Hot relics: which ones, how much, how many, and how to know more

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Progress on Old and New Themes in Cosmology, Avignon, April 18--22, 2011

Hot relics: what are they?

- Any particle species whose production is associated with some thermal process and that decoupled while relativistic at relatively late times [T< O(100) MeV].
  - **Generic property**: significant relativistic energy density before and around matter-radiation equality

- If **non-relativistic today**:
  - Contribute to dark matter, but not all (otherwise inconsistent with hierarchical structure formation).

Hot relics: which ones?

Guaranteed

Standard model neutrinos
Question: what is their energy density?

Maybe

Many BSM models predict hot relics.

Worth looking for
(also searched for by particle physics experiments)

Light (sub-eV to eV mass) sterile neutrinos; motivated by anomalies in neutrino experiments.

QCD axions (dependent on Peccei-Quinn scale); motivated by the strong CP problem.

Hot relics: why should we care?

- **Disclaimer**: We do not expect hot relics to make up all of the dark matter.

- We study them because of the possibility to constrain or detect physics of or beyond the standard model.
  - Consistency checks against lab experiments.

- Even if you don't care about this particular sort of physics:
  - The presence of hot relics may shift the values of those cosmological parameters you care about, e.g., w_{DE}.

1. Guaranteed hot relics:
e, μ, τ neutrinos

Cosmic neutrino background...

- Prediction of the standard hot big bang.
- Process of decoupling fixed by weak interactions.
  - **Temperature** today: $T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB},0} = 1.95\,\mathrm{K}$
  - **Number density** per flavour: $n_{\nu,0} = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T_{\nu,0}^3 = 112\ \mathrm{cm}^{-3}$
  - **Energy density** per flavour: $\Omega_\nu h^2 = \frac{m_\nu}{93\,\mathrm{eV}}$

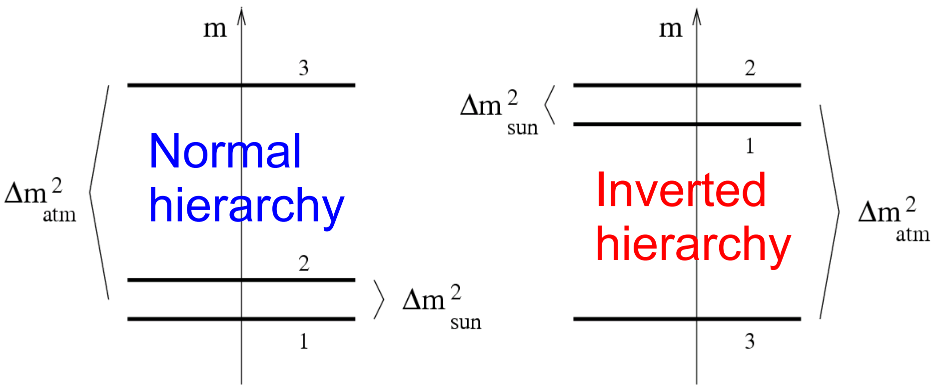
If m_ν > 1 meV

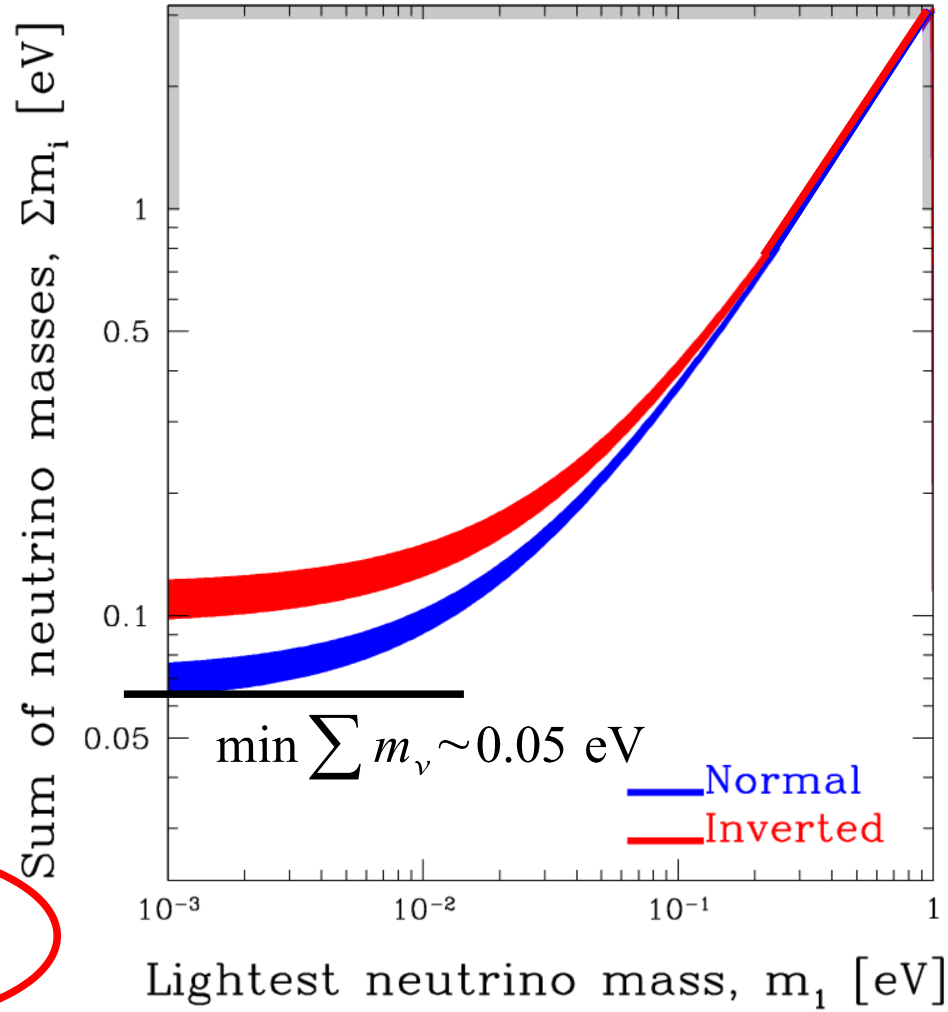
Neutrinos can be a significant component of the total dark matter content.

Neutrino dark matter...

- Neutrino oscillations:

$\Delta m^2_{atm} \sim 10^{-3}\ \mathrm{eV}^2 \quad \Delta m^2_{sun} \sim 10^{-5}\ \mathrm{eV}^2$

