Cosmology and neutrinos

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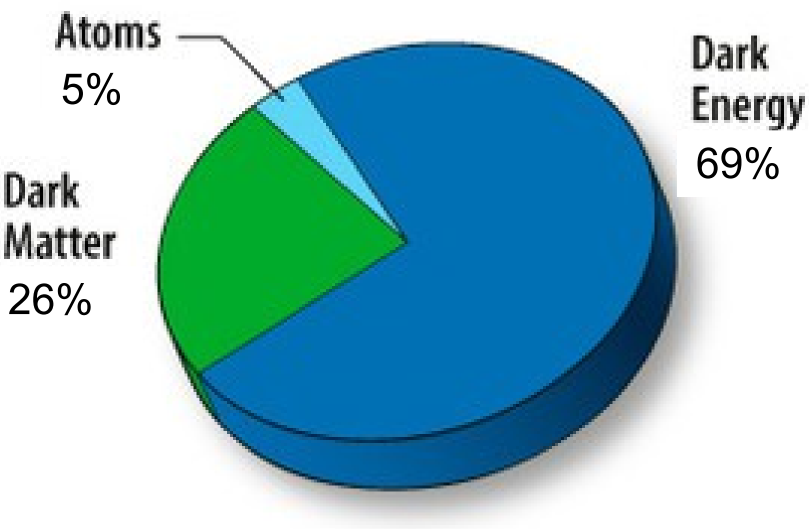
NNN2015/UD2, Stony Brook, October 28 – 31, 2015

The concordance flat ΛCDM model...

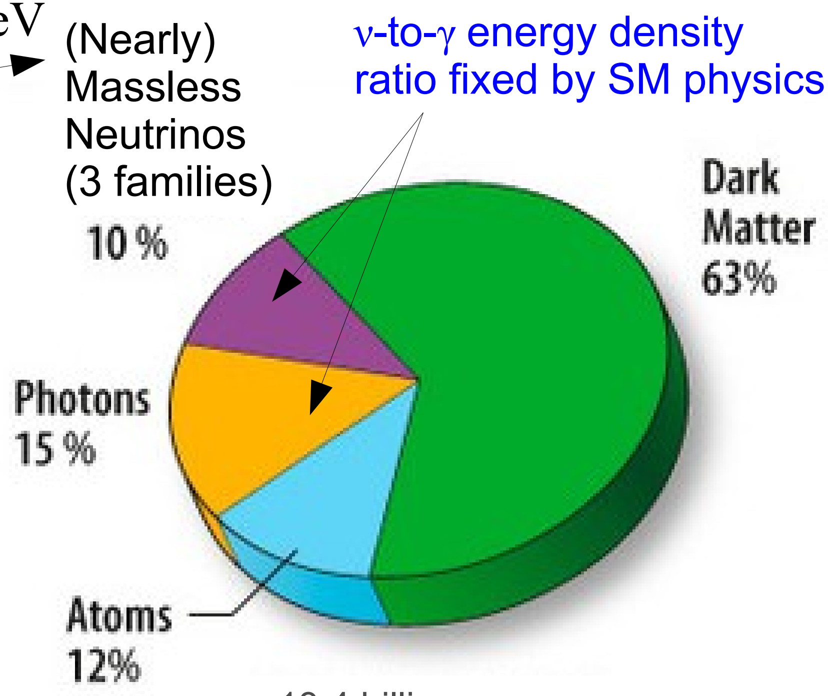
The simplest model consistent with **present observations**.

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

ν-to-γ 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 can be extended beyond 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**. $N_{\mathrm{eff}} \neq 3\,??$
  - Sterile neutrinos and discrepancies potentially solved by them?

This talk

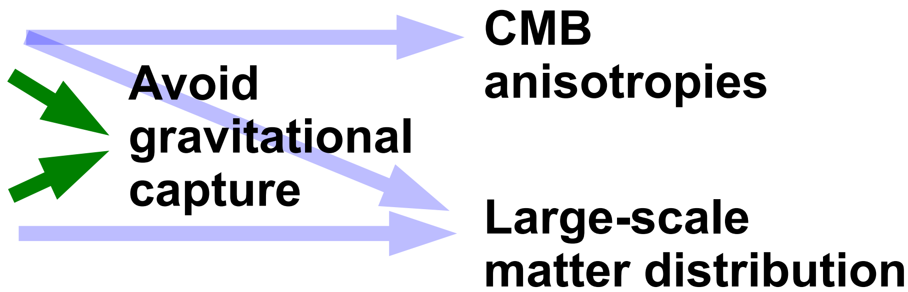
- **Hidden interactions**
  - Neutrino-neutrino, neutrino-dark matter, neutrino-dark energy.

Measuring neutrino masses with cosmology...

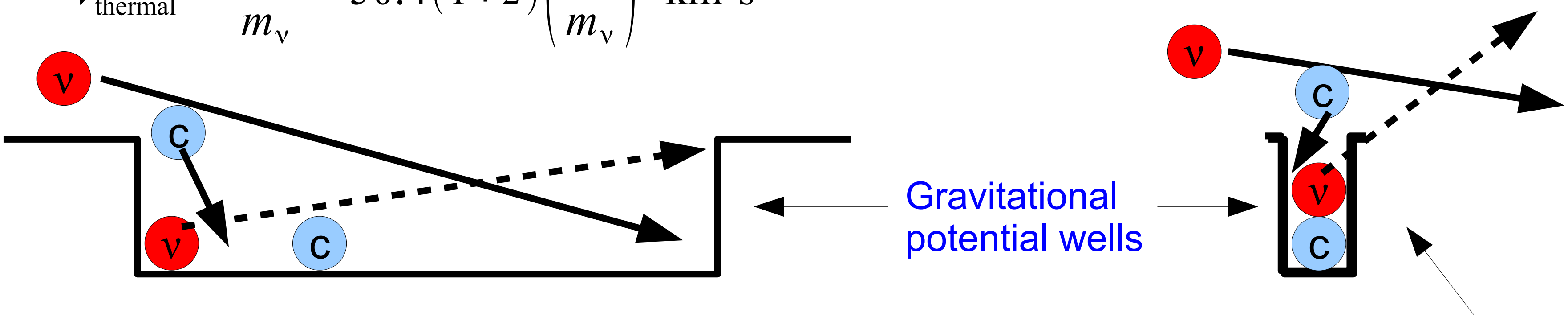
Free-streaming neutrinos...

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.



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



Non-clustering

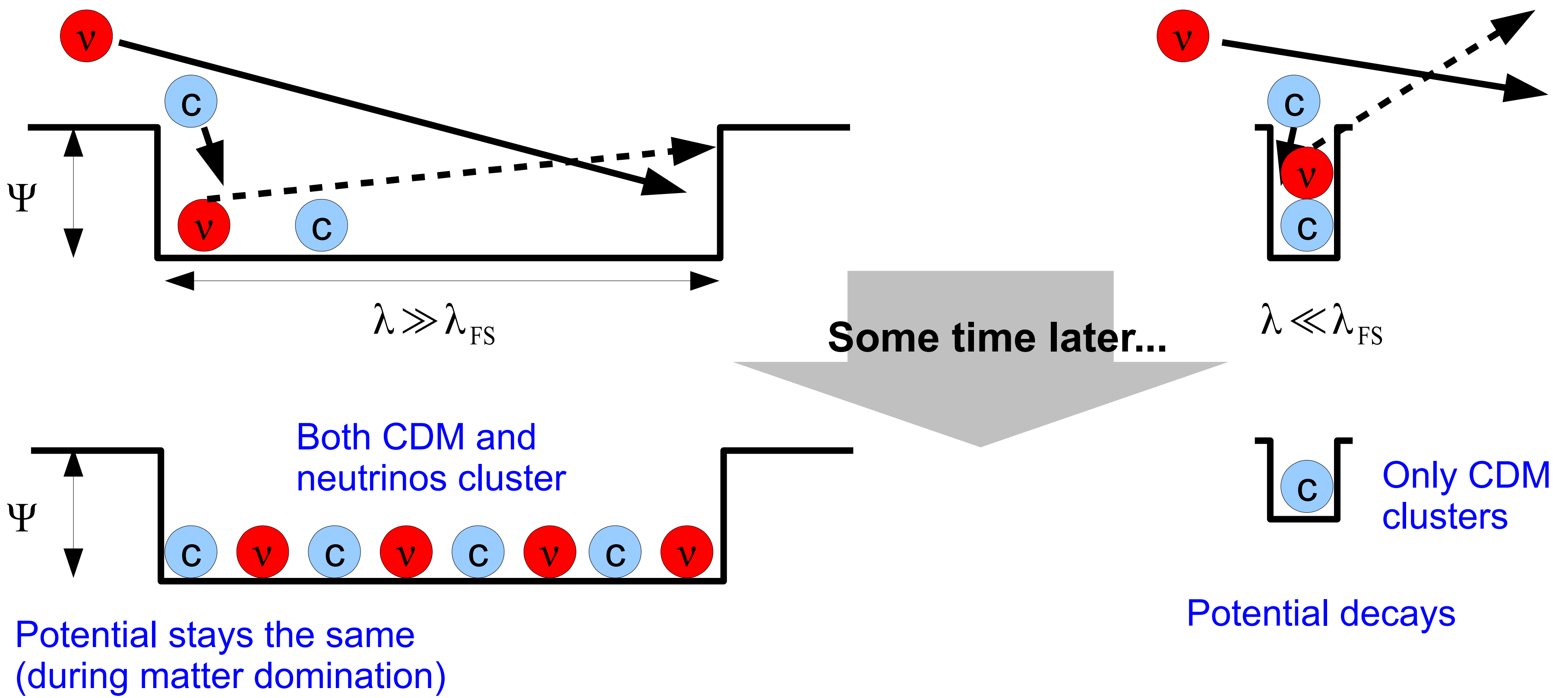
$\lambda \ll \lambda_{FS}$

$k \gg k_{FS}$

Free-streaming scale:

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

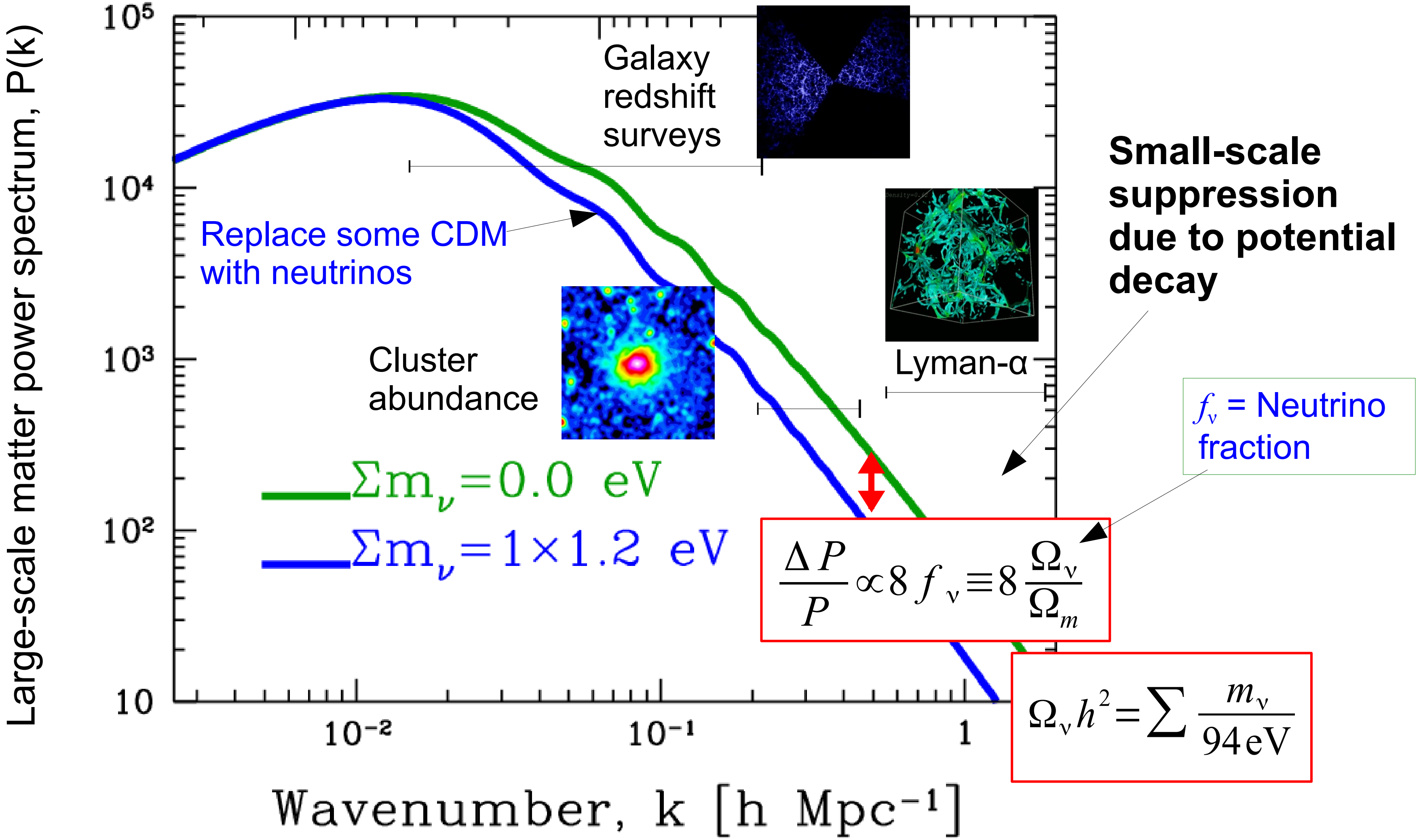
Consider a neutrino and a cold dark matter particle encountering two gravitational potential wells of different sizes in an expanding universe:



