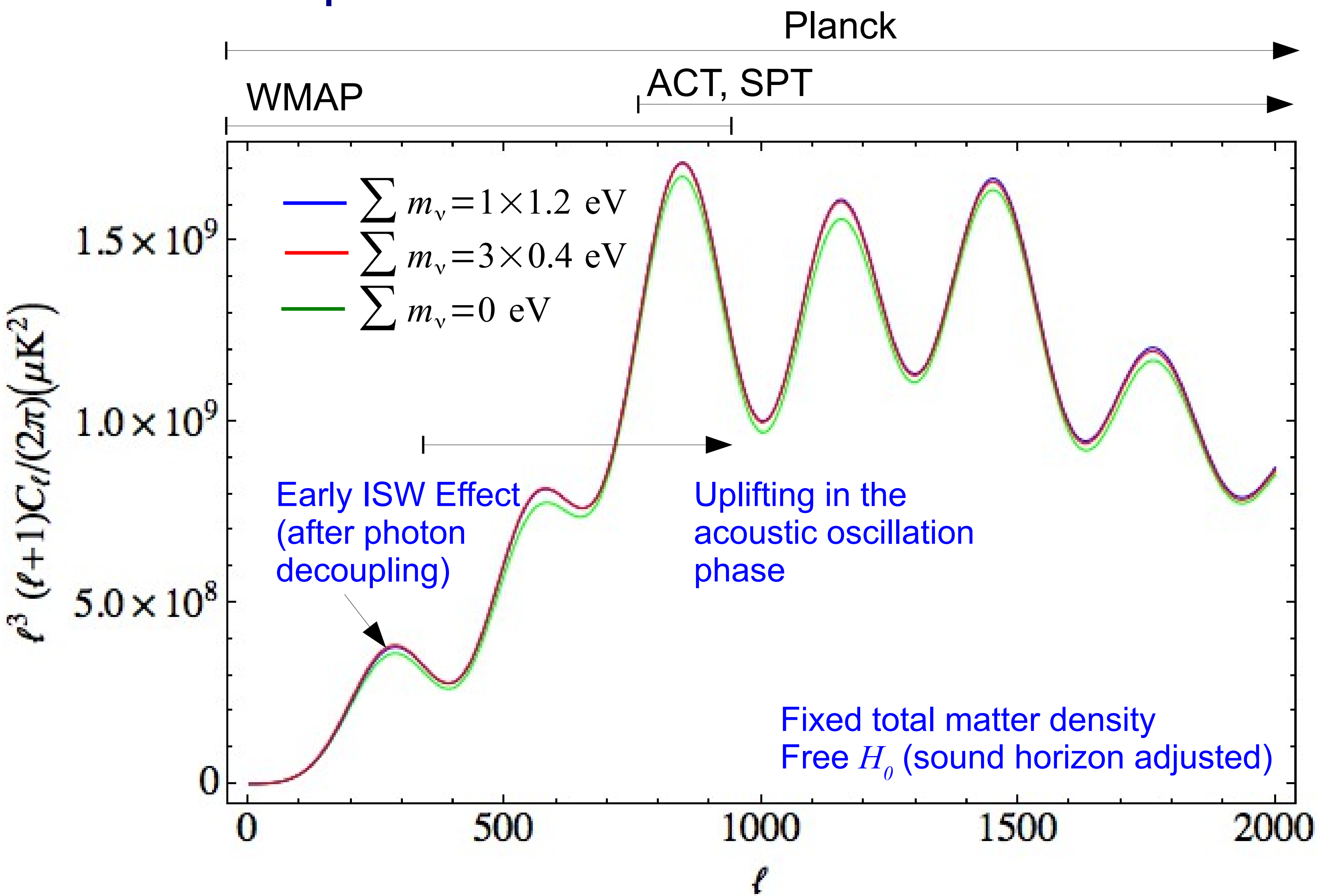
Potential decay before γ decoupling:

$$\left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} \uparrow \quad |\Psi| \downarrow \quad \longrightarrow \quad \left.\frac{\Delta T}{T}\right|_{\text{observed}} \uparrow$$


Sachs-Wolfe effect:
Observed CMB temperature fluctuation
$\frac{\Delta T}{T}_{\text{observed}} = \frac{\Delta T}{T}_{\text{intrinsic}} + \Psi$
Gravitational potential
$\Psi = 0$
Ψ
Redshift
Blueshift
CMB photon
Observer
Potential decay before γ decoupling:
$\frac{\Delta T}{T}_{\text{intrinsic}} \uparrow \quad |\Psi| \downarrow \rightarrow \frac{\Delta T}{T}_{\text{observed}} \uparrow$
acoustic oscillations
Integrated Sachs-Wolfe effect (potential decay after γ decoupling):
time
Temperature enhancement
$\frac{\Delta T}{T}_{\text{ISW}}(\hat{n}) = \int_0^{\tau_0} d\tau\, e^{-\kappa(\tau)} [\dot{\Psi}(\tau, \hat{n}(\tau_0 - \tau)) + \dot{\Phi}(\tau, \hat{n}(\tau_0 - \tau))]$


Sachs-Wolfe effect:
Observed CMB temperature fluctuation
$\frac{\Delta T}{T}_{\mathrm{observed}} = \frac{\Delta T}{T}_{\mathrm{intrinsic}} + \Psi$
Gravitational potential
$\Psi = 0$
Redshift
Blueshift
Observer
Potential decay happens in standard ΛCDM cosmology anyway.
Replacing some CDM with massive neutrinos simply causes the **potentials to decay more** on scales below the free-streaming scale.
Potential decay be
$\frac{\Delta T}{T}_{\mathrm{observed}}$
Integrated Sac
time
Temperature enhancement
$\frac{\Delta T}{T}_{\mathrm{ISW}}(\hat{n}) = \int_0^{\tau_0} d\tau\, e^{-\kappa(\tau)} [\dot{\Psi}(\tau, \hat{n}(\tau_0 - \tau)) + \dot{\Phi}(\tau, \hat{n}(\tau_0 - \tau))]$