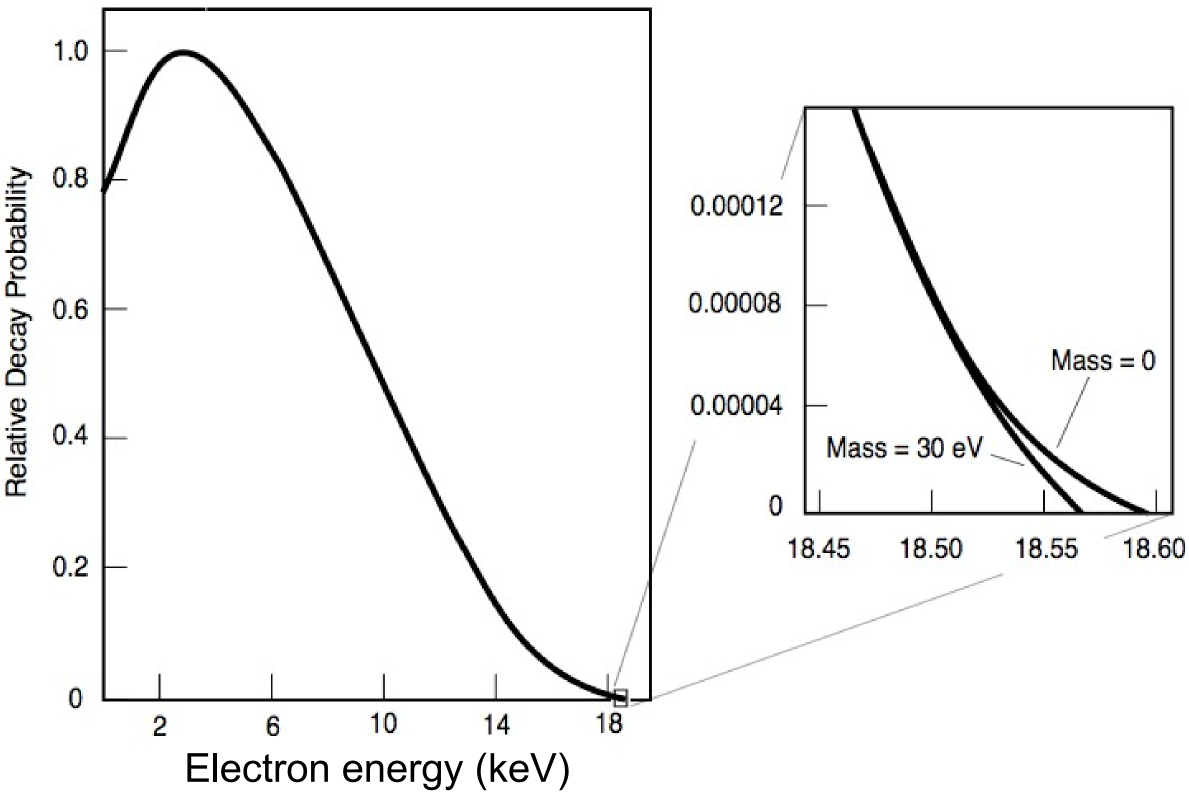




Mininum amount of neutrino dark matter

$$\min \sum m_\nu \sim 0.05\ \mathrm{eV} \rightarrow \min \Omega_\nu \sim 0.1\,\%$$

- Upper limit on neutrino masses from tritium β-decay:



Large mixing means

$|U_{ei}|^2 \sim O(0.1 \to 1)$

$$m_e \equiv \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} < 2.2 \text{ eV}$$

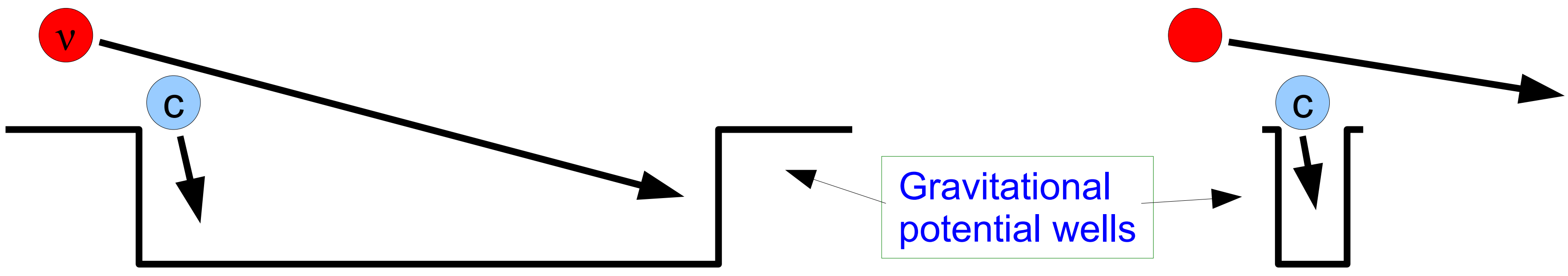
Lobashev [Troitsk] 2003
Krauss et al. [Mainz] 2005

$$\max \sum m_\nu \sim 7 \text{ eV} \to \max \Omega_\nu \sim 12\,\%$$

Free-streaming neutrinos...

- At low redshifts, neutrinos become nonrelativistic:.
  - But still have large thermal speed: $c_\nu \simeq 81(1+z)\left(\frac{\text{eV}}{m_\nu}\right)$ km s^{-1}

    → hinder ν clustering on small scales.



- Free-streaming length scale & wavenumber:

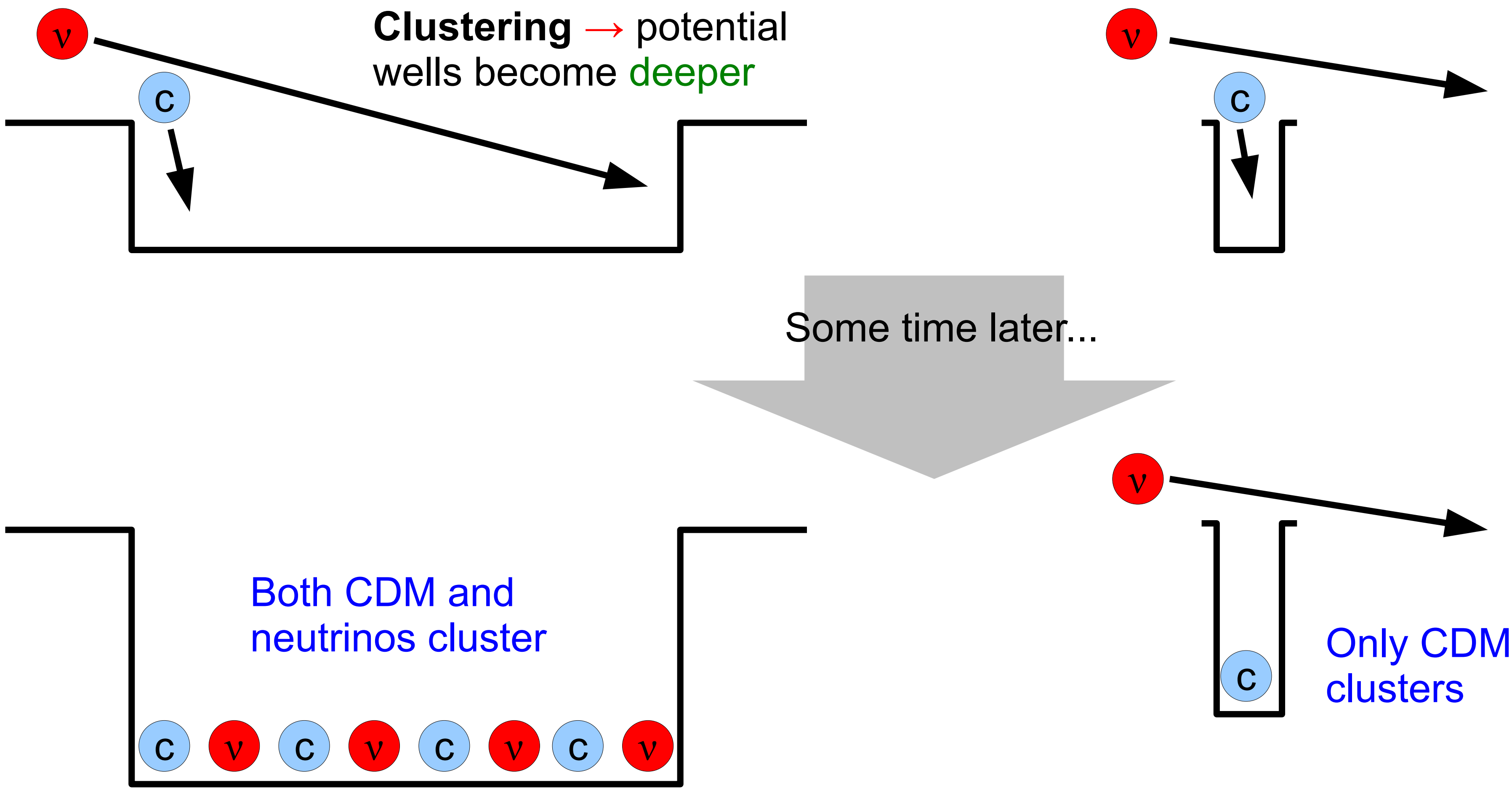
$$\lambda_{\text{FS}} \equiv \sqrt{\frac{8\pi^2 c_\nu^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\text{eV}}{m_\nu}\right) \; h^{-1}\ \text{Mpc}$$