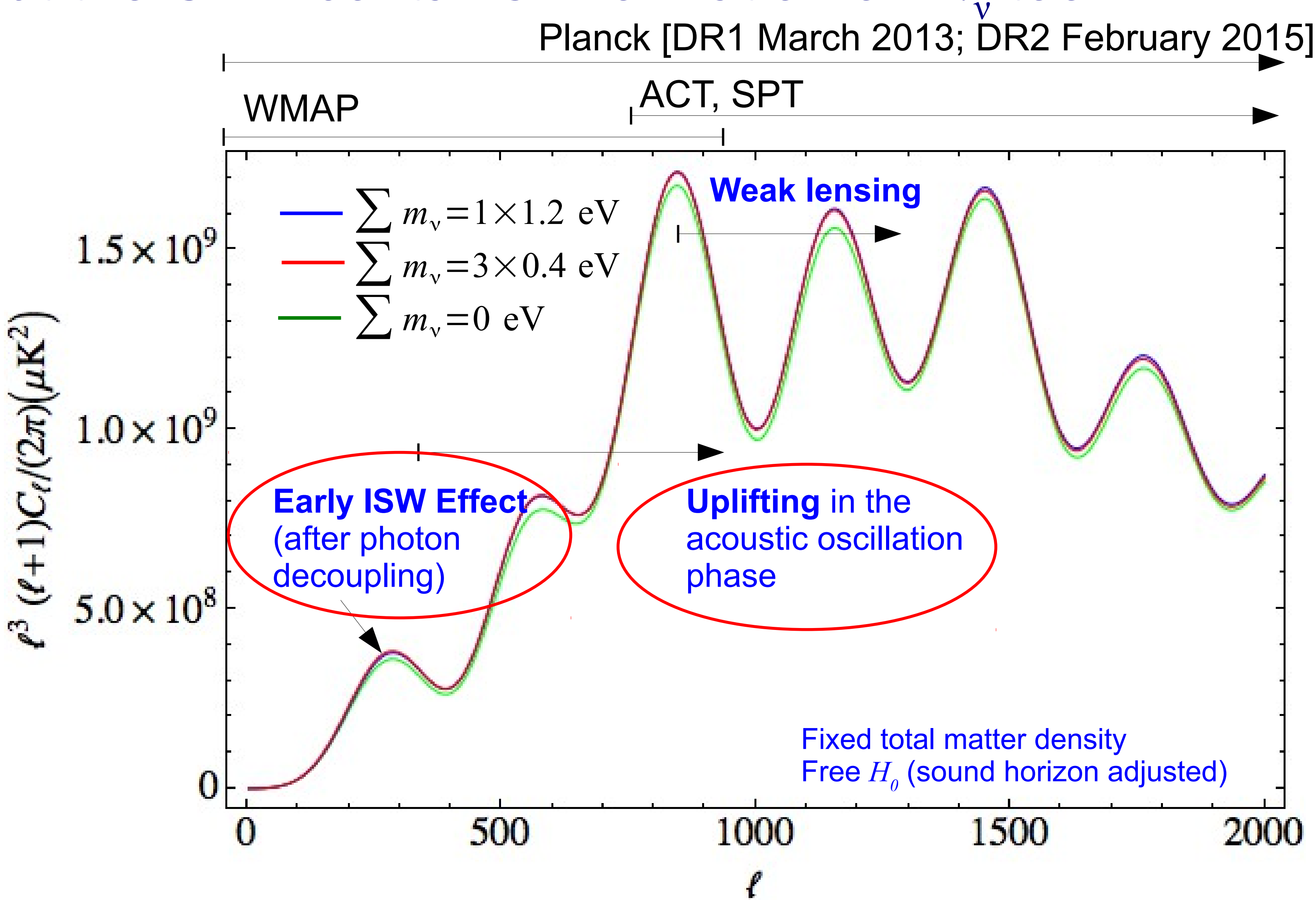
→ **Cosmological neutrino mass measurement** is based on observing this free-streaming induced potential decay at $\lambda \ll \lambda_{FS}$.

You've all seen this one...

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



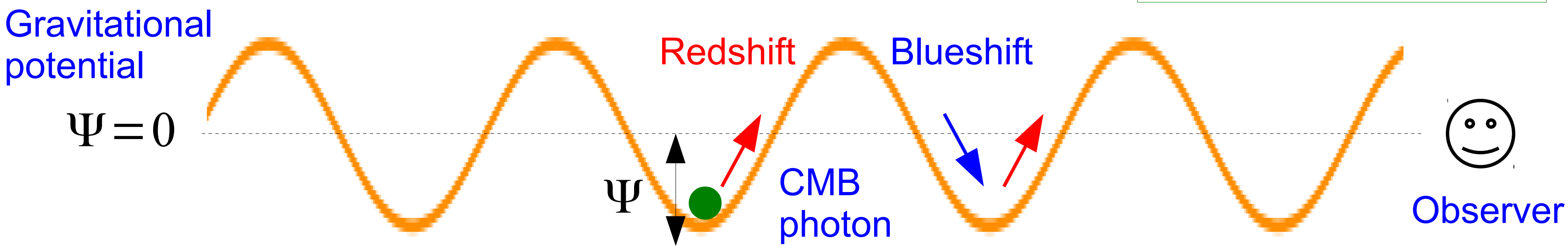
But the CMB contains information on m_ν too...



Sachs-Wolfe effect:

Observed CMB temperature fluctuation

$$\frac{\Delta T}{T}_{\text{observed}} = \frac{\Delta T}{T}_{\text{intrinsic}} + \Psi$$



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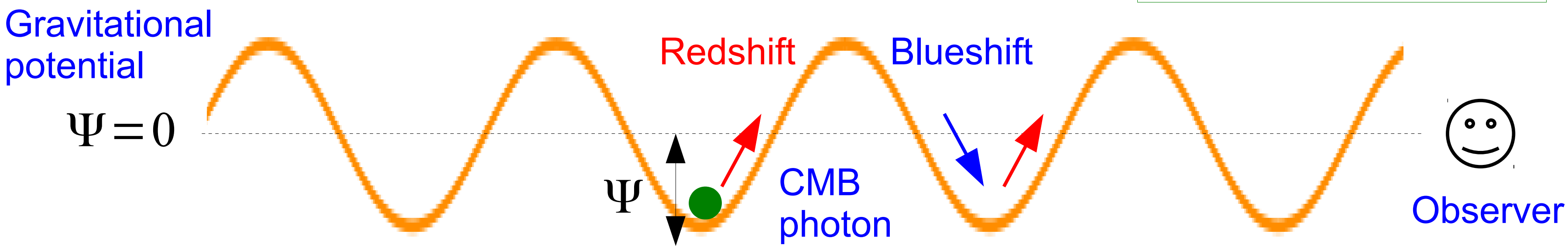
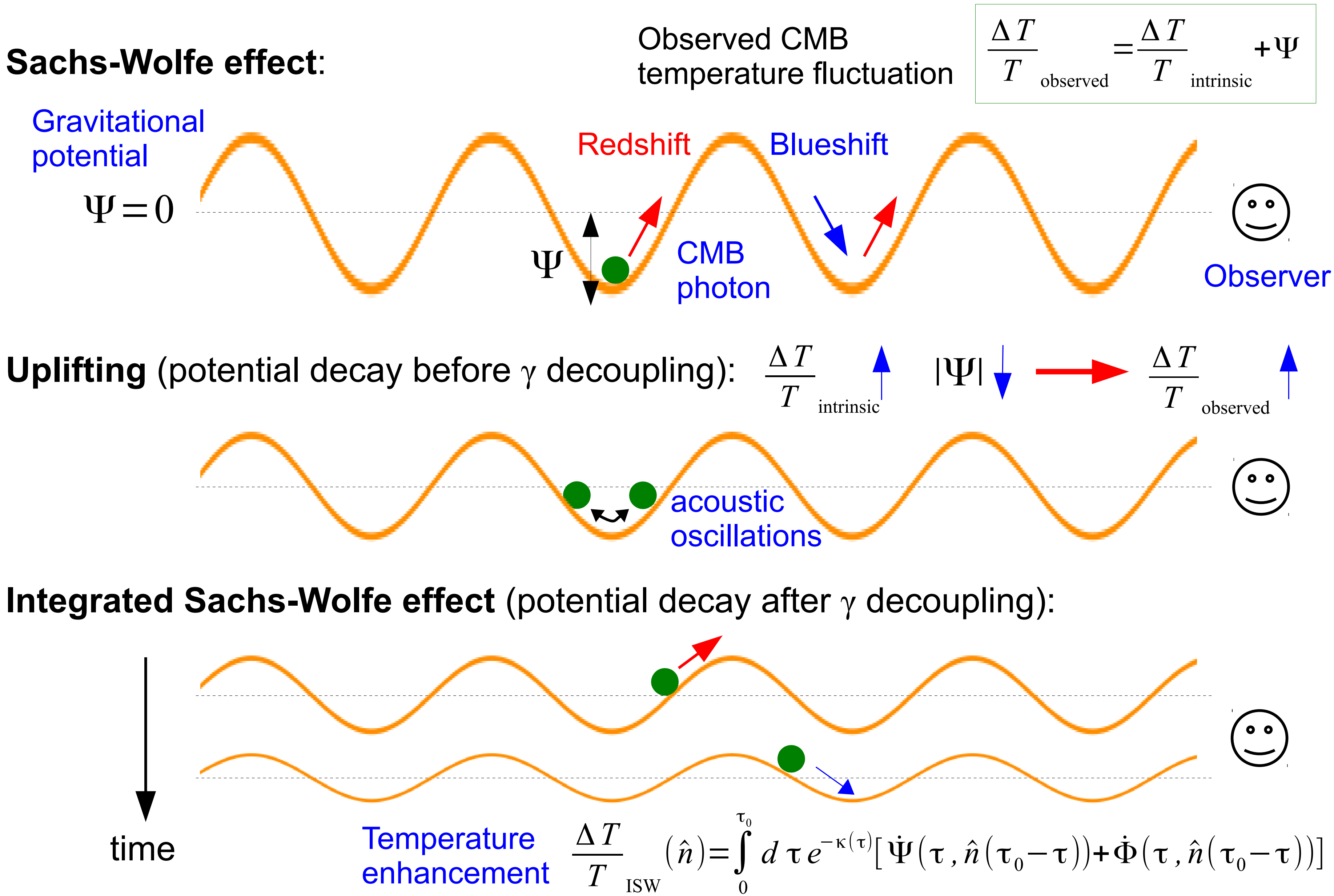


Uplifting (potential decay before γ decoupling): $\left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} \uparrow$ $|\Psi| \downarrow$ → $\left.\frac{\Delta T}{T}\right|_{\text{observed}} \uparrow$


Sachs-Wolfe effect:
Observed CMB temperature fluctuation
$\frac{\Delta T}{T}_{\text{observed}} = \frac{\Delta T}{T}_{\text{intrinsic}} + \Psi$
Gravitational potential
$\Psi = 0$
Redshift
Blueshift
Ψ
CMB photon
Observer
Uplifting (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
$\frac{\Delta T}{T}_{\text{ISW}}(\hat{n}) = \int_0^{\tau_0} d\tau\, e^{-\kappa(\tau)} [\dot{\Psi}(\tau, \hat{n}(\tau_0 - \tau)) + \dot{\Phi}(\tau, \hat{n}(\tau_0 - \tau))]$

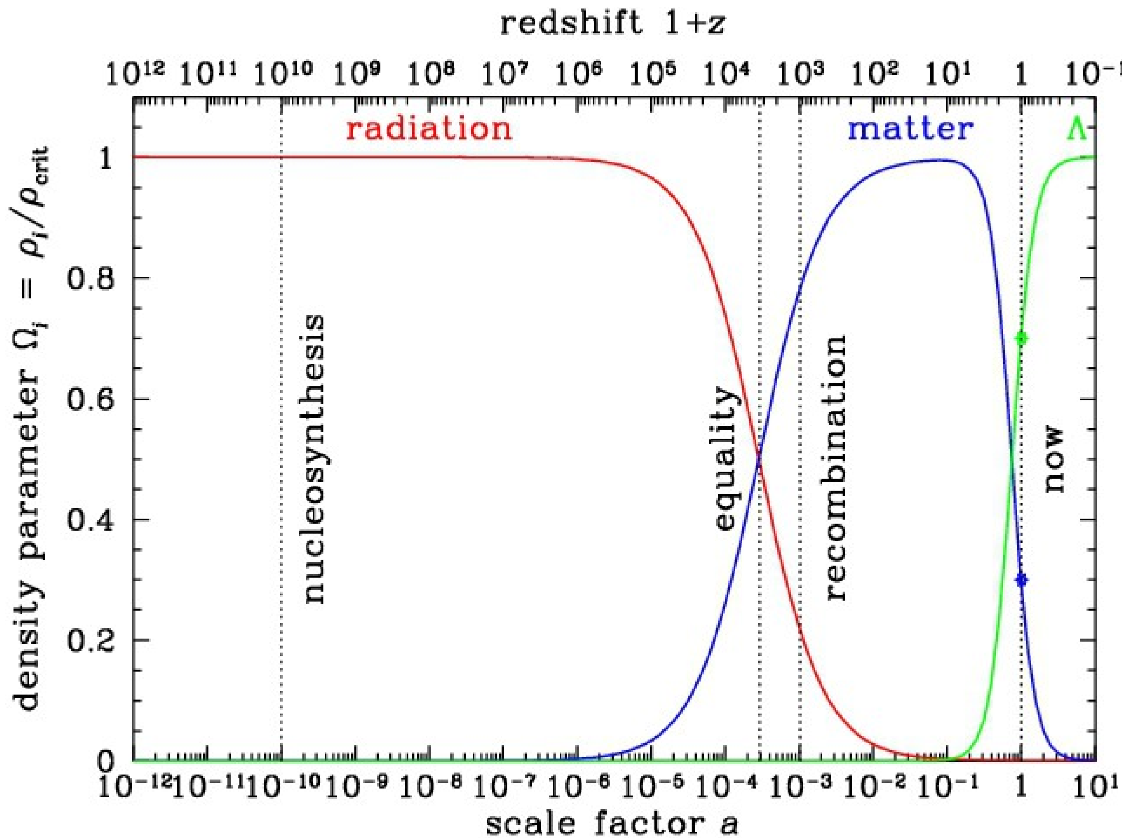
Potential decay happens anyway, even in ΛCDM, whenever the universe is not completely by nonrelativistic matter.