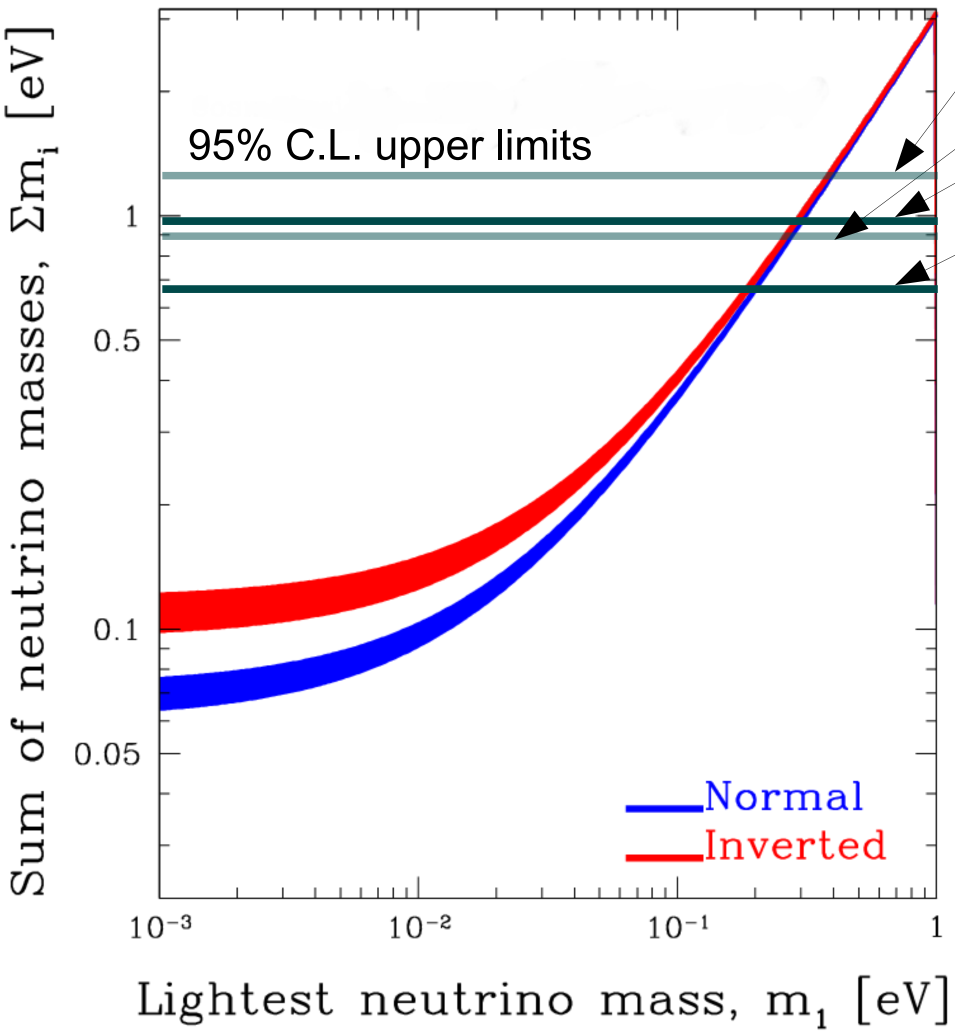
CMB anisotropies...



Present constraints…

Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

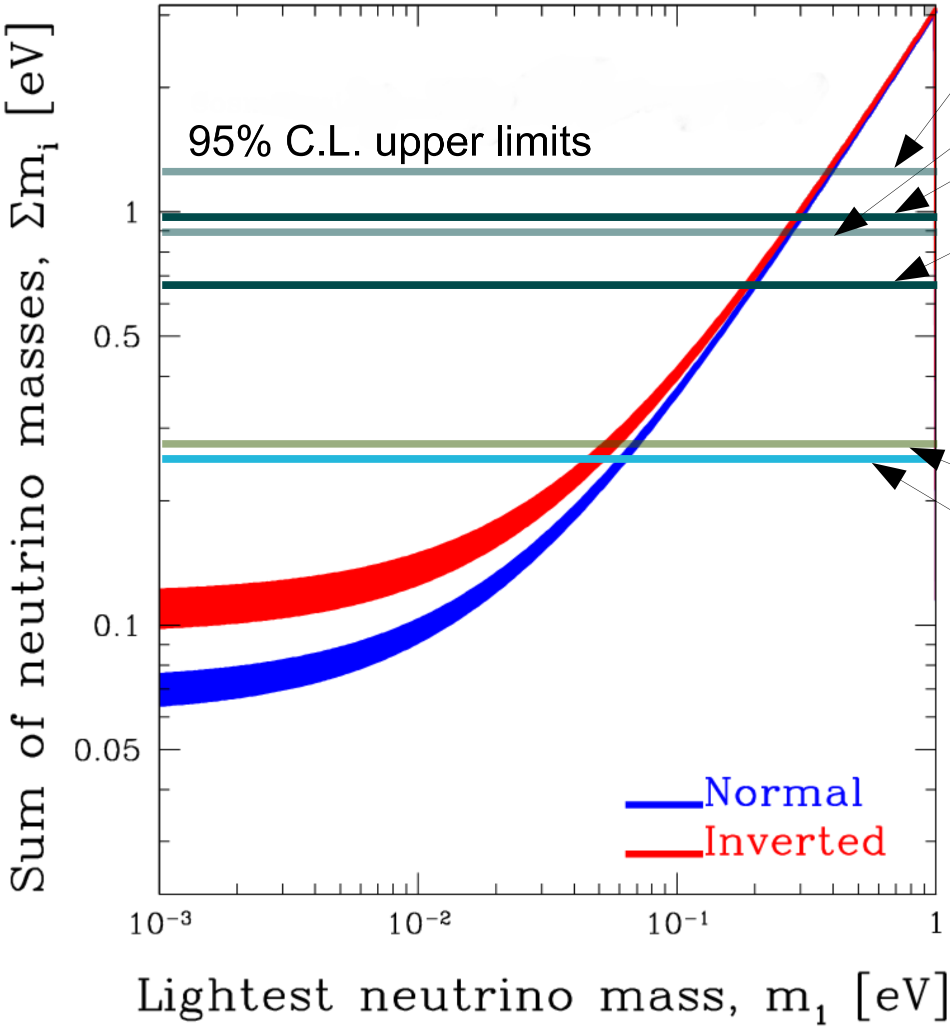
Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