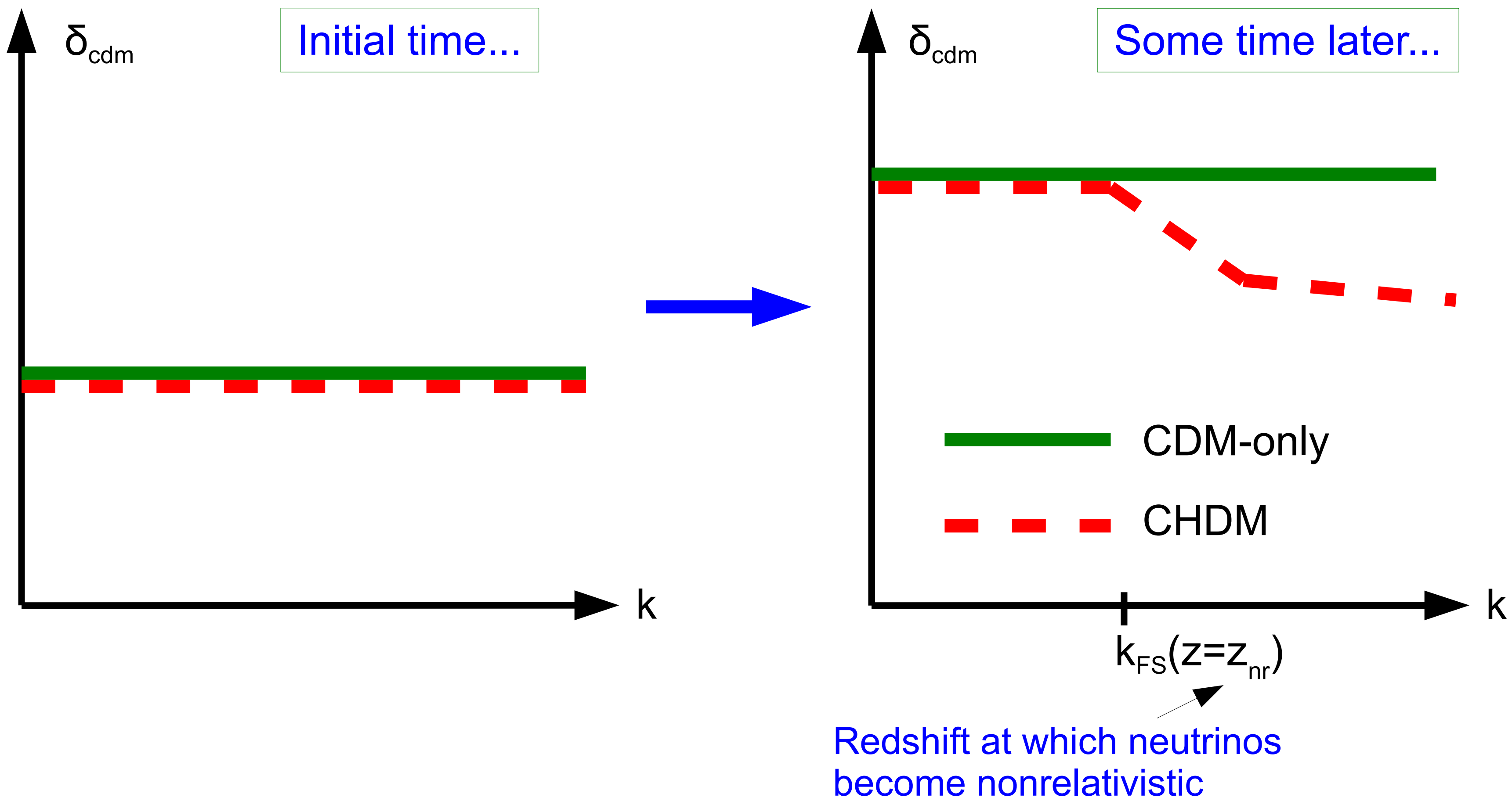
$$k_{\text{FS}} \equiv \frac{2\pi}{\lambda_{\text{FS}}}$$

$\lambda \gg \lambda_{\text{FS}}$, $k \ll k_{\text{FS}}$ Clustering

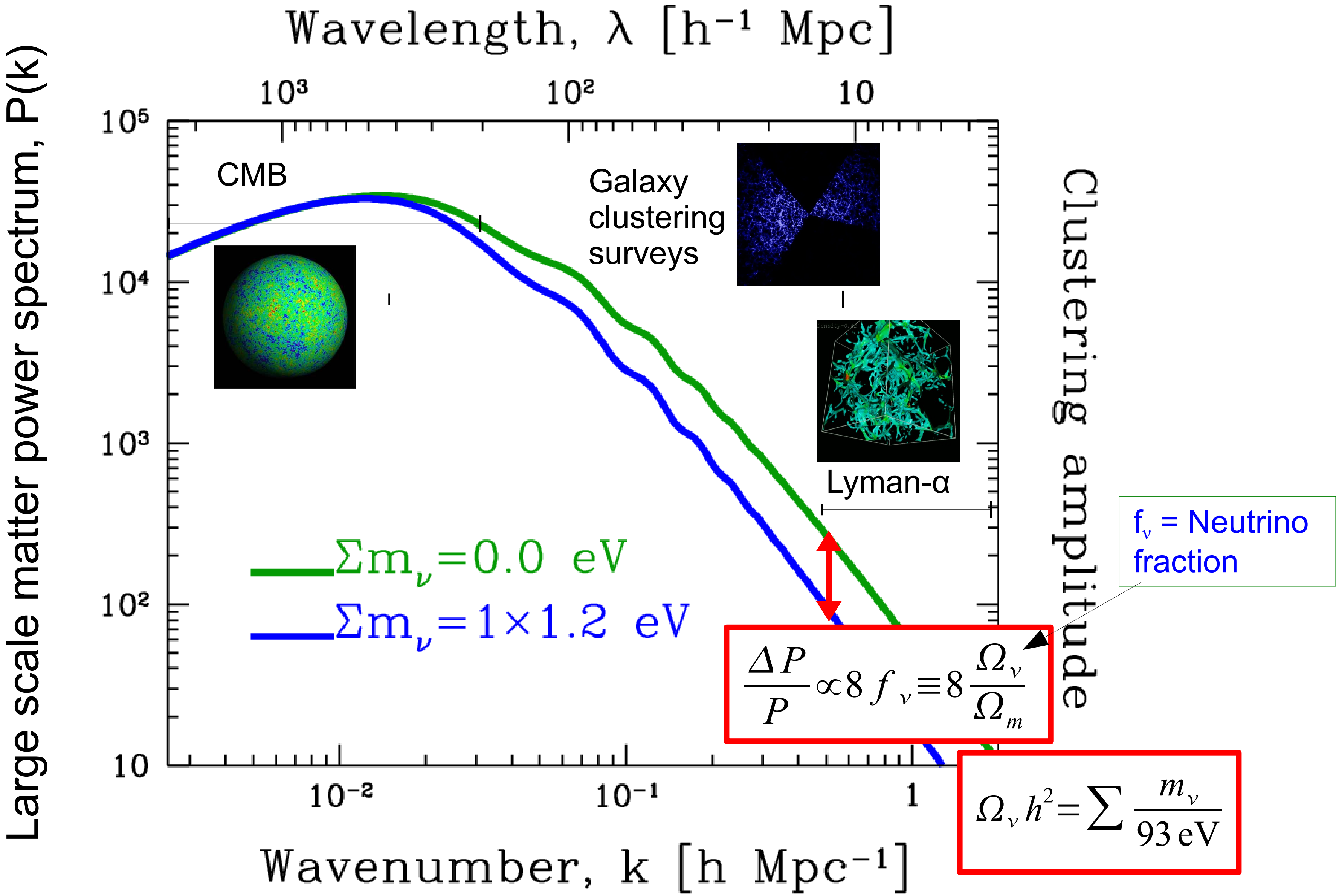
$\lambda \ll \lambda_{\text{FS}}$, $k \gg k_{\text{FS}}$ Non-clustering