- It is good for probing neutrino masses because **O(0.1–1) eV-mass neutrinos** become nonrelativistic around recombination.

  → Changes the “matter” content, and hence the scale and time dependence of the potential decay.

O(0.1–1) eV mass neutrino

Relativistic → Nonrelativistic



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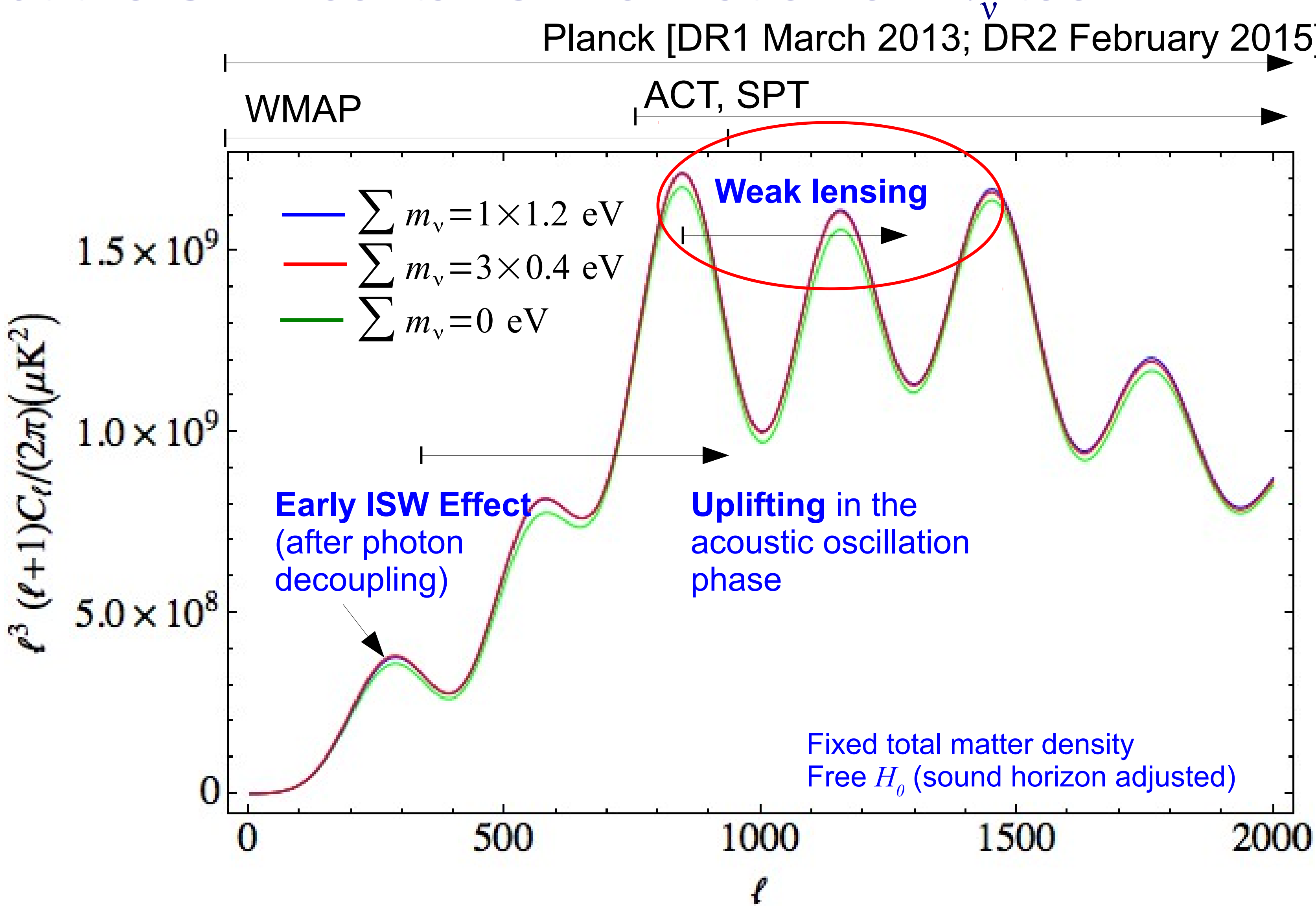
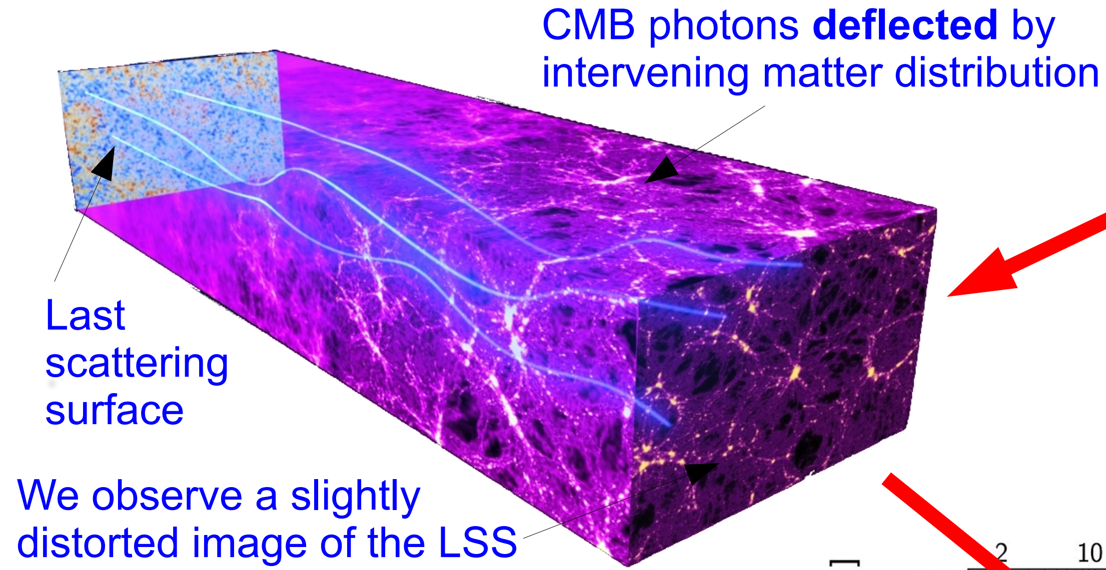
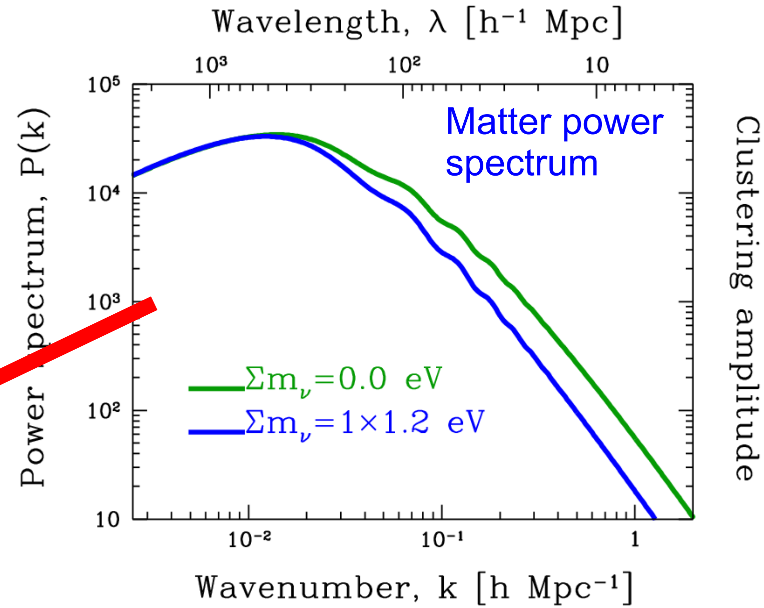
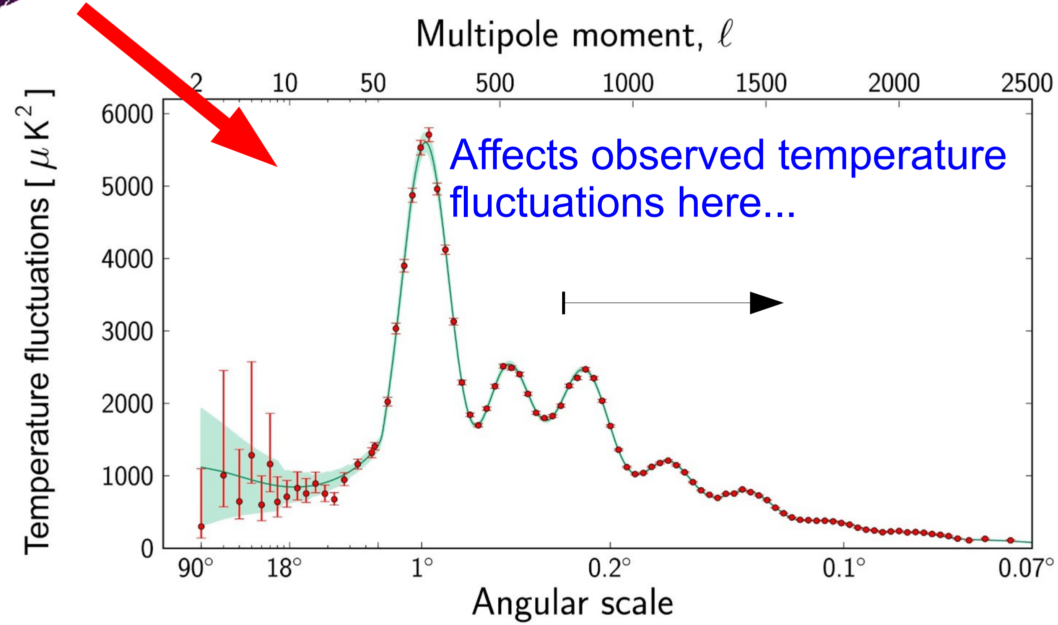


Weak gravitational lensing...

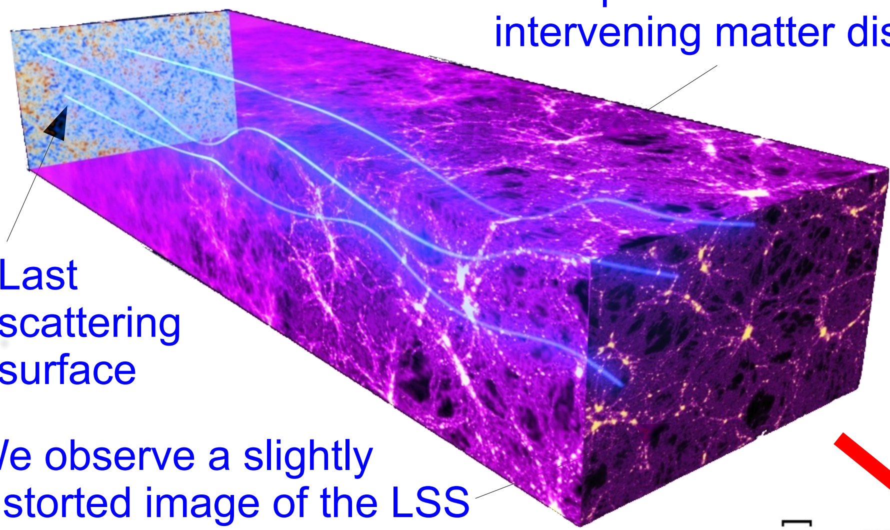






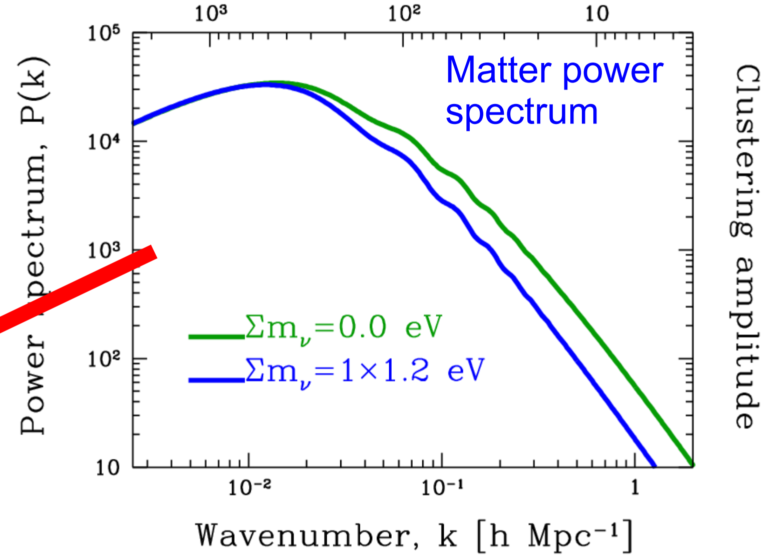
Weak gravitational lensing...