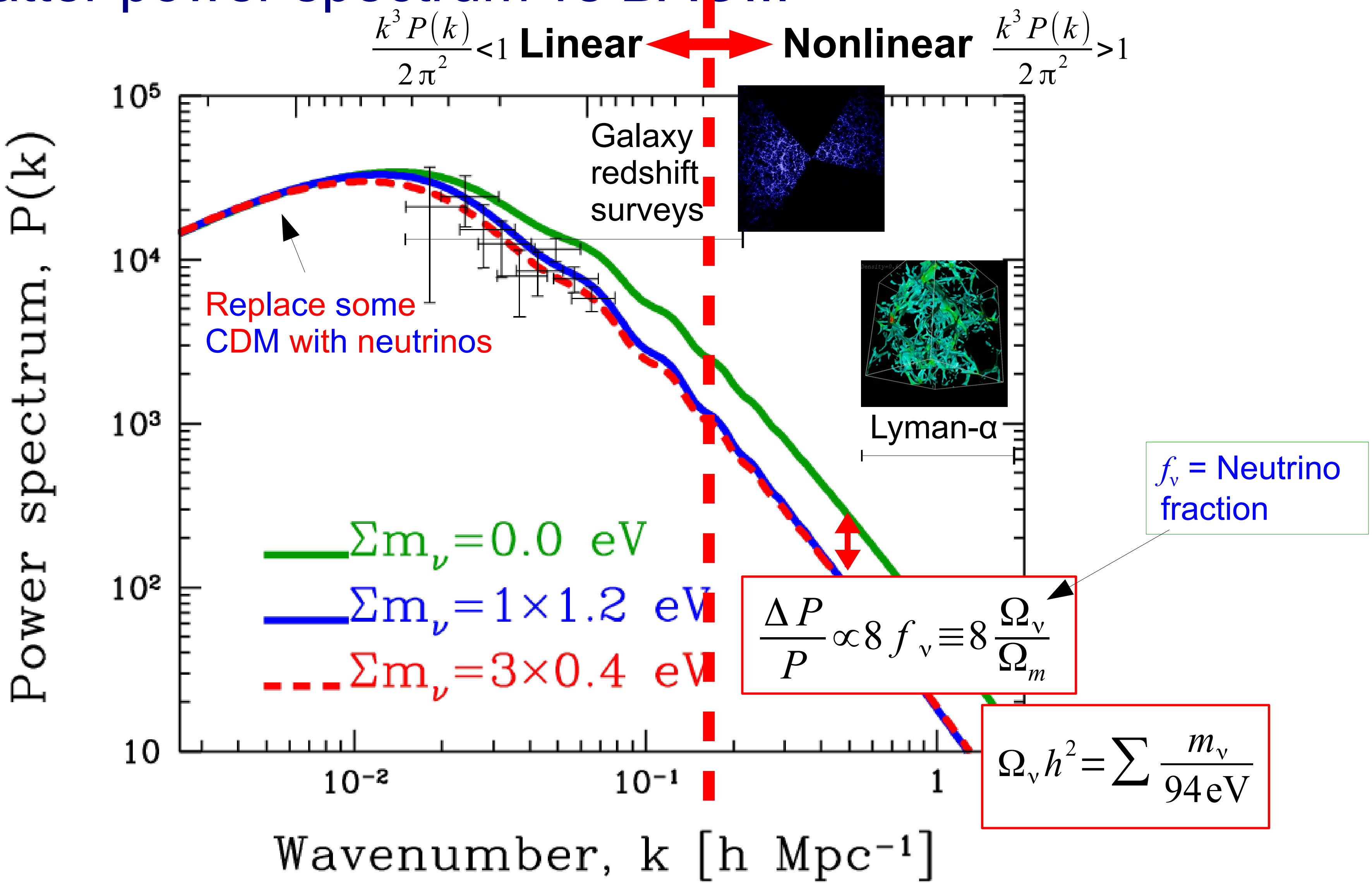
Planck + WP + (ACT ℓ > 1000 + SPT ℓ > 2000) + baryon acoustic oscillations