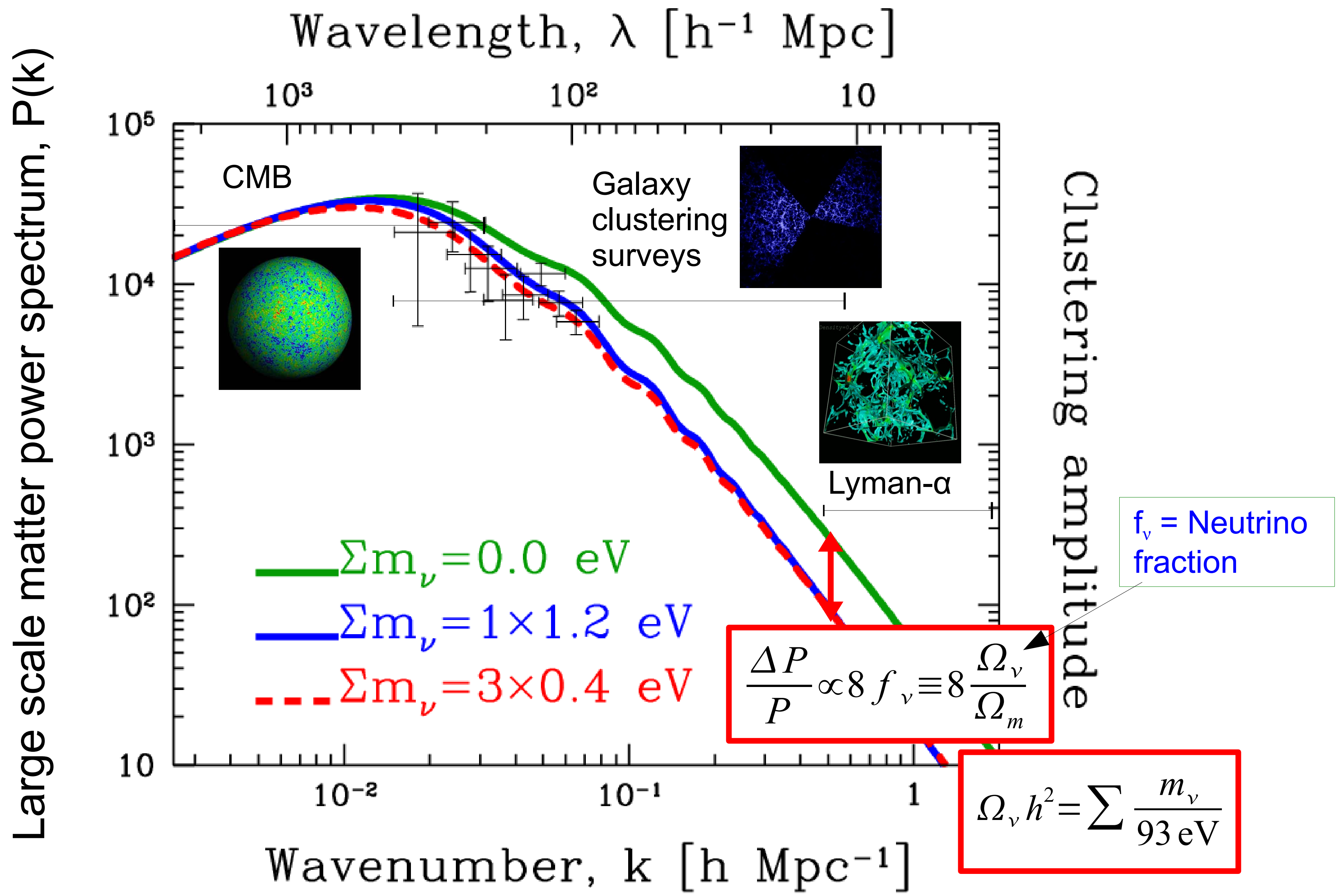
- In turn, free-streaming (non-clustering) neutrinos slow down the growth of gravitational potential wells on **scales** $\lambda \ll \lambda_{FS}$ or **wavenumbers** $k \gg k_{FS}$.