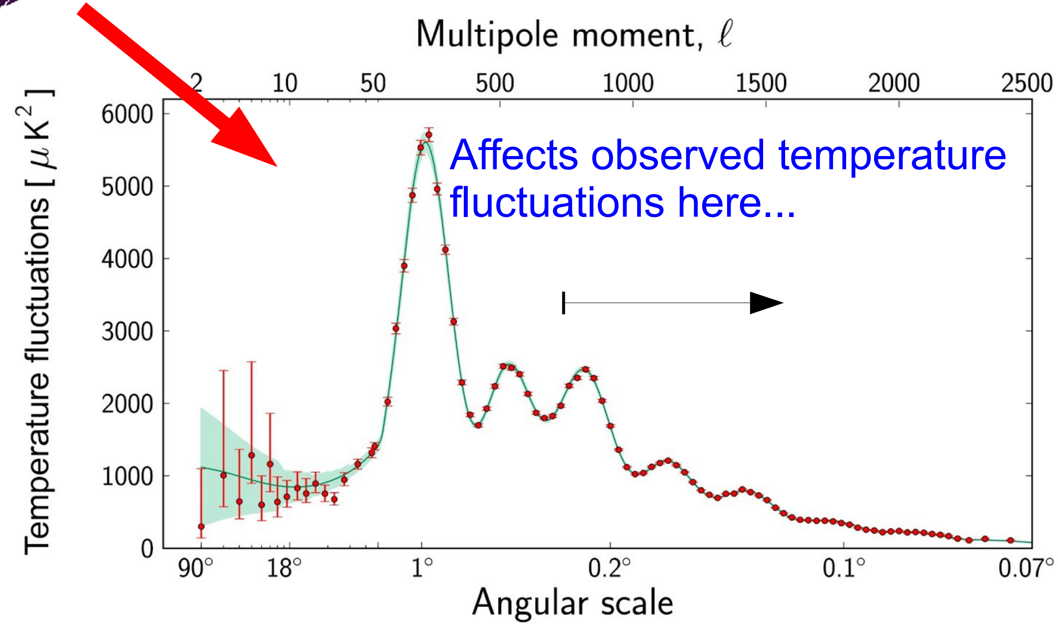
CMB photons **deflected** by intervening matter distribution



Last scattering surface

We observe a slightly distorted image of the LSS





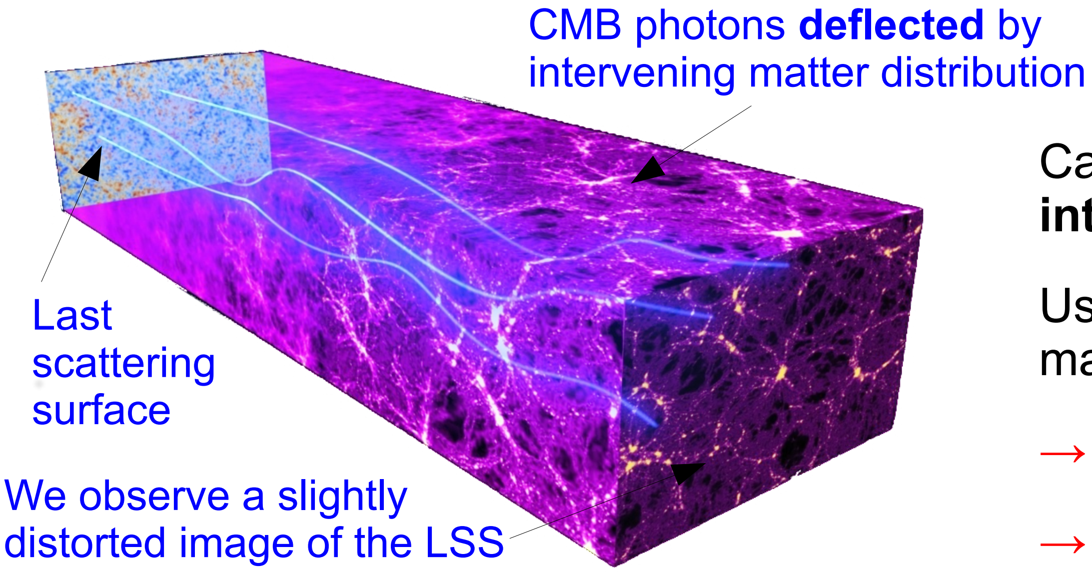
Planck TT+TE+EE+lowP

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

... largely because of this lensed TT signal.

Ade et al. 1502.01589

Weak lensing: lensing potential power spectrum...



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

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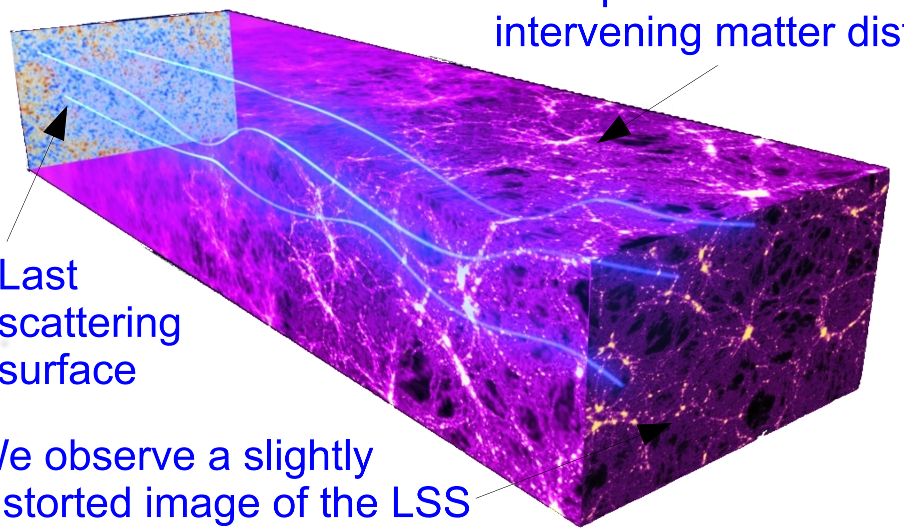

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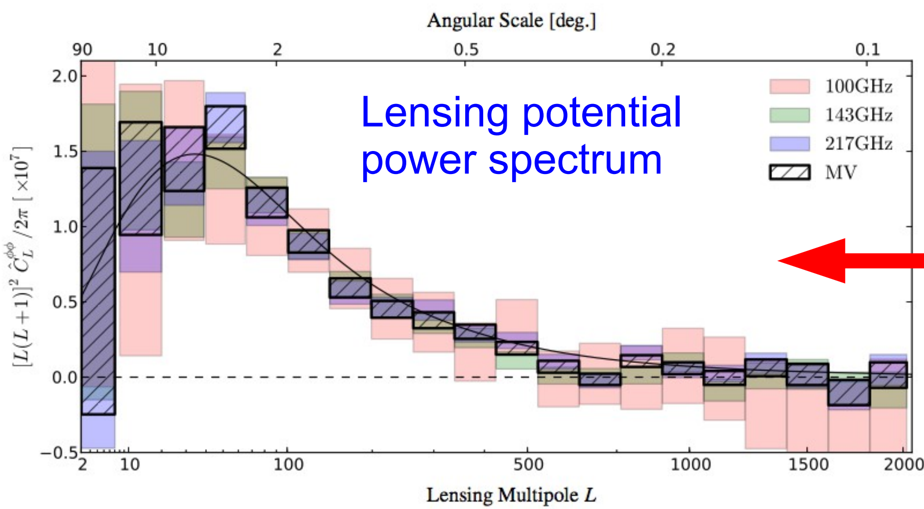

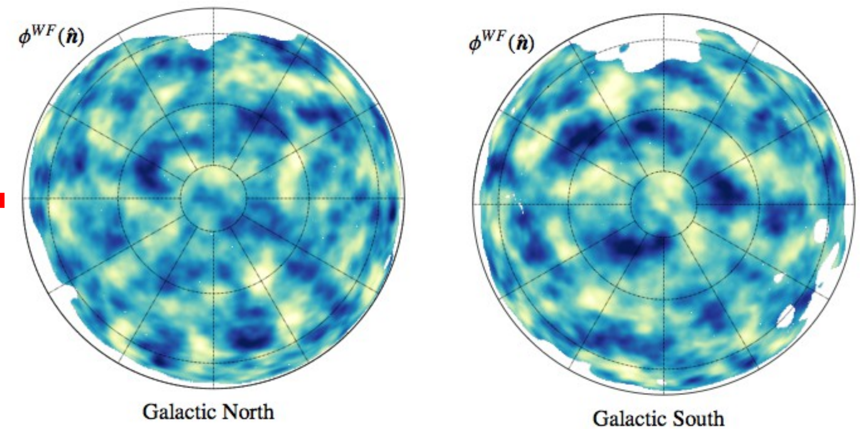

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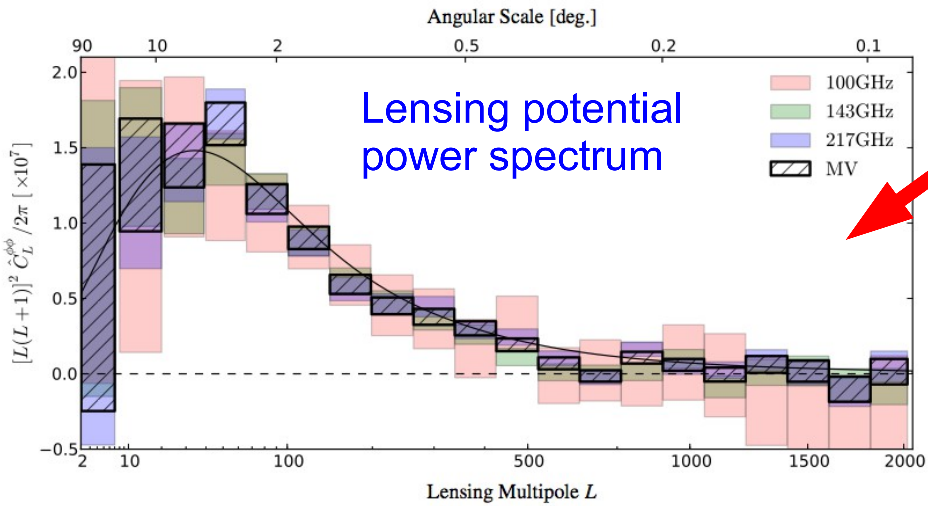
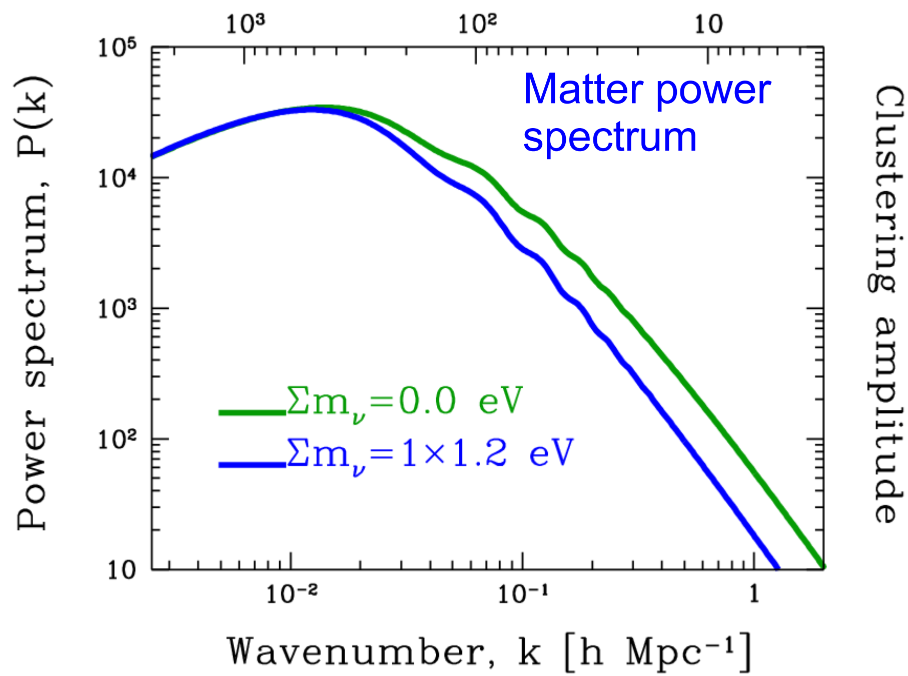


This is essentially this integrated along the line-of-sight (with some geometric factors folded in).