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

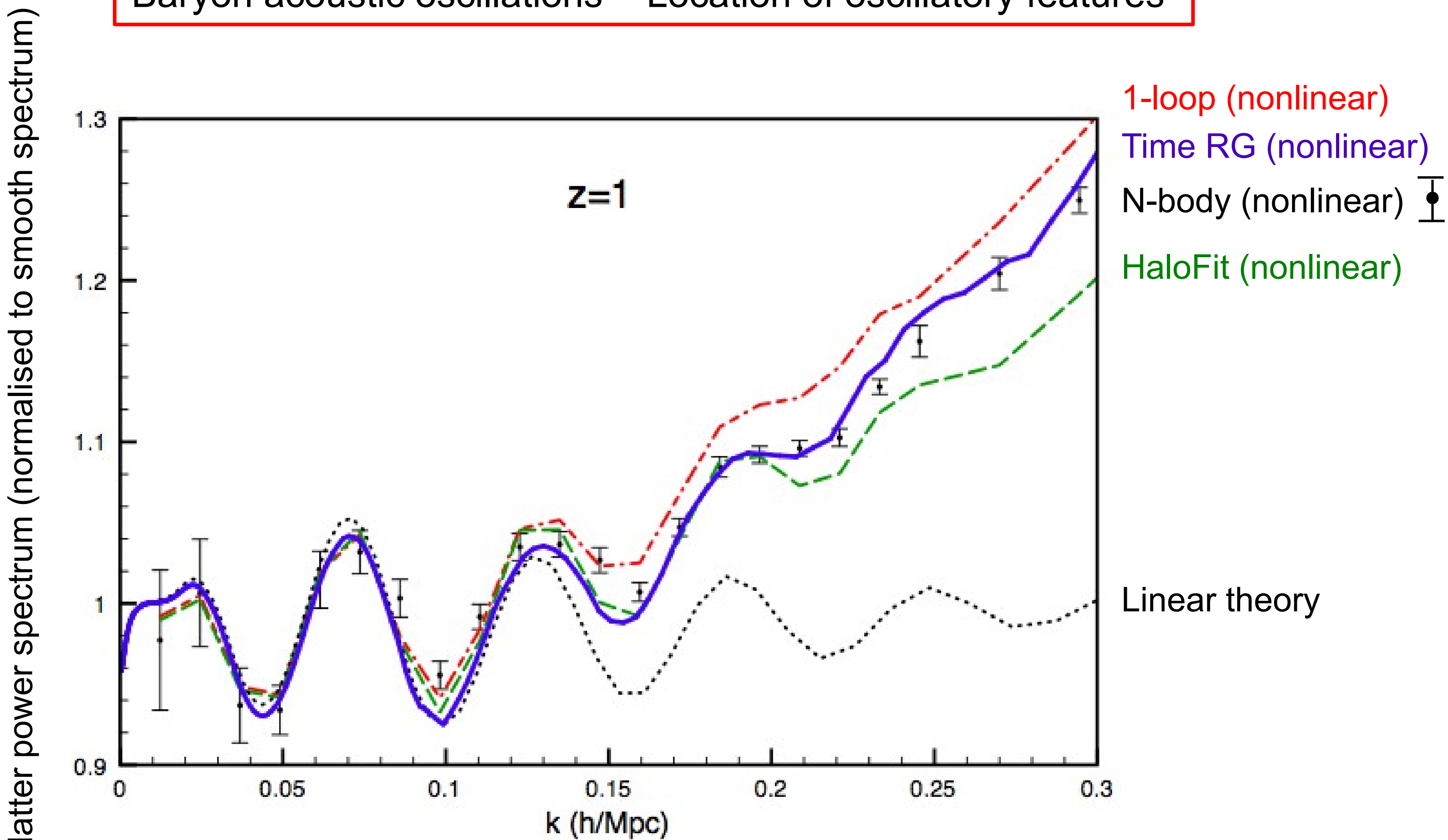
Best minimal bound

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

Matter power spectrum vs BAO...



Matter power spectrum = Shape
Baryon acoustic oscillations = Location of oscillatory features



Pietroni 2008

In a nutshell...

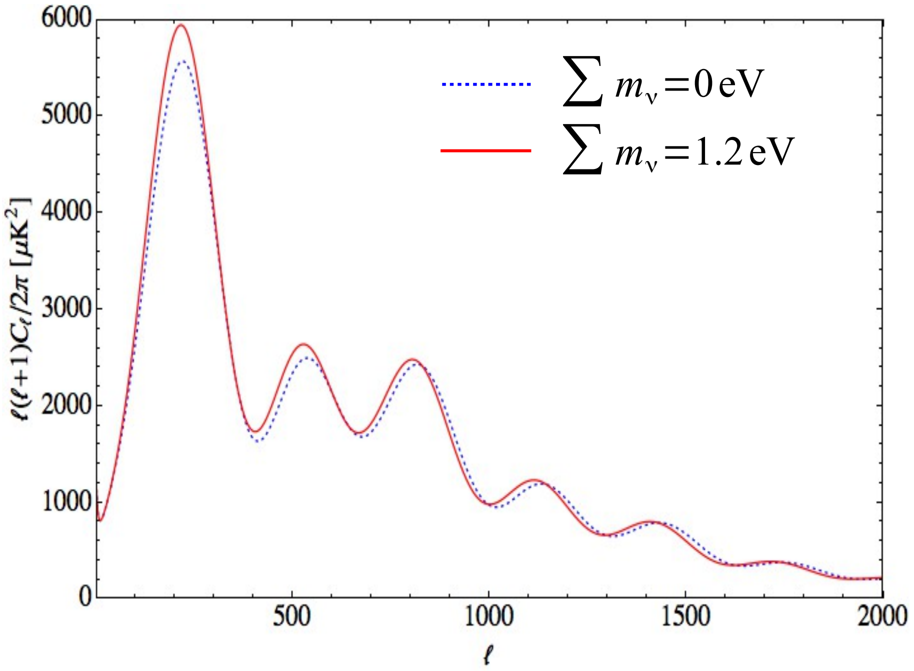
- Formally, the best minimal (7-parameter) upper bound on $\Sigma\, m_\nu$ is still hovering around 0.3 eV post-Planck.