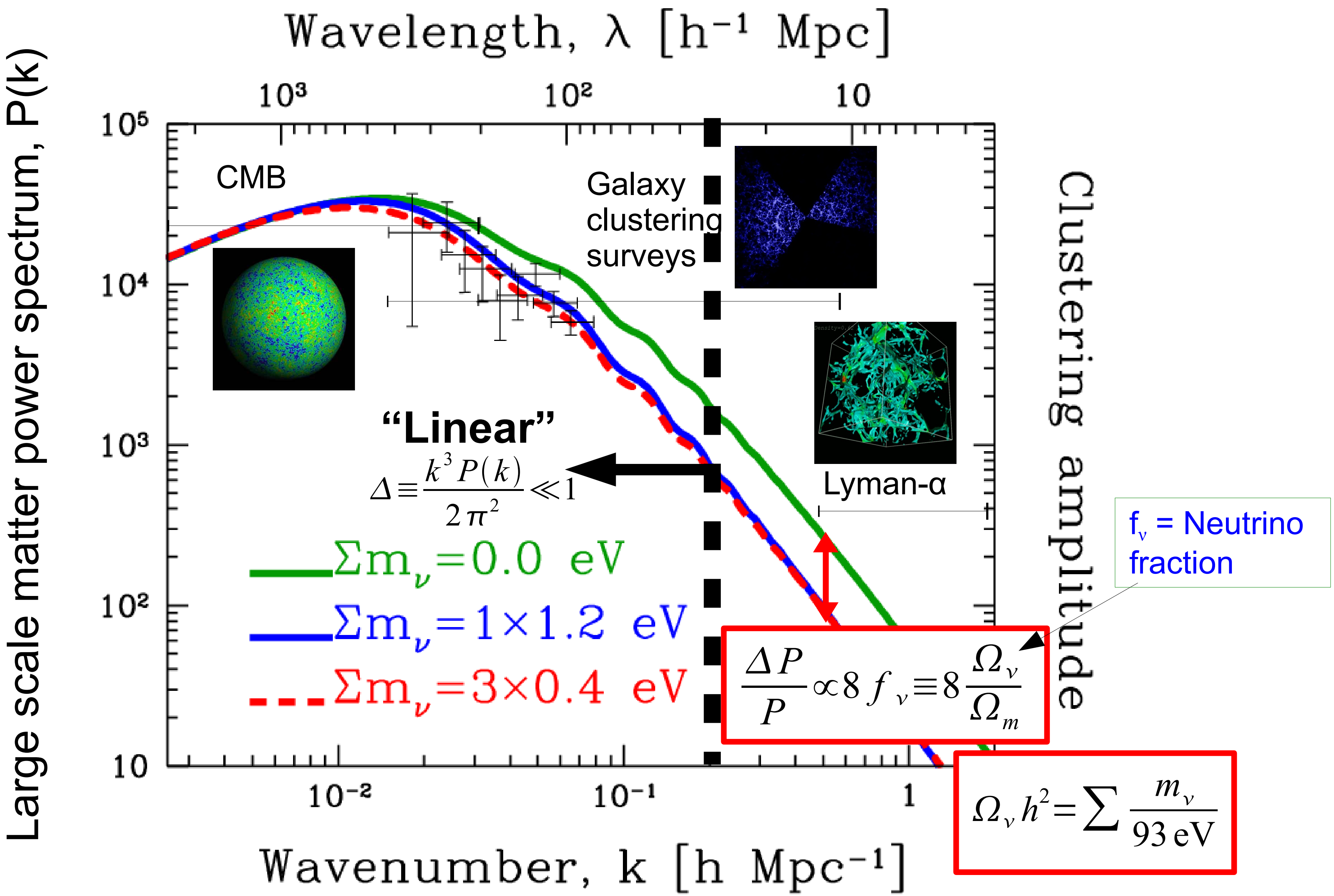




- The presence of HDM slows down the growth of CDM perturbations at large wavenumbers k.


Wavelength, λ [h^{-1} Mpc]
10^3
10^2
10
10^5
10^4
10^3
10^2
10
10^{-2}
10^{-1}
1
Wavenumber, k [h Mpc^{-1}]
Large scale matter power spectrum, P(k)
Clustering amplitude
CMB
Galaxy clustering surveys
Lyman-α
Σm_ν=0.0 eV
Σm_ν=1×1.2 eV
f_ν = Neutrino fraction
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$


Wavelength, λ [h⁻¹ Mpc]
Large scale matter power spectrum, P(k)
Wavenumber, k [h Mpc⁻¹]
Clustering amplitude
CMB
Galaxy clustering surveys
Lyman-α
Σmν=0.0 eV
Σmν=1×1.2 eV
Σmν=3×0.4 eV
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$
f_ν = Neutrino fraction
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$



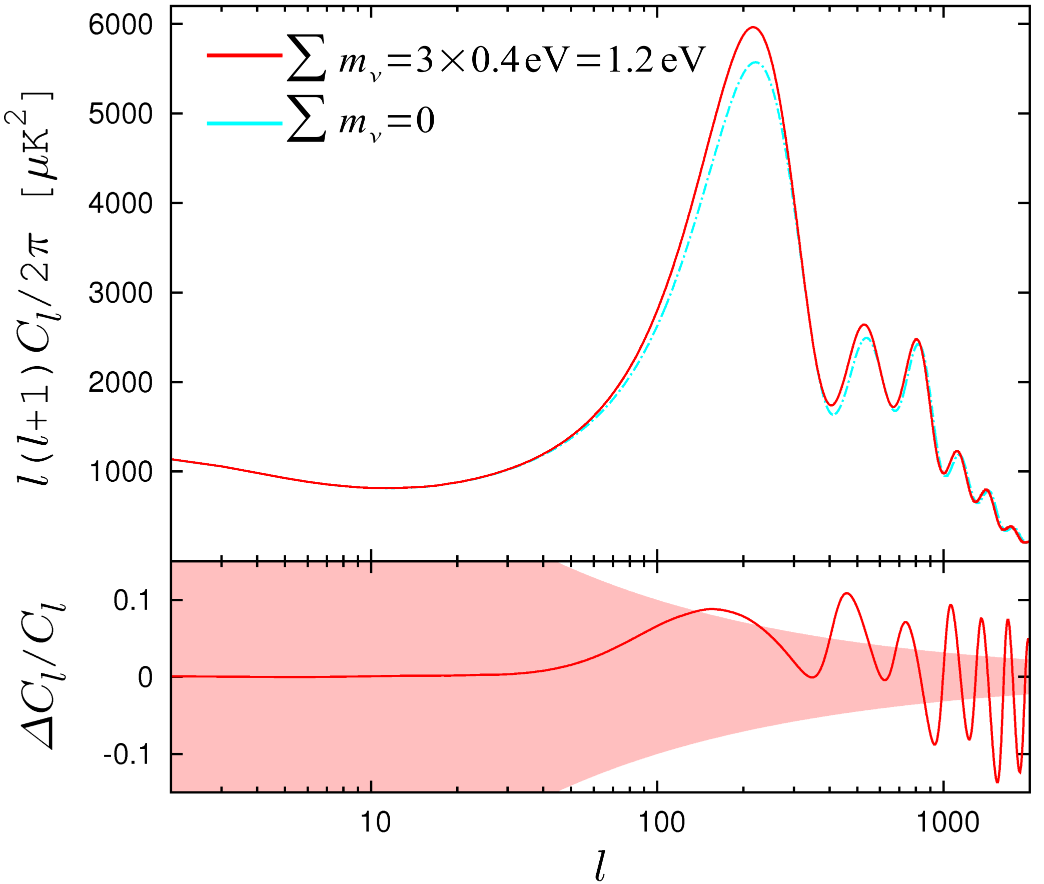
Wavelength, λ [h⁻¹ Mpc]
Large scale matter power spectrum, P(k)
Wavenumber, k [h Mpc⁻¹]
Clustering amplitude
CMB
Galaxy clustering surveys
Lyman-α
"Linear"
$\Delta \equiv \frac{k^3 P(k)}{2\pi^2} \ll 1$
$\Sigma m_\nu = 0.0$ eV
$\Sigma m_\nu = 1\times1.2$ eV
$\Sigma m_\nu = 3\times0.4$ eV
f_ν = Neutrino fraction
$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$

Neutrino effects on the CMB anisotropies...

- Present constraints come mainly via the early ISW effect:
  - γ decoupling: T ~ 0.26 eV.
  - Equality at T ~ 1 eV.
- A **O(0.1-1) eV** neutrino becomes nonrelativistic in the same time frame.