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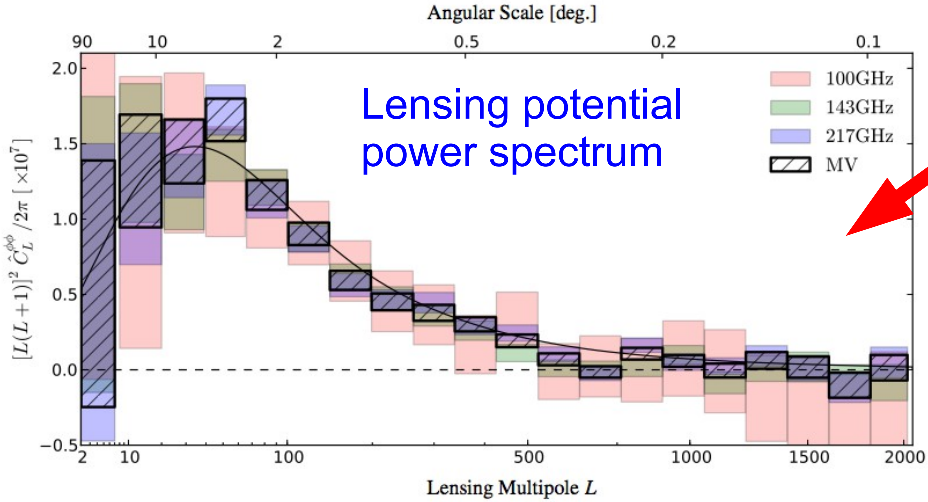

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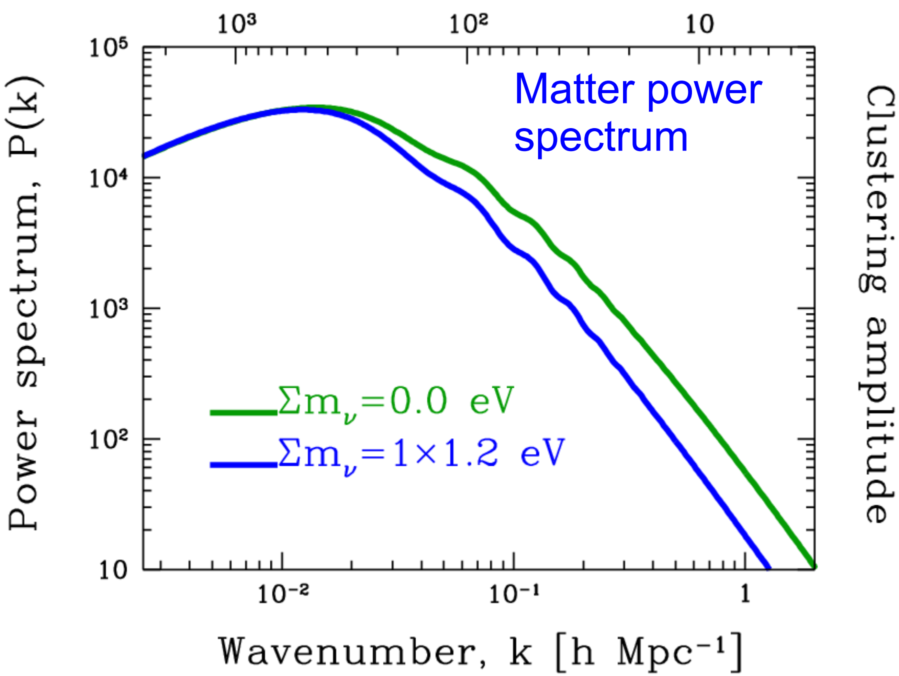


Planck TT+TE+EE+lowP+lensing

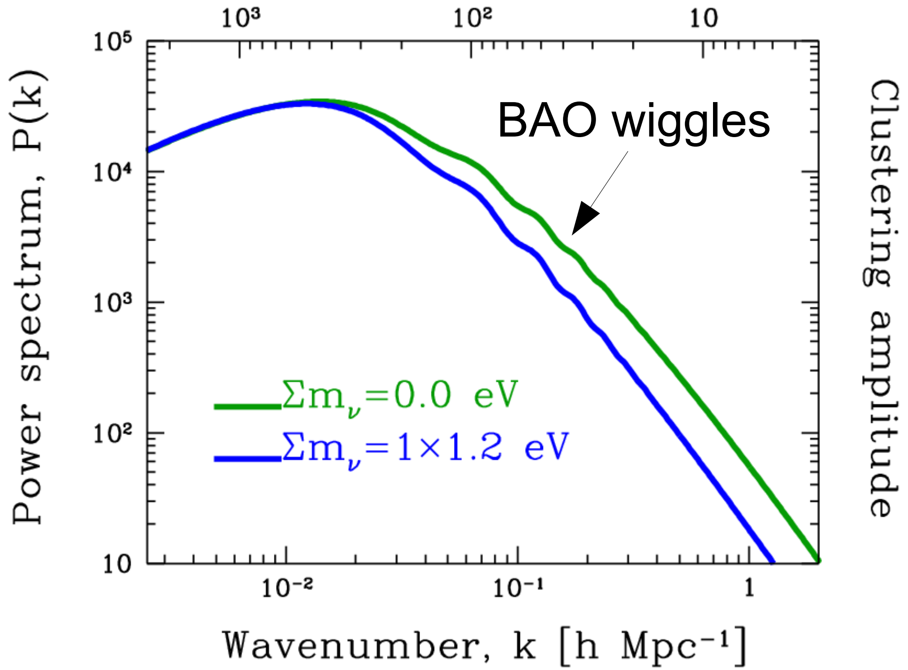
$$\sum m_\nu < 0.59\ \text{eV}\quad (95\%\,\text{C.L.})$$

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") [Most robust]
- **Shape** (directly sensitive to neutrino mass):
  - Galaxy power spectrum
  - Cluster abundance
  - Lyman alpha forest



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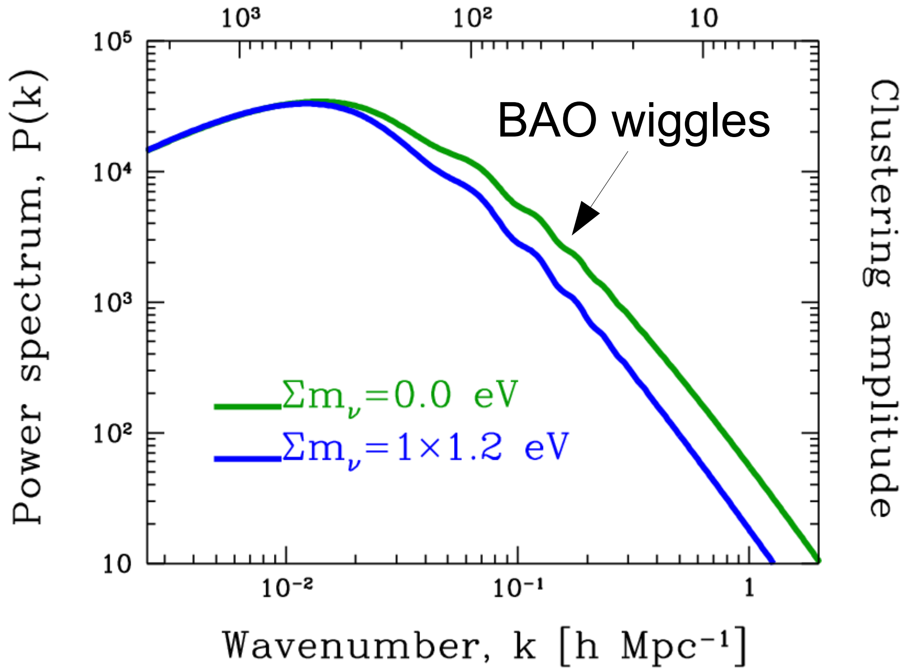


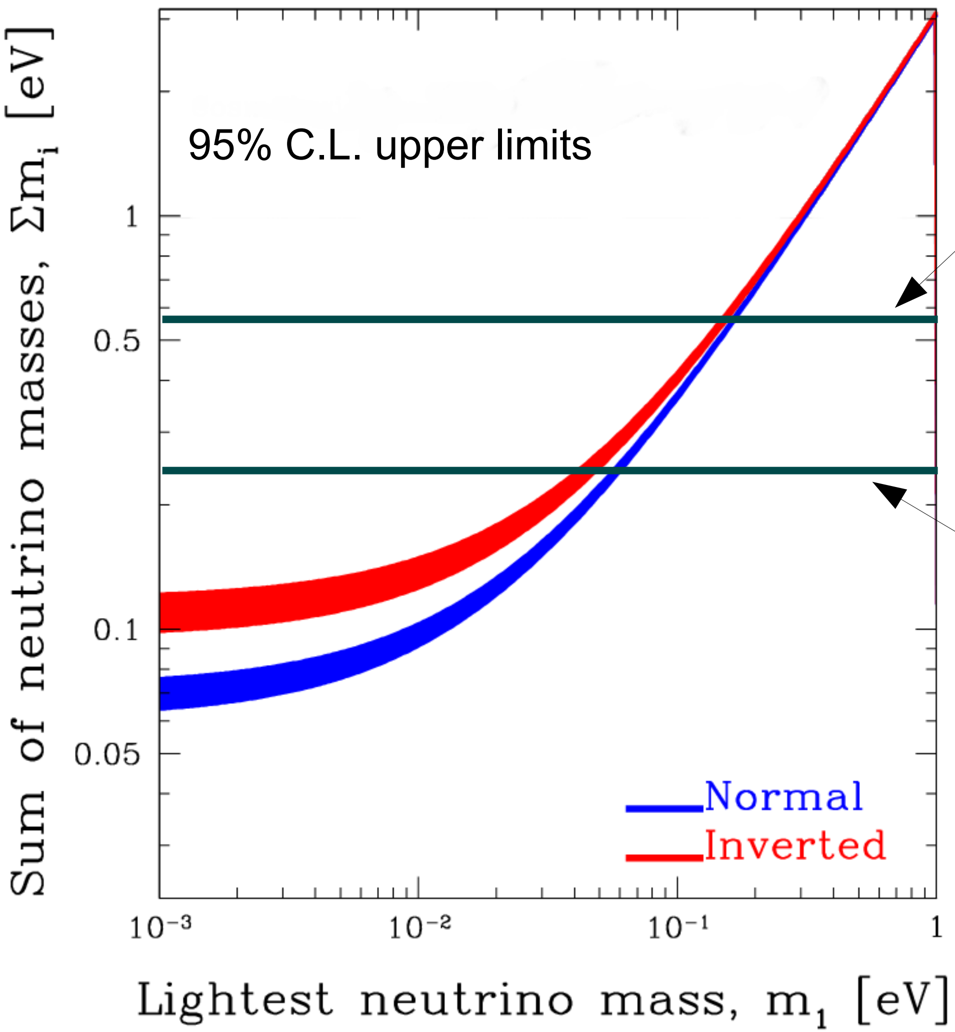
Planck TT+TE +EE+lowP+**BAO** $\sum m_\nu < 0.17 \text{ eV} \quad (95\% \text{C.L.})$

"Party line"

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

Pre- vs Post-Planck constraints...