- The bound has however become more robust against uncertainties:
  - 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?

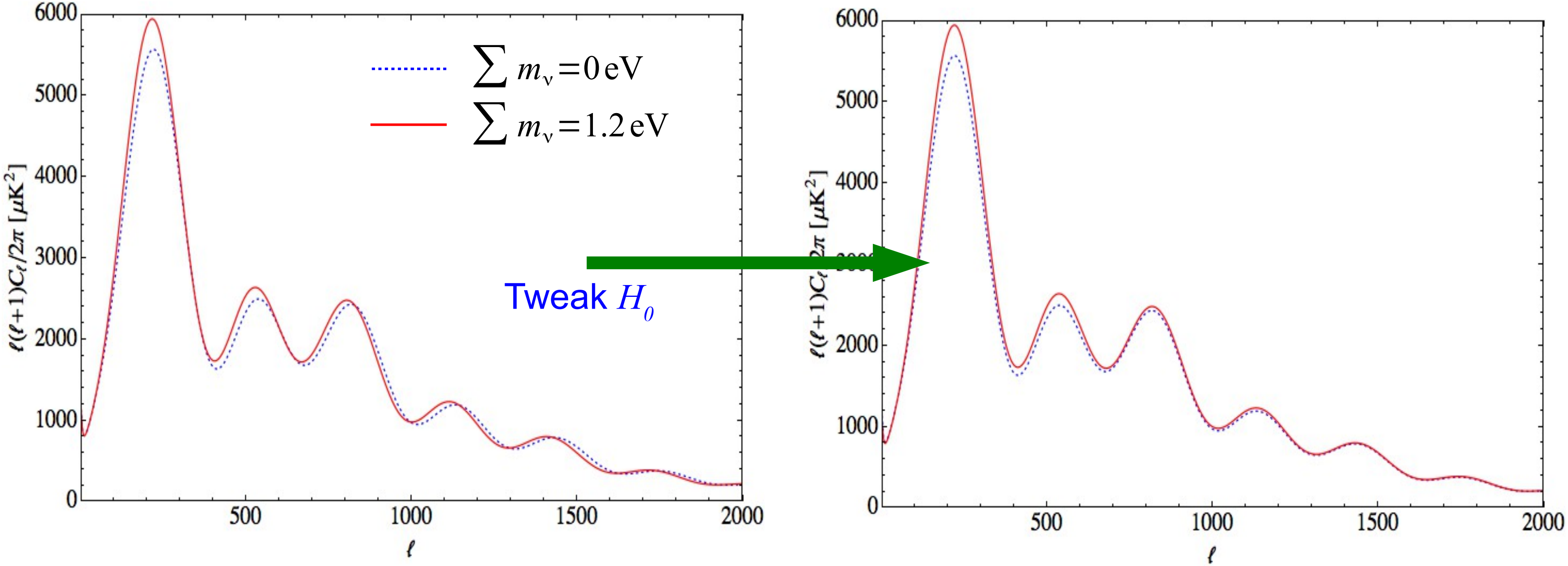
Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



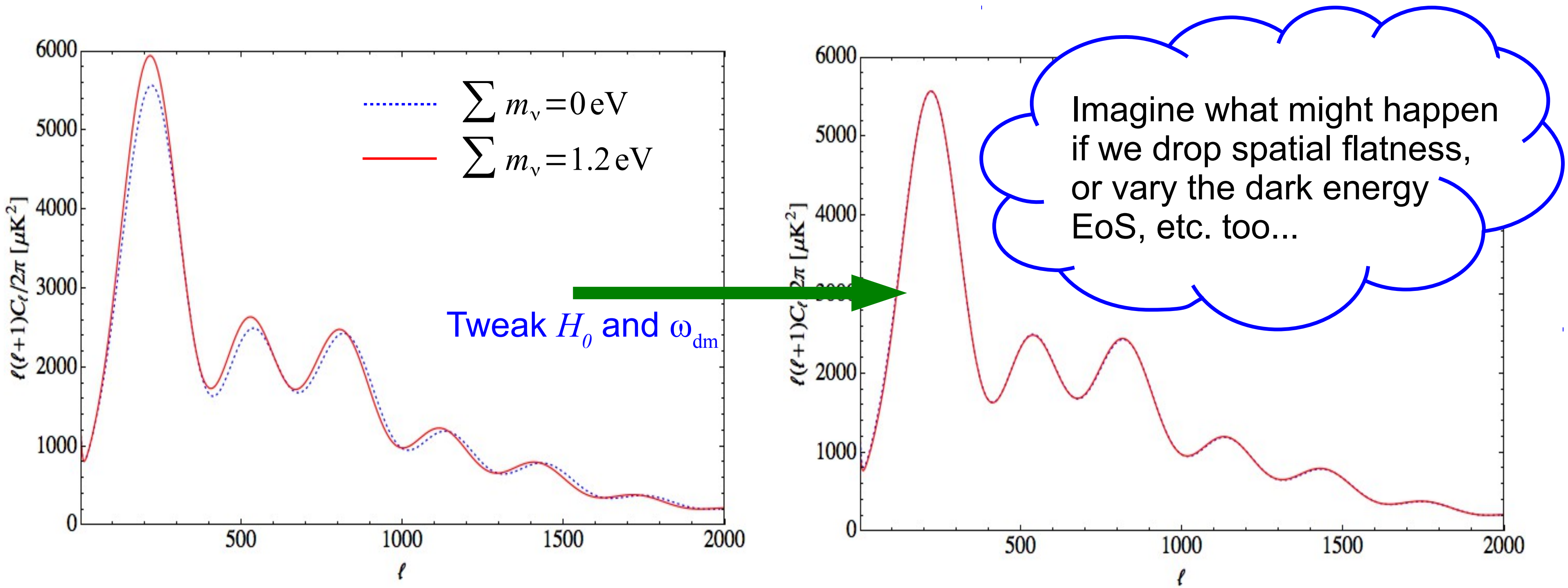
Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