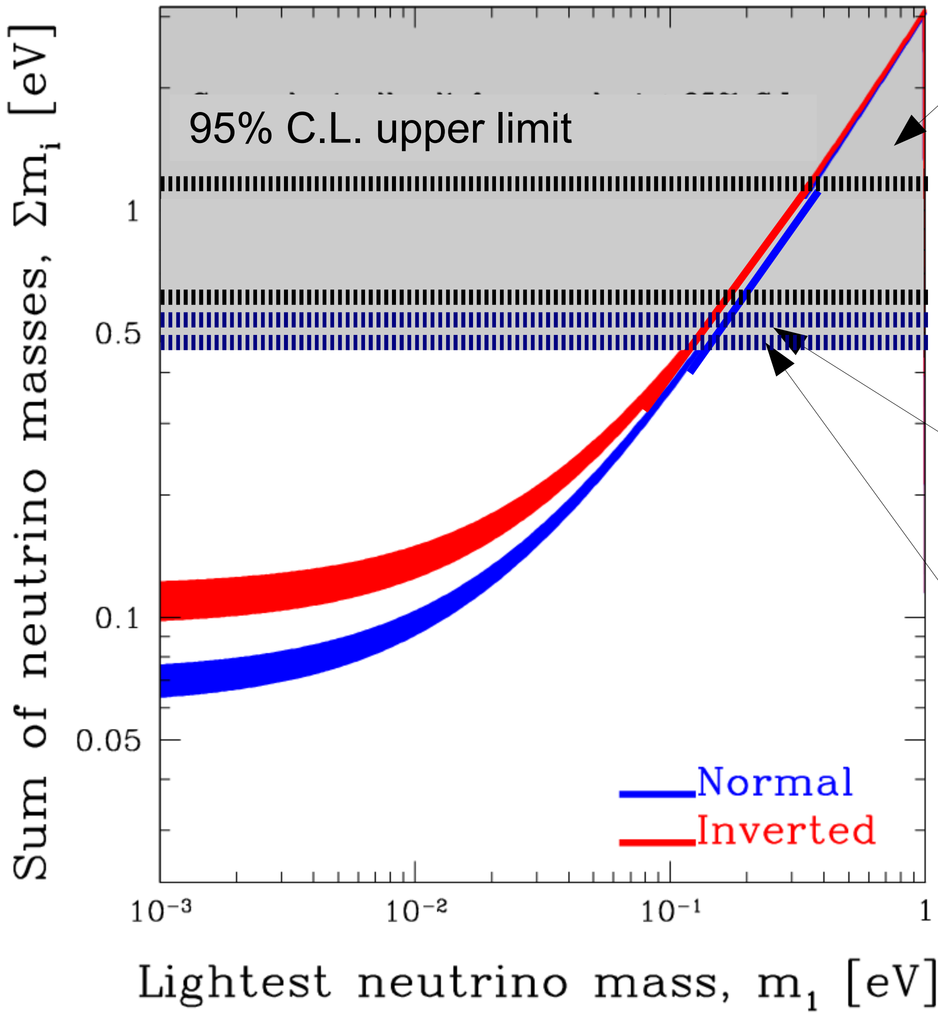
WMAP7 only (ΛCDM+m_ν):

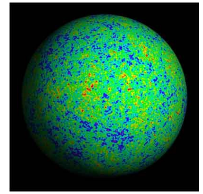
$$\sum m_\nu < 1.3 \quad \text{eV} \, (95\% \, \text{C.L.})$$



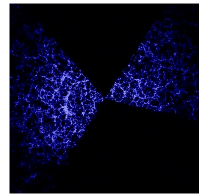
Komatsu et al. 2010, Hannestad et al. 2010

Present status...

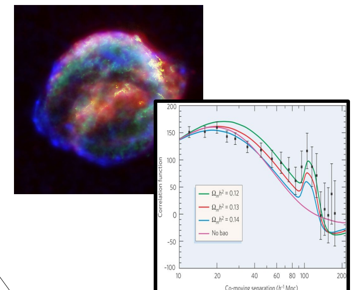




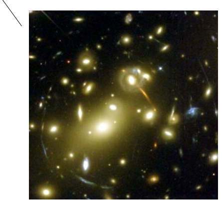
WMAP7 only*
Komatsu et al. 2010



WMAP7+SDSS-HPS *
Hannestad, Mirizzi, Raffelt & Y^3W 2010



WMAP5+SDSS-HPS +SN+HST
Reid et al. 2009
(extended models)



WMAP5+Weak lensing*
Tereno et al. 2008
Ichiki et al. 2008

* ΛCDM+m_ν

Cosmological and Astrophysical Neutrino Mass Measurements*

K. N. Abazajian[1], E. Calabrese[2], A. Cooray[3], F. De Bernardis[3], S. Dodelson[4,5,6], A. Friedland[7], G. M. Fuller[8], S. Hannestad[9], B. G. Keating[8], E. V. Linder[10,11], C. Lunardini[12], A. Melchiorri[2], R. Miquel[13,14],E. Pierpaoli[15], J. Pritchard[16], P. Serra[17], M. Takada[18], Y. Y. Y. Wong[19]

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(Dated: March 29, 2011)

arXiv:1103.5083 [astro-ph.CO]

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2-0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST [100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS [81], TMT [99], GMT [89]
21 cm	∞	$0.1-0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

in combination with WMAP; 95% upper limits

Abazajian et al. 1103.5083

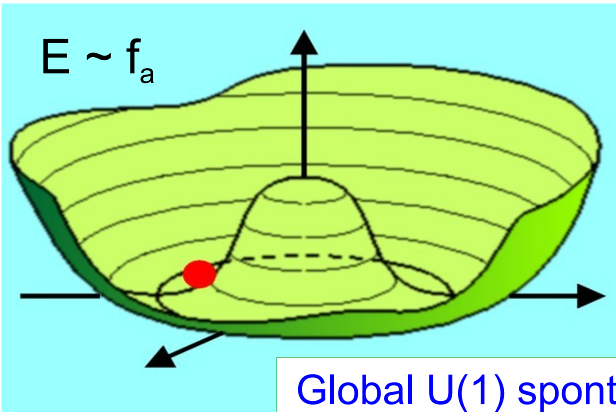
2. Non-standard hot relics...

2a. Thermal QCD axions...

QCD axions and the PQ Mechanism...

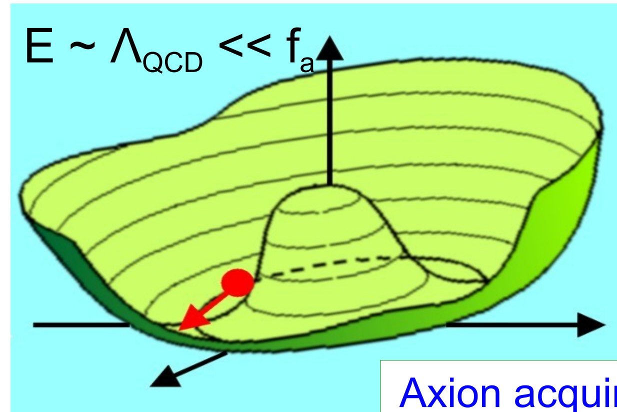
Peccei & Quinn, 1977
Wilczek, 1978
Weinberg, 1978

- A popular solution to the **strong CP problem**.



Global U(1) spontaneously broken at E ~ f_a

$U(1)_{PQ}$ explicitly broken by instanton effects at E ~ Λ_{QCD} ~ 200 MeV.