ΛCDM+neutrino mass (7 parameters)



Planck TT+TE+EE+lowP+lensing

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

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

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

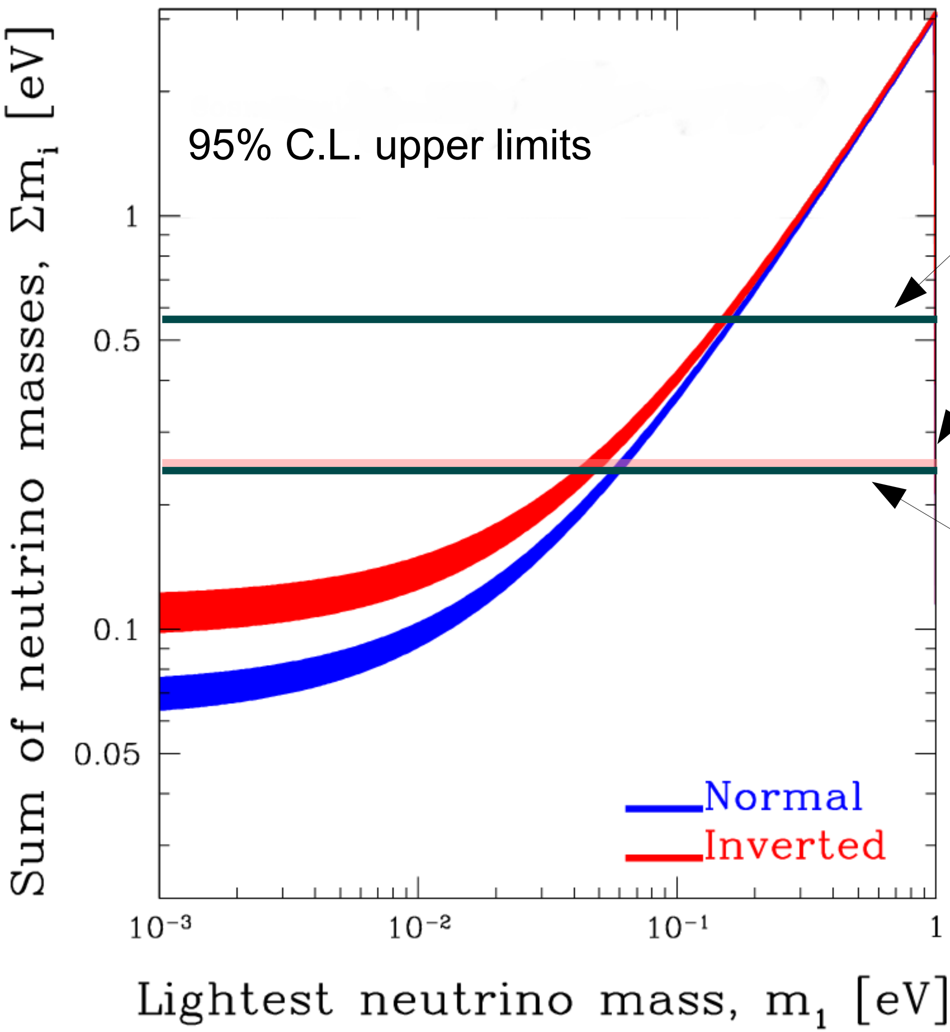
ΛCDM parameters

$$(\omega_b, \omega_m, H_0, A_s, n_s, \tau)$$

- baryon density: ω_b
- matter density: ω_m
- Hubble parameter: H_0
- primordial fluctuation amplitude & spectral index: A_s, n_s
- optical depth to reionisation: τ

Pre- vs Post-Planck constraints...

ΛCDM+neutrino mass (7 parameters)



Planck TT+TE+EE+lowP+lensing

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

Planck1+ WMAP polarisation + HighL + BAO

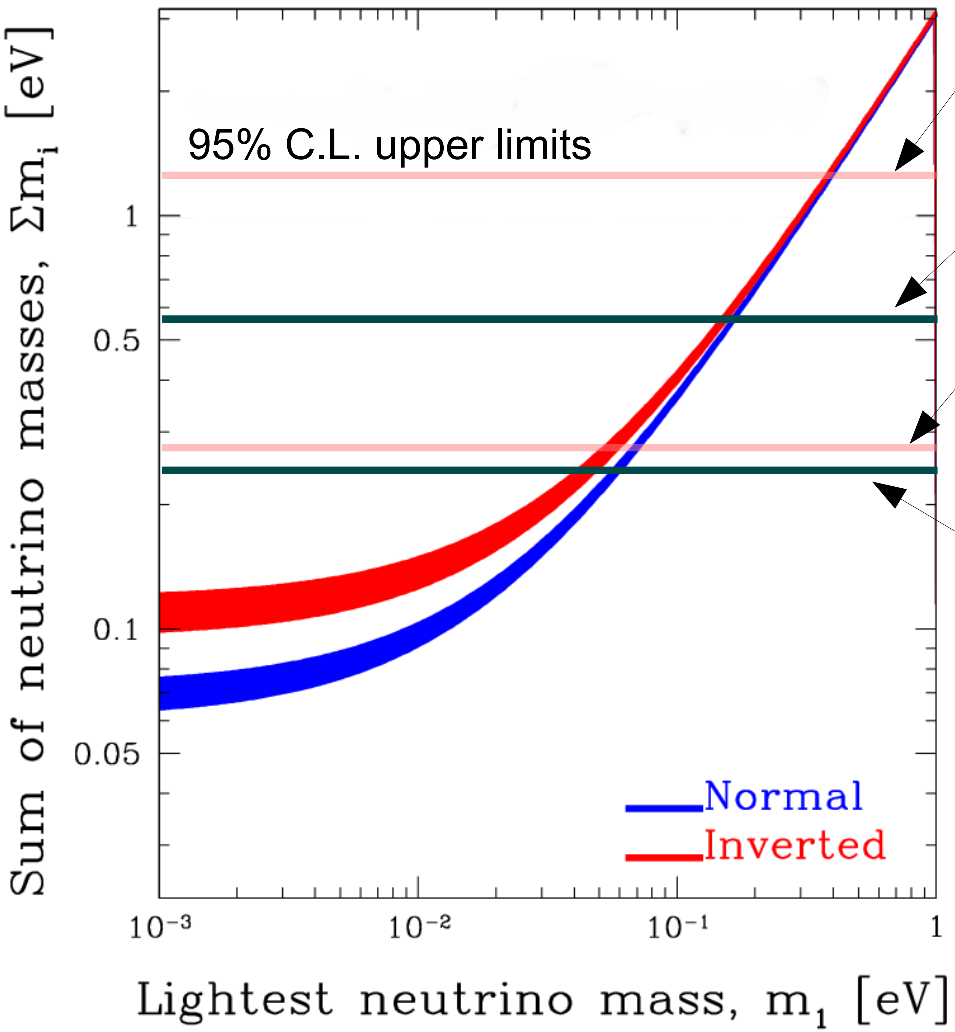
Planck TT+TE+EE+lowP+lensing + baryon acoustic oscillations

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

Formally similar to bound from data release 1, but is **now completely independent of WMAP**.

Pre- vs Post-Planck constraints...

ΛCDM+neutrino mass (7 parameters)



WMAP9 + ACT

Planck TT+TE+EE+lowP+lensing

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

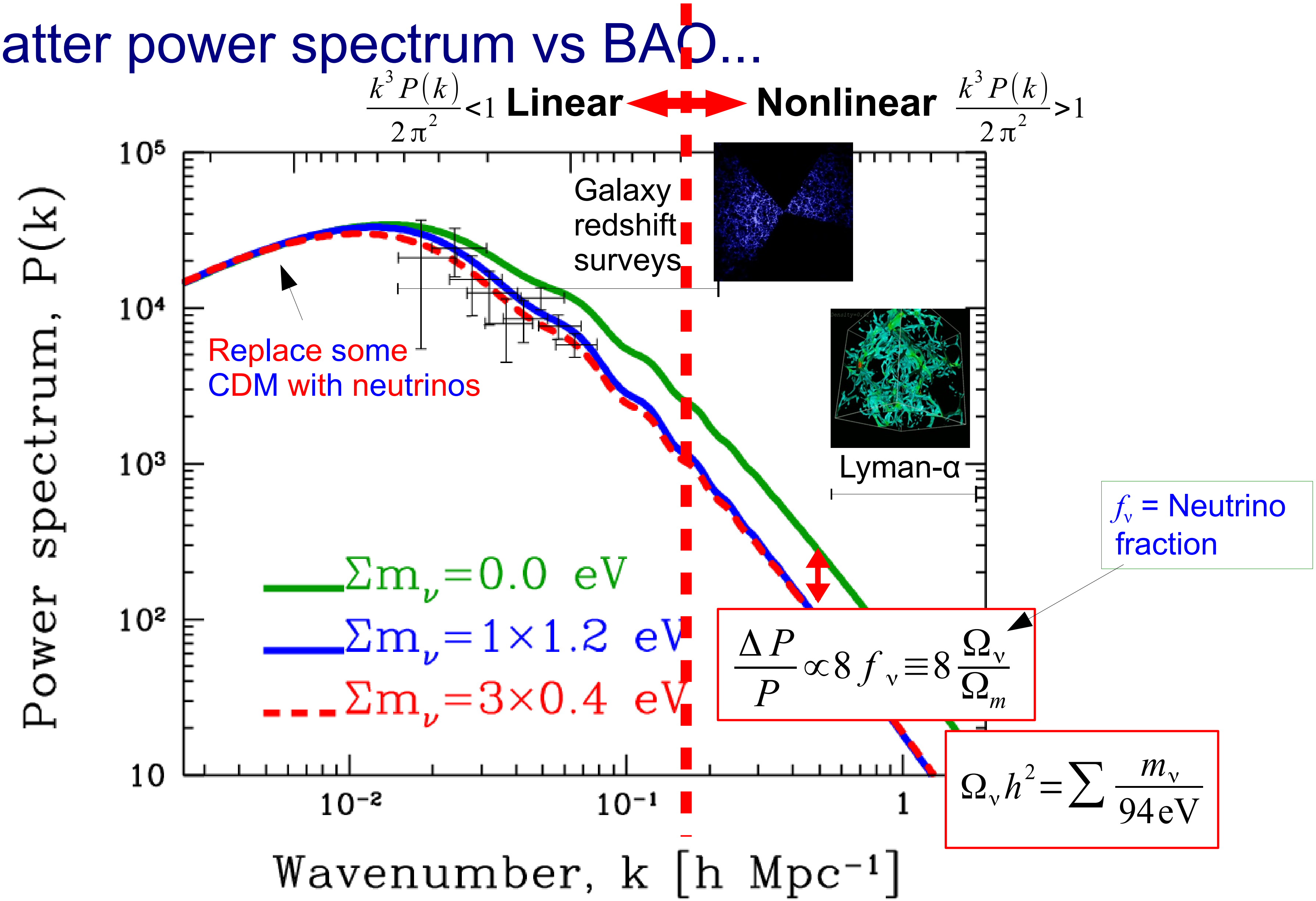
WMAP7+ matter power spectrum + HST H_0

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

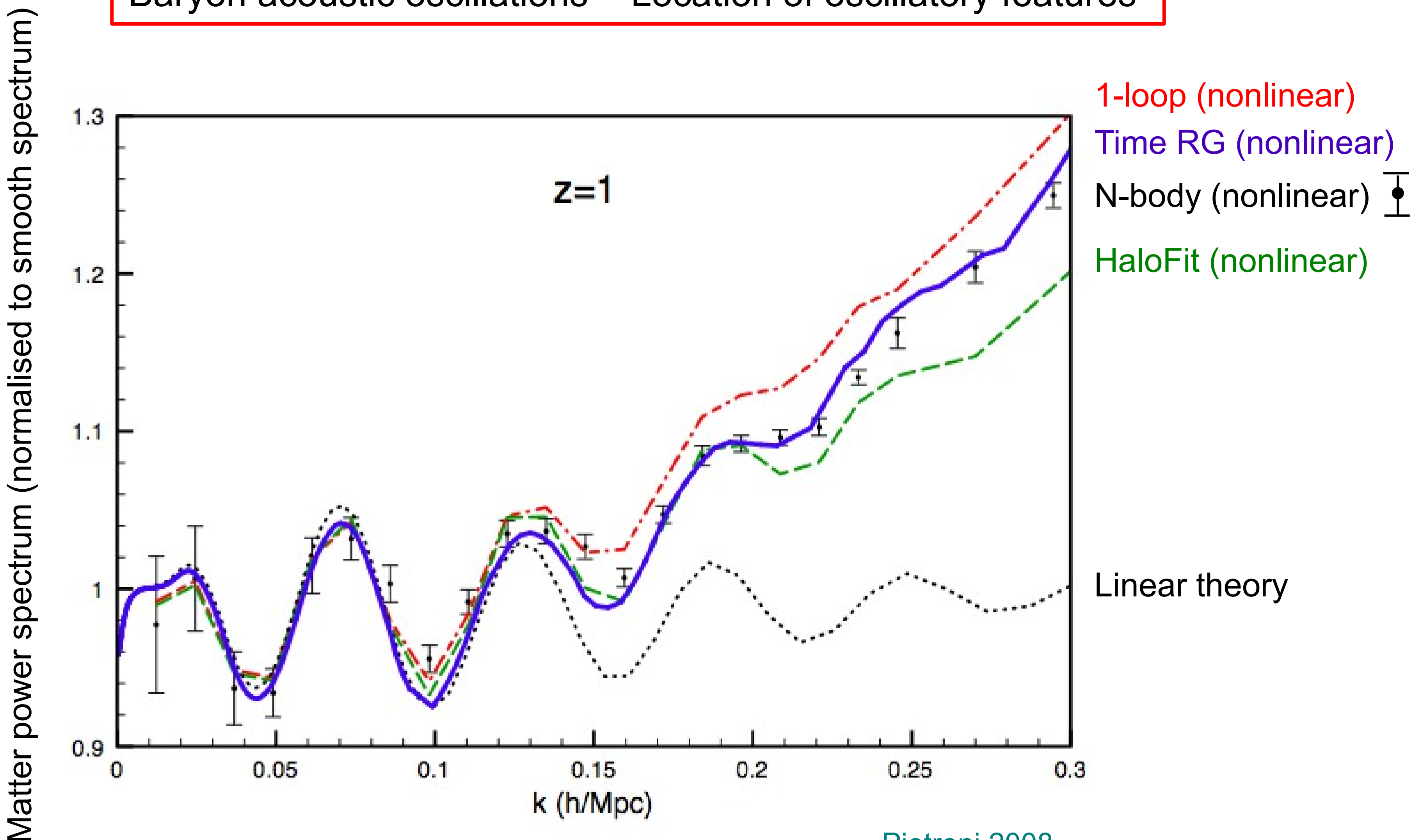
$$\sum m_\nu < 0.23 \text{ eV} \quad (95\%\text{C.L.})$$

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

The take-home message...