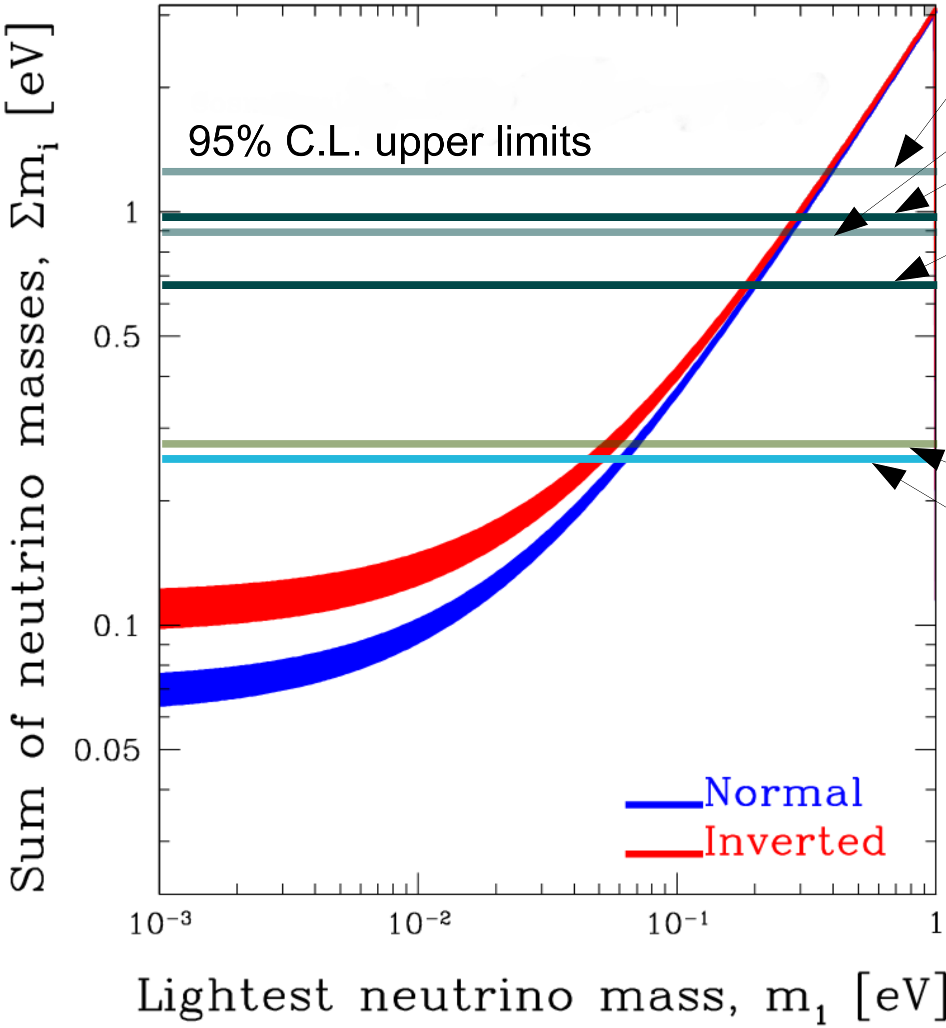
Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

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

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

Best minimal bound

Dropping assumption of spatial flatness:

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

Other extensions??

Discrepancies potentially resolved by neutrino physics??

Planck discrepancies with other observations...

- **Hubble parameter H_0**: Planck-inferred value lower than local HST measurement.
  - Alleviated by postulating $N_{eff} > 3$?
- **Small-scale RMS fluctuation σ_8**: Planck CMB prefers a higher value than galaxy cluster count and galaxy shear from CFHTLens.