Axion acquires a mass

- Low energy **effective theory**:

$$L_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G}$$

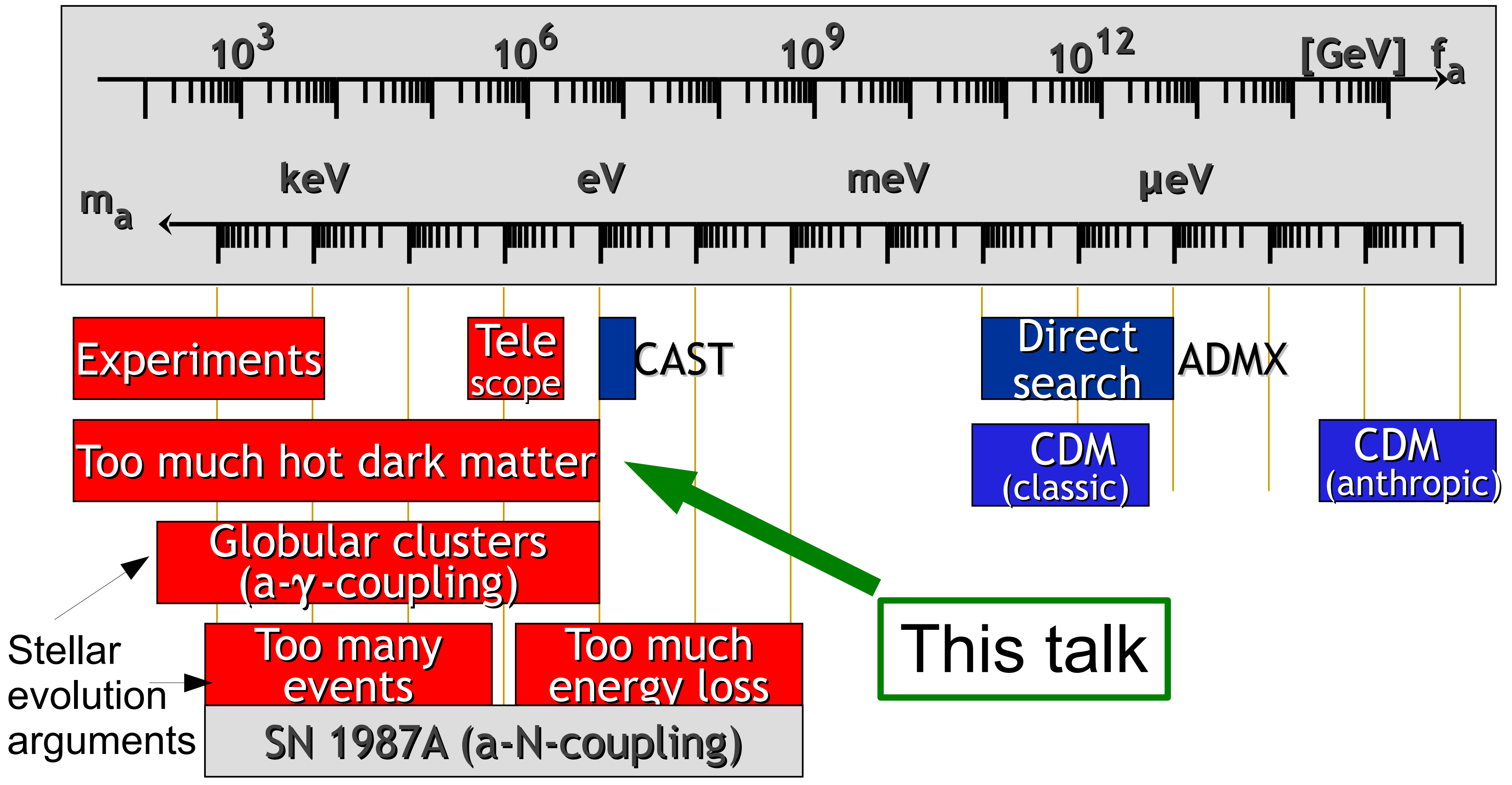
Peccei-Quinn scale

Axion mass

$z \equiv m_u / m_d = 0.553 \pm 0.043$

$$m_a \approx \frac{z^{1/2}}{1+z}\frac{f_\pi m_\pi}{f_a} = \frac{6.0\,\text{eV}}{f_a/10^6\,\text{GeV}}$$

QCD axion parameter space...



Thermal production of QCD axions...

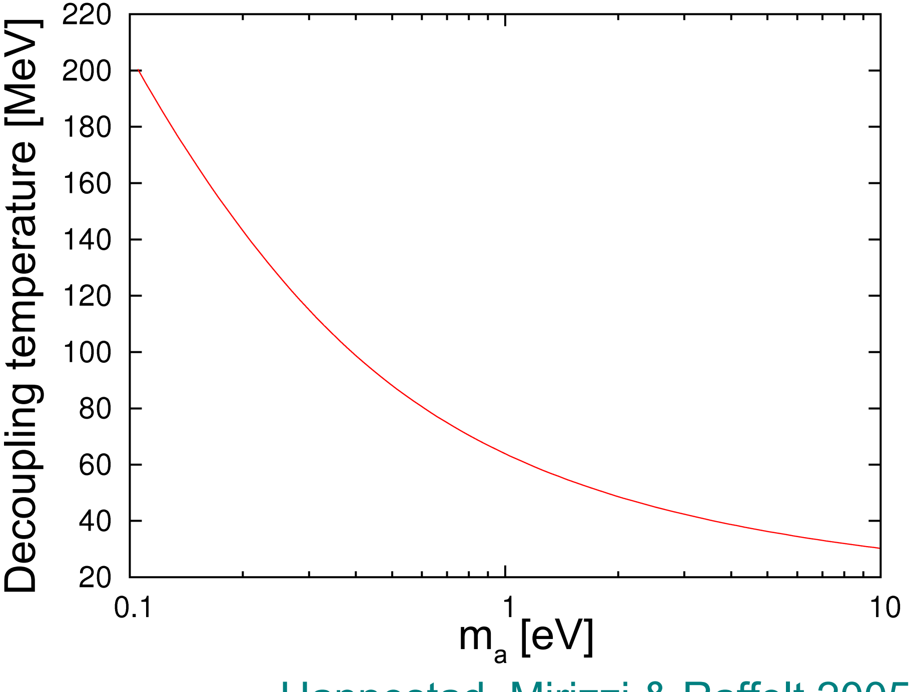
- If the PQ scale is low, then the coupling may be strong enough to produce a thermal axion background, decoupling after the QCD phase transition.

- Relevant scattering process: $\pi\,\pi \rightarrow a\,\pi$

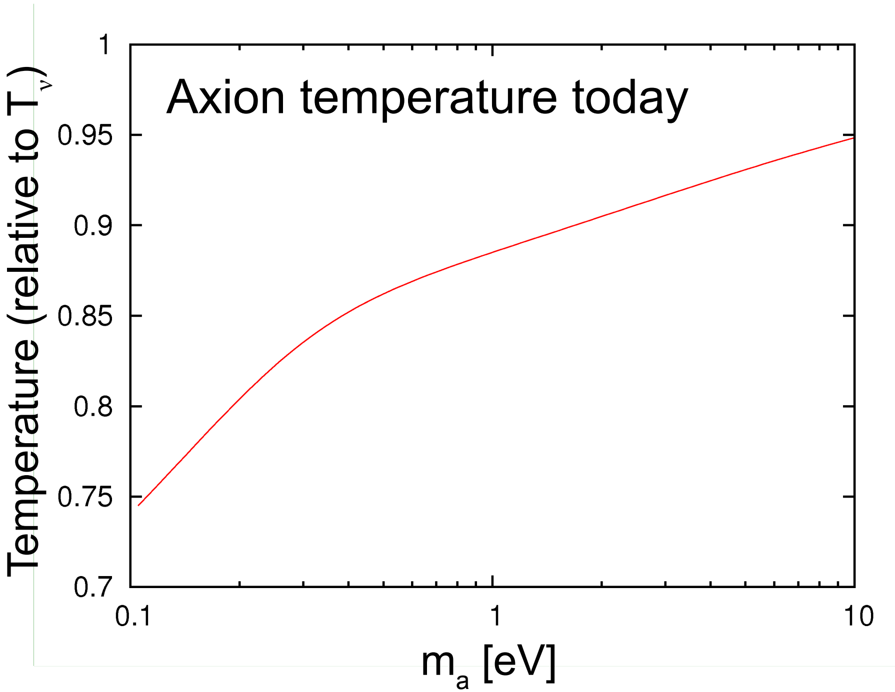
$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}\left(\pi^0 \pi^+ \partial_\mu \pi^- + \pi^0 \pi^- \partial_\mu \pi^+ - 2\pi^+ \pi^- \partial_\mu \pi^0\right)\partial^\mu a$$