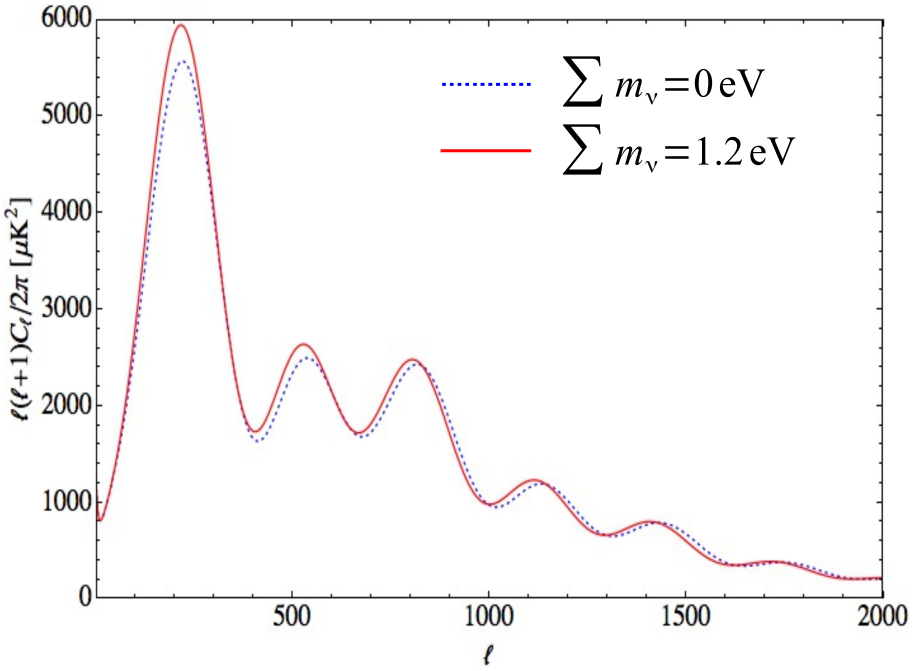
- Formally, the best “party-line” minimal (7-parameter) upper bound on $\Sigma\, m_\nu$ is still hovering around 0.2—0.3 eV post-Planck2.
  - Marginally better than Planck 1 (0.25 eV).

- 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?

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).



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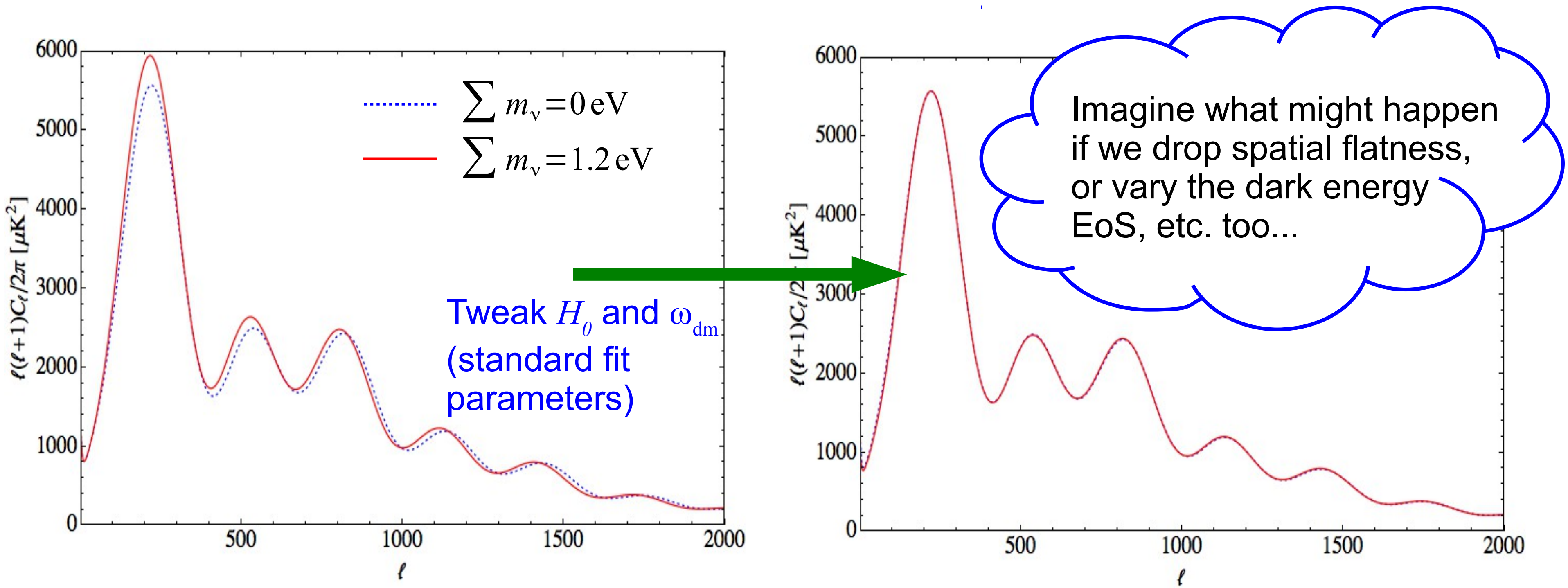


What Planck has to say about this issue?

- I couldn't find anything in the Planck2 papers...
- However, from V1 (March 2013):

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

ΛCDM+neutrino mass (7 parameters) $\sum m_\nu < 0.25$ eV (95% C.L.) Best minimal bound

Dropping assumption of spatial flatness: $\sum m_\nu < 0.32$ eV (95% C.L.)

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

- Similar degradation if the number of neutrinos is allowed to vary (more later).

A fourth neutrino??

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

Any particle species that

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

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

Smallest relevant scale enters the horizon

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

$$= (3.046 + \Delta N_{\mathrm{eff}}) \rho_\nu^{(0)}$$

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_{eff} ...

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

ΛCDM+N_{eff} (7 parameters)

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

68% C.I.

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

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

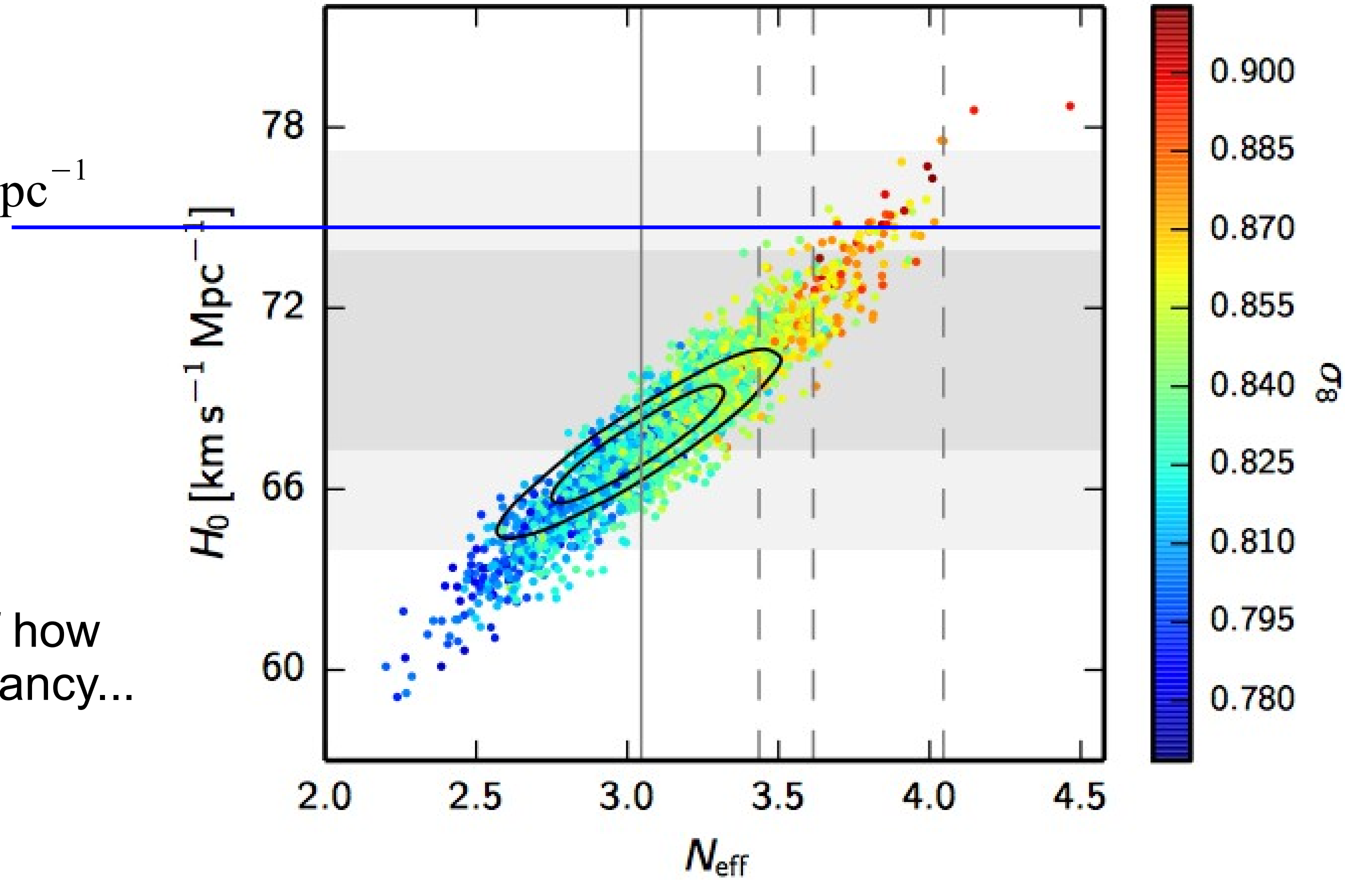
Looks like the end of the N_{eff} story... **But note this...**

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.

Riess et al. 2011

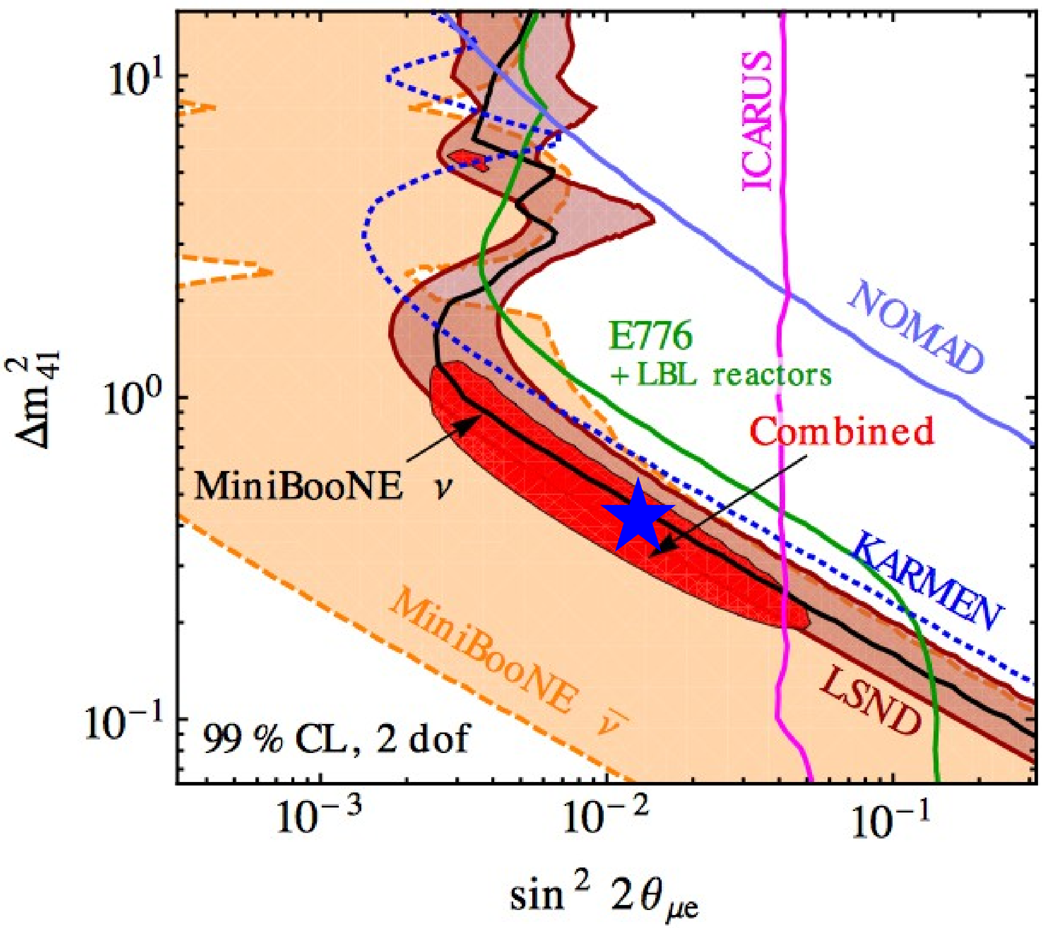
$H_0 = 74.8 \pm 3.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



You decide for yourself how to interpret this discrepancy...

Implications for the short baseline sterile neutrino...