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2

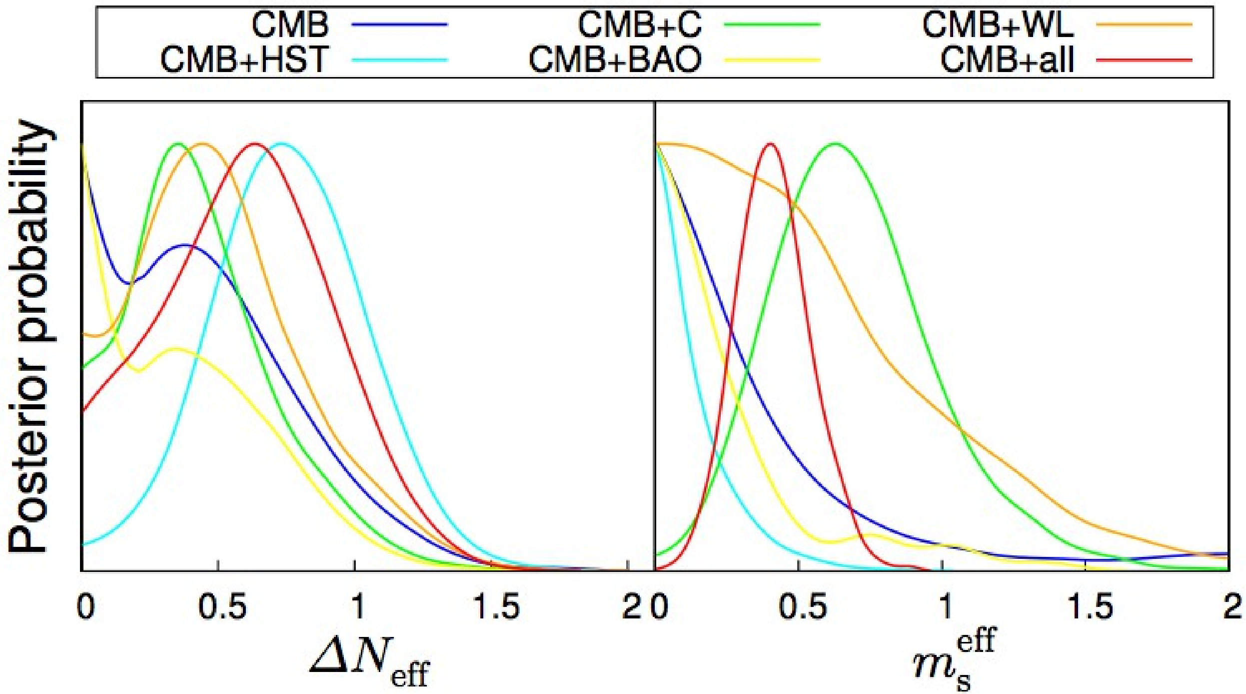
Planck SZ clusters $\sigma_8(\Omega_m/0.27)^{0.3} = 0.782 \pm 0.01$ Ade et al. [Planck collaboration] 2013

CFHTLens galaxy shear $\sigma_8(\Omega_m/0.27)^{0.46} = 0.774 \pm 0.04$ Heymans et al. 2013

A neutrino solution??

My take: These discrepancies are most likely due to poorly understood nonlinearities.

- Cluster counts are particularly difficult to model.
- But at face value a sterile neutrino solution is possible.

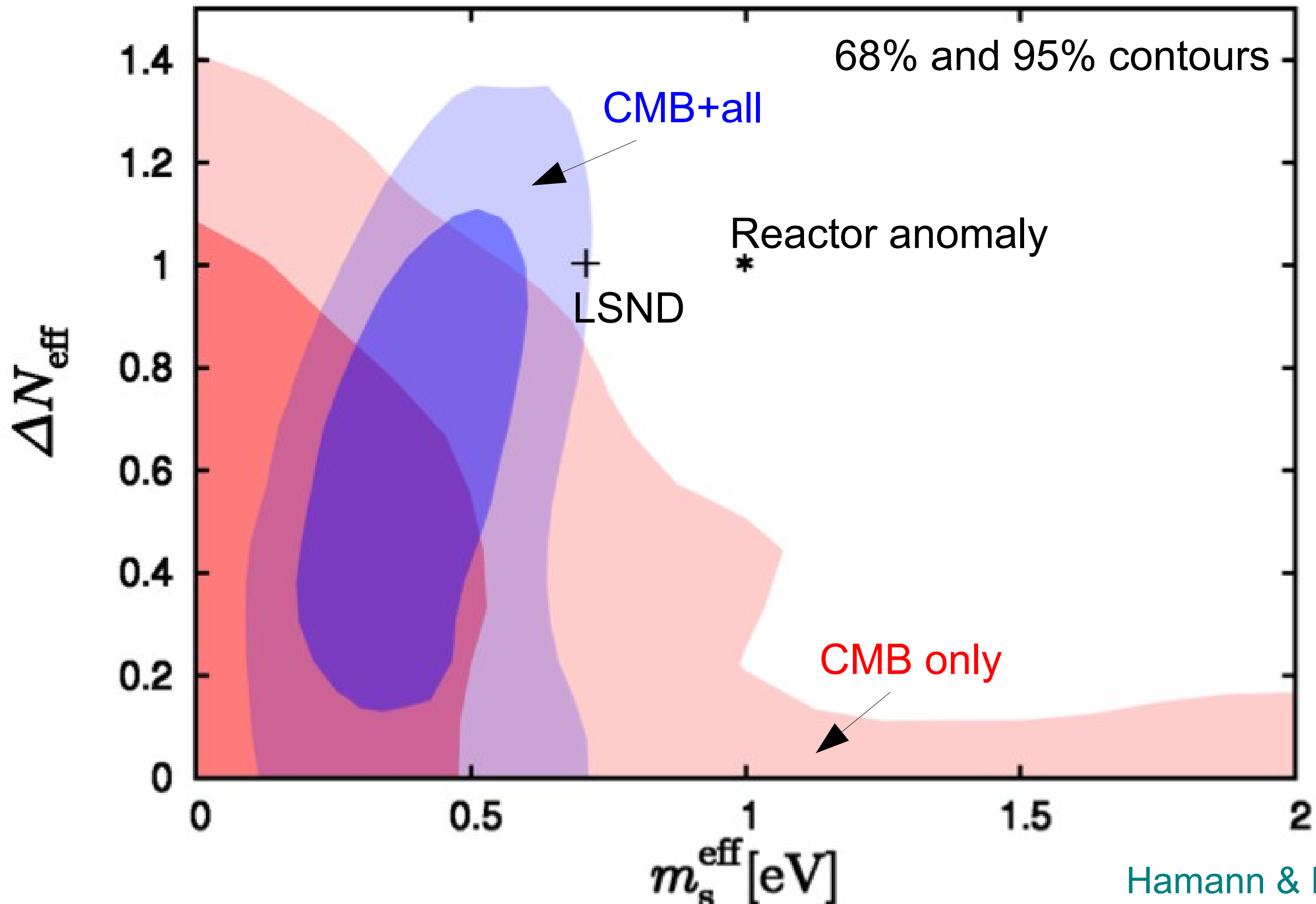


CMB+all
(ΛCDM+ΔN_{eff}+m_s
8-parameter model)

$$\Delta N_{\mathrm{eff}} = 0.61 \pm 0.30$$
$$m_s = (0.41 \pm 0.13)\ \mathrm{eV}$$

Hamann & Hasenkamp 2013
also Wyman et al. 2013

A neutrino solution??

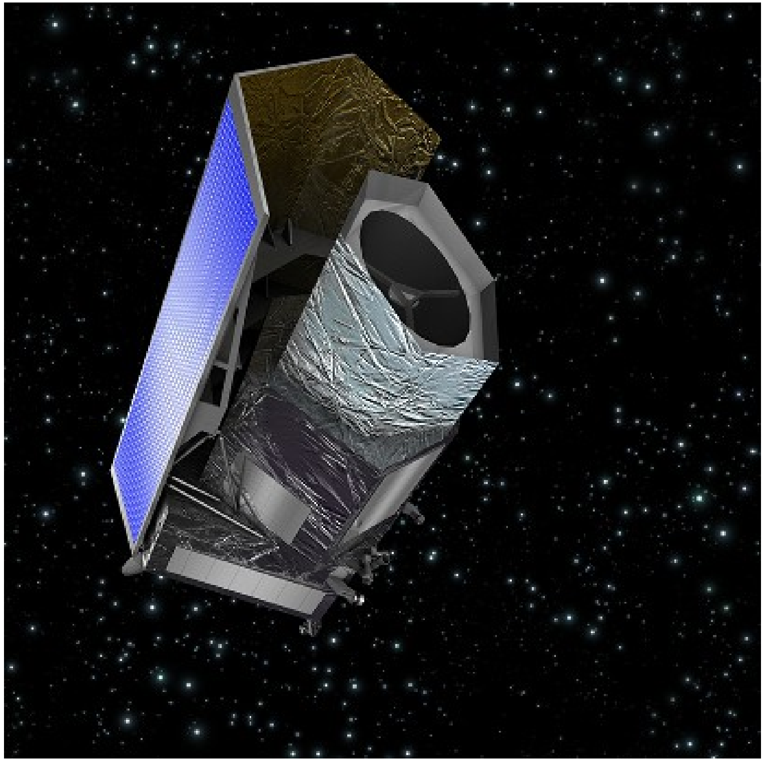


Hamann & Hasenkamp 2013
also Wyman et al. 2013

Future sensitivities…
(Planck is not the end of the story!!)

ESA Euclid mission selected for implementation...

Launch planned for 2019.



- 6-year lifetime
- 15000 deg^2 (>1/3 of the sky)
- Galaxies and clusters out to z~2
  - Photo-z for 1 billion galaxies
  - Spectro-z for 50 million galaxies
- Optimised for weak gravitational lensing (cosmic shear)

Expected sensitivity...

A **7-parameter forecast**: Hamann, Hannestad & Y³W 2012

Data	$10^3 \times \sigma(\omega_{dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\text{eV}$
c	2.02	1.427	0.143
cs	0.423	0.295	0.025
cg	0.583	0.317	0.016
cg_l	0.828	0.448	0.019
cg_b	0.723	0.488	0.039
cg_bl	1.165	0.780	0.059
csg	0.201	0.083	0.011
csgx	0.181	0.071	0.011
csg_b	0.385	0.268	0.023
$\text{csg}_\text{b}\text{x}$	0.354	0.244	0.022

c = CMB (Planck); g = Euclid galaxy clustering
s = Euclid cosmic shear; x = Euclid shear-galaxy cross

Most optimistic
Σm_ν potentially detectable at 5σ+ with Planck+Euclid (assuming nonlinearities to be completely under control)

Expected sensitivity...

A **7-parameter forecast**: Hamann, Hannestad & Y[3]W 2012

Data	$10^3 \times \sigma(\omega_{\rm dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/{\rm eV}$
c	2.02	1.427	0.143
cs	0.423	0.295	0.025
cg	0.583	0.317	0.016
$\rm cg_l$	0.828	0.448	0.019
$\rm cg_b$	0.723	0.488	0.039
$\rm cg_{bl}$	1.165	0.780	0.059
csg	0.201	0.083	0.011
csgx	0.181	0.071	0.011
$\rm csg_b$	0.385	0.268	0.023
$\rm csg_bx$	0.354	0.244	0.022

c = CMB (Planck); g = Euclid galaxy clustering
s = Euclid cosmic shear; x = Euclid shear-galaxy cross

Moderate
2σ+ detection (only shear nonlinearities under control)

Very pessimistic
No knowledge of nonlinearities

Most optimistic
Σm_ν potentially detectable at 5σ+ with Planck+Euclid (assuming nonlinearities to be completely under control)

Summary...

- Precision cosmological observables can be used to “measure” the absolute neutrino mass scale based on the effect of **neutrino free-streaming**.
- **Existing precision cosmological data** already provide strong constraints on the neutrino mas sum.
  - No significant formal improvement between the best pre-Planck and post-Planck upper bounds (at least not for the minimal 7-parameter model).
  - But the **post-Planck** bound is arguably more robust.
- There are **outstanding discrepancies** between Planck and measurements from HST, clusters, and cosmic shear.
  - Taken at face value these discrepancies can be resolved by new neutrino physics (although not necessarily the same physics in all cases...).
  - But personally I'd take it *cum grano salis*.