"3+1 scenario"



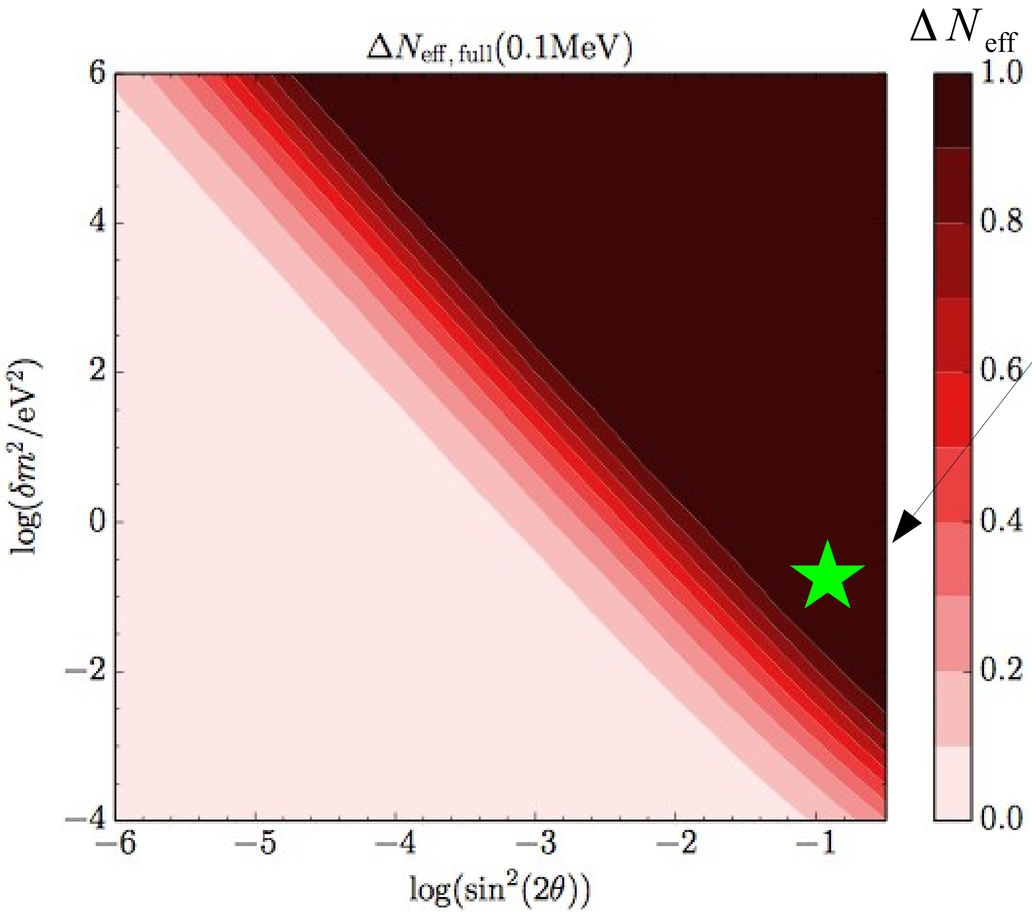
$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i} \nu_i$$

$$\sin^2 2\theta_{SBL} \equiv 4 |U_{e4} U_{\mu 4}|^2 \sim 10^{-2}$$

$$\Delta m^2_{SBL} \equiv \Delta m^2_{14} \sim 0.5 \text{ eV}^2$$

Kopp, Machado, Maltoni & Schwetz 2012

The SBL sterile neutrino can be thermalised in the early universe via a combination of oscillations and scattering (of the active neutrino).



SBL-preferred

$$m_{\rm SBL} \sim \sqrt{\Delta m^2_{\rm SBL}} \sim 0.7 \;\; {\rm eV}$$
$$\Delta N_{\rm eff} \sim 1$$

Obviously at odds with Planck limits...

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

Planck TT + lowP + lensing + BAO

Hannestad, Hansen, Tram & Y[3]W 2015
also Hannestad, Tamborra & Tram 2012
and works of Abazajian, Di Bari, Foot,
Kainulainen, etc. from 1990s-early 2000s

Can we get around these constraints?

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 should be no conflict.

- **Some possible mechanisms**:
  - Suppress the effective mixing angle with new matter effects in the early universe:

New physics required
    - A large lepton asymmetry ($L \gg B \sim 10^{-10}$); $L \sim 10^{-2}$ will do. Foot & Volkas 1995
    - Hidden sterile neutrino self-interaction Dasgupta & Kopp 2014, Hannestad, Hansen & Tram 2014 Saviano et al. 2014, Archidiacono et al. 2015
  - A low reheating temperature (T_R < 10 MeV) → incomplete thermalisation of even the SM neutrinos.

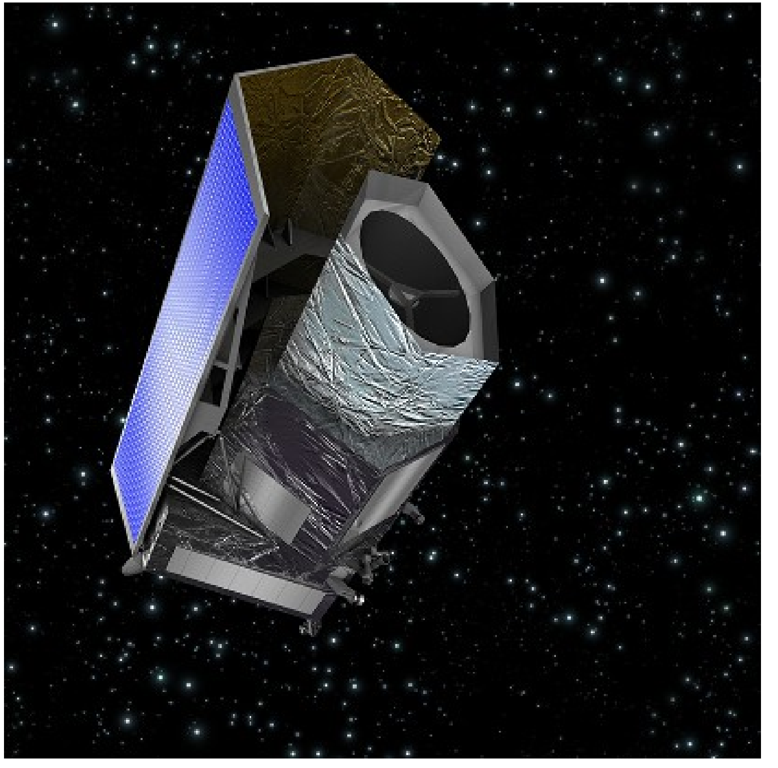
May run into problems with baryogenesis and dark matter production.

Future sensitivities...

ESA Euclid mission selected for implementation...

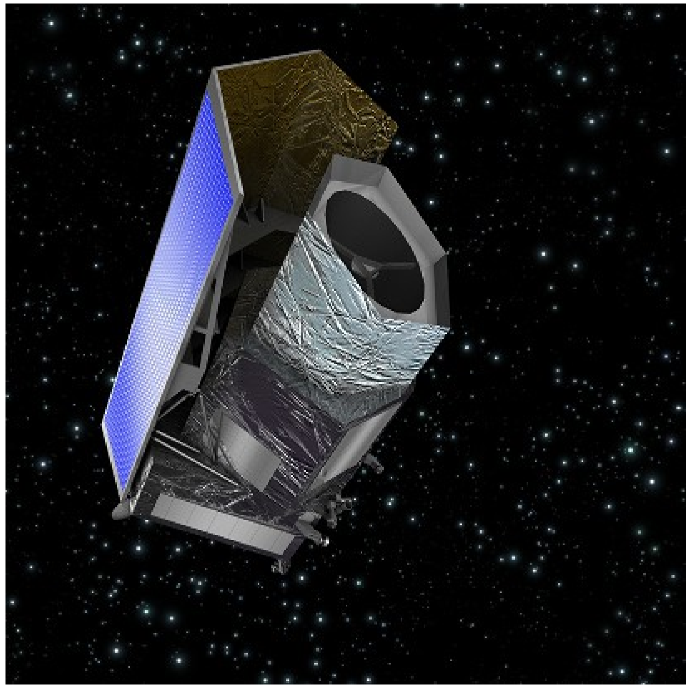
Launch planned for 2020.

- 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)



ESA Euclid mission selected for implementation...

Type Ia supernovae



Galaxy clusters
(cluster mass function)

Baryon acoustic oscillations (BAO)

Galaxy distribution
(photo-z and spectro-z)

Cosmic shear
(weak gravitational lensing of galaxies)

But everything I am about to say applies also to similar surveys such as LSST.

Forecasted sensitivities...

A lot of numbers floating around at the moment (depending on whose papers you read)...

Dark energy EoS

9-parameter model

Data	$10^3 \times \sigma(\omega_{\rm dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\mathrm{eV}$	$\sigma(N_{\rm eff}^{\rm ml})$	$\sigma(w)$
cs	1.864	0.638	0.064	0.081	0.0310
cg	1.121	0.655	0.020	0.086	0.0163
csg	0.885	0.324	0.012	0.056	0.0083
csgx	0.874	0.292	0.012	0.055	0.0065
$\mathrm{csg_b}$	1.400	0.529	0.042	0.068	0.0207
$\mathrm{csg_bx}$	1.390	0.482	0.042	0.068	0.0186
csgx (7-parameter)	0.181	0.071	0.011	-	-
$\mathrm{csg_bx}$ (7-parameter)	0.354	0.244	0.022	-	-

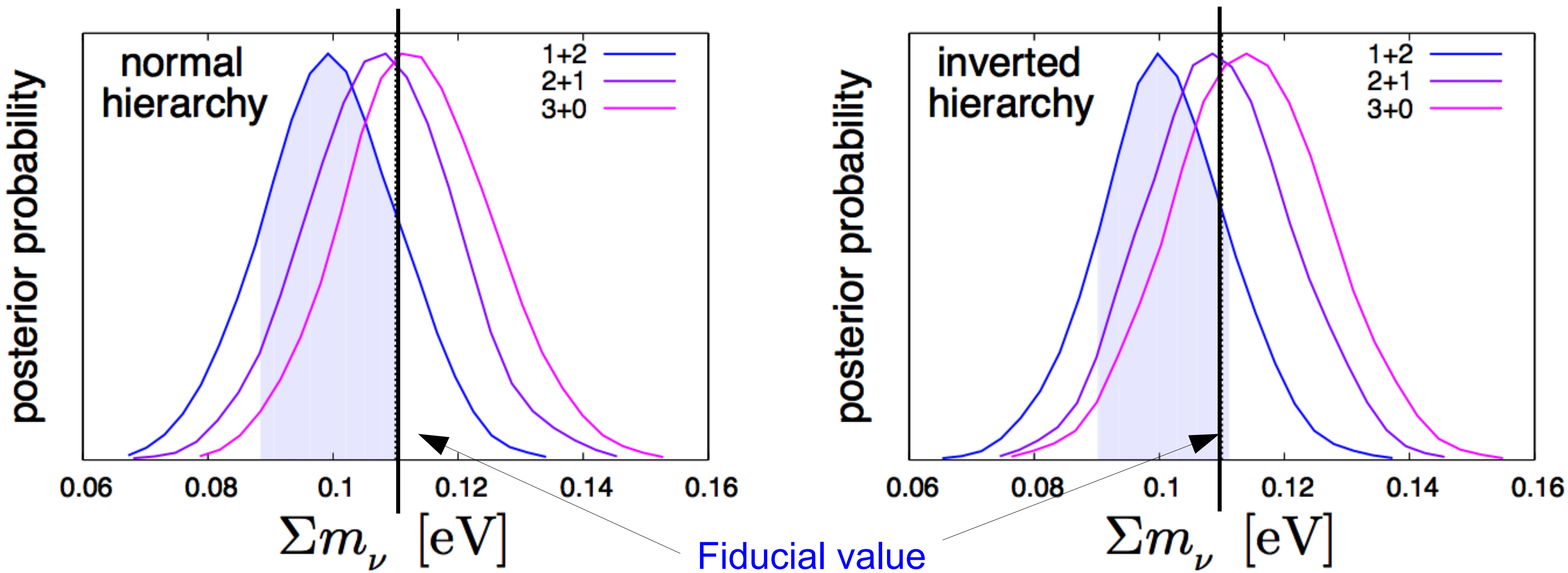
c=CMB (Planck); g=galaxy power spectrum; s=cosmic shear; x=shear-galaxy cross-correlation

- **Optimistic linear galaxy bias**: $\sigma(\Sigma m_\nu) \sim 0.01$ eV
- **Very pessimistic linear galaxy bias**: factor of 3.5 deterioration...

Good enough to resolve the mass spectrum/hierarchy?

Unfortunately not, even in the most optimistic scenario.

- In fact we can model the mass spectrum any way we like and the data cannot tell.



1+2 = 1 massive + 2 massless
2+1 = 2 (equally) massive + 1 massless
3+0 = 3 (equally) massive + 0 massless

→ We always recover the fiducial value within 1σ.

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, Planck1 and Planck2 upper bounds (at least not for the minimal 7-parameter model).
  - But the **Planck2** bound is arguably more robust against nonlinearities and is completely independent of other CMB measurements (e.g., WMAP).

- The **fourth neutrino**??
  - No evidence at all. But a 2.5σ discrepancy between Planck and direct measurements of H_0 remains.