$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi 1993



Hannestad, Mirizzi & Raffelt 2005



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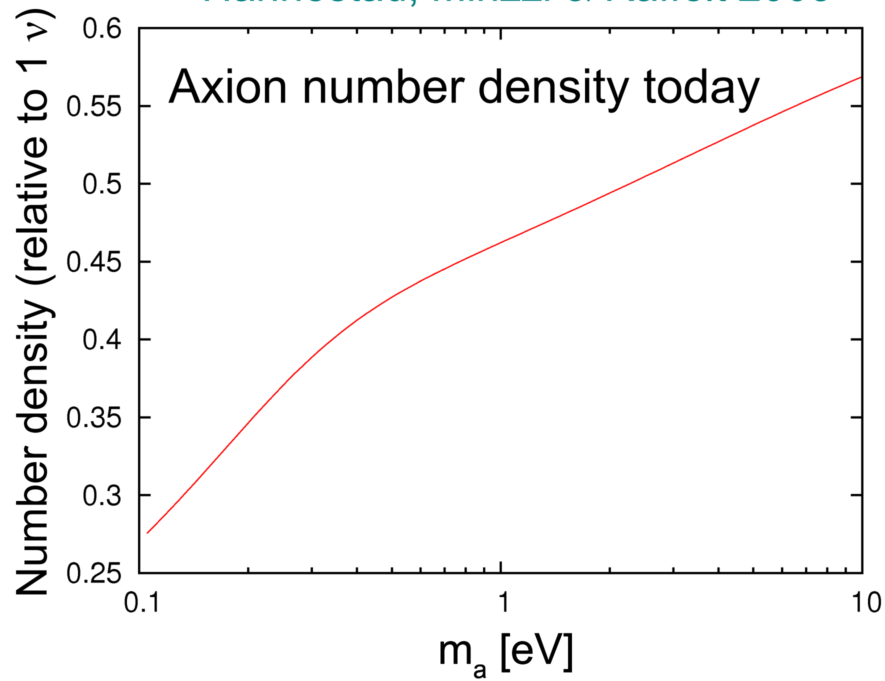
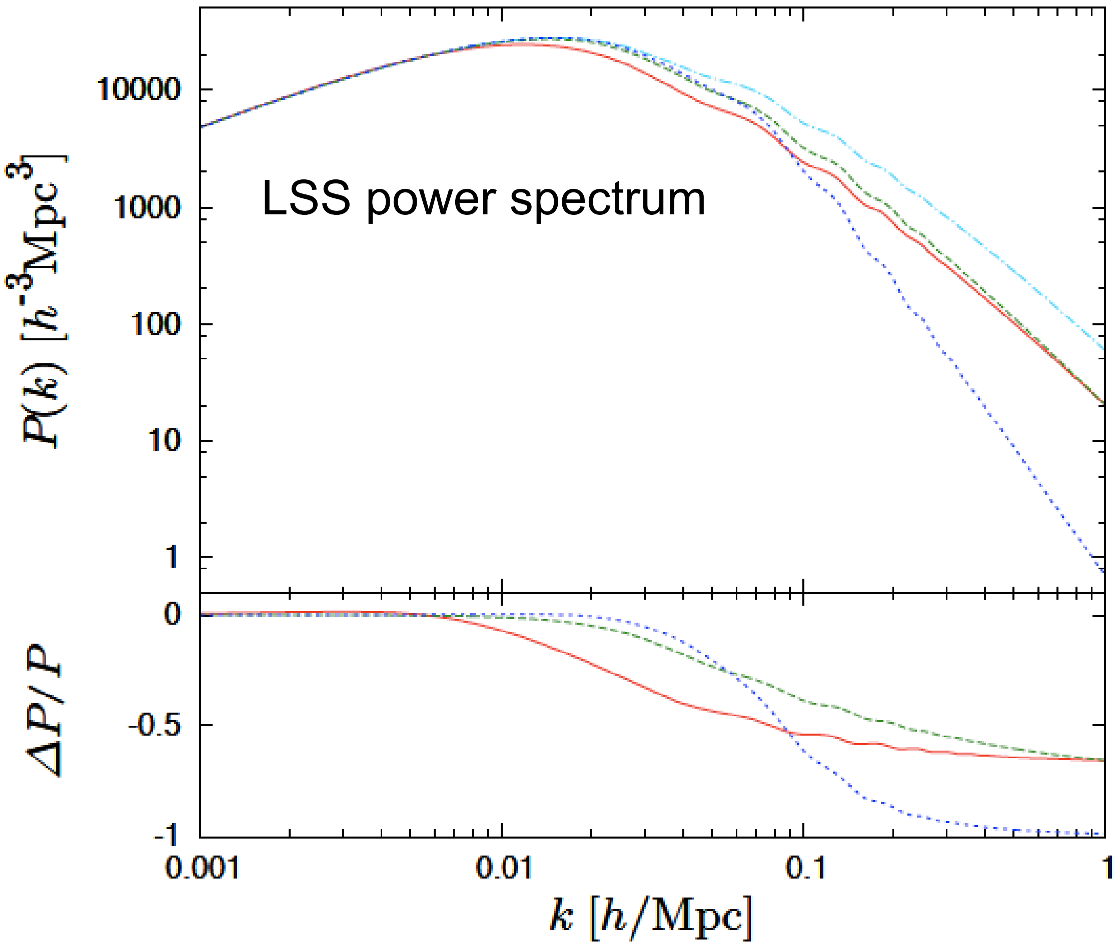


Axion free-streaming length

$$\lambda_{\rm fs} \sim 4.2 \sqrt{\frac{1+z}{\Omega_m h^2}} \frac{T_a}{T_\nu} \left(\frac{\rm eV}{m_\nu}\right) \ \rm Mpc$$

Expect free-streaming features that are qualitatively **similar** to neutrinos, but **not identical**.

Effects on cosmological observables...



$\omega_{\rm cdm}=0.112 \quad \omega_\nu=0 \quad \omega_a=0$
$(\Lambda\,\mathrm{CDM})$

$\omega_{\rm cdm}=0.099 \quad \omega_\nu=0.013 \quad \omega_a=0$
$(\sum m_\nu = 3\times 0.4\,\mathrm{eV} = 1.2\,\mathrm{eV})$

$\omega_{\rm cdm}=0.099 \quad \omega_\nu=0 \quad \omega_a=0.013$
$(m_a = 2.4\,\mathrm{eV})$

$\omega_{\rm cdm}=0.0498 \quad \omega_\nu=0 \quad \omega_a=0.0622$
$(m_a = 10\,\mathrm{eV})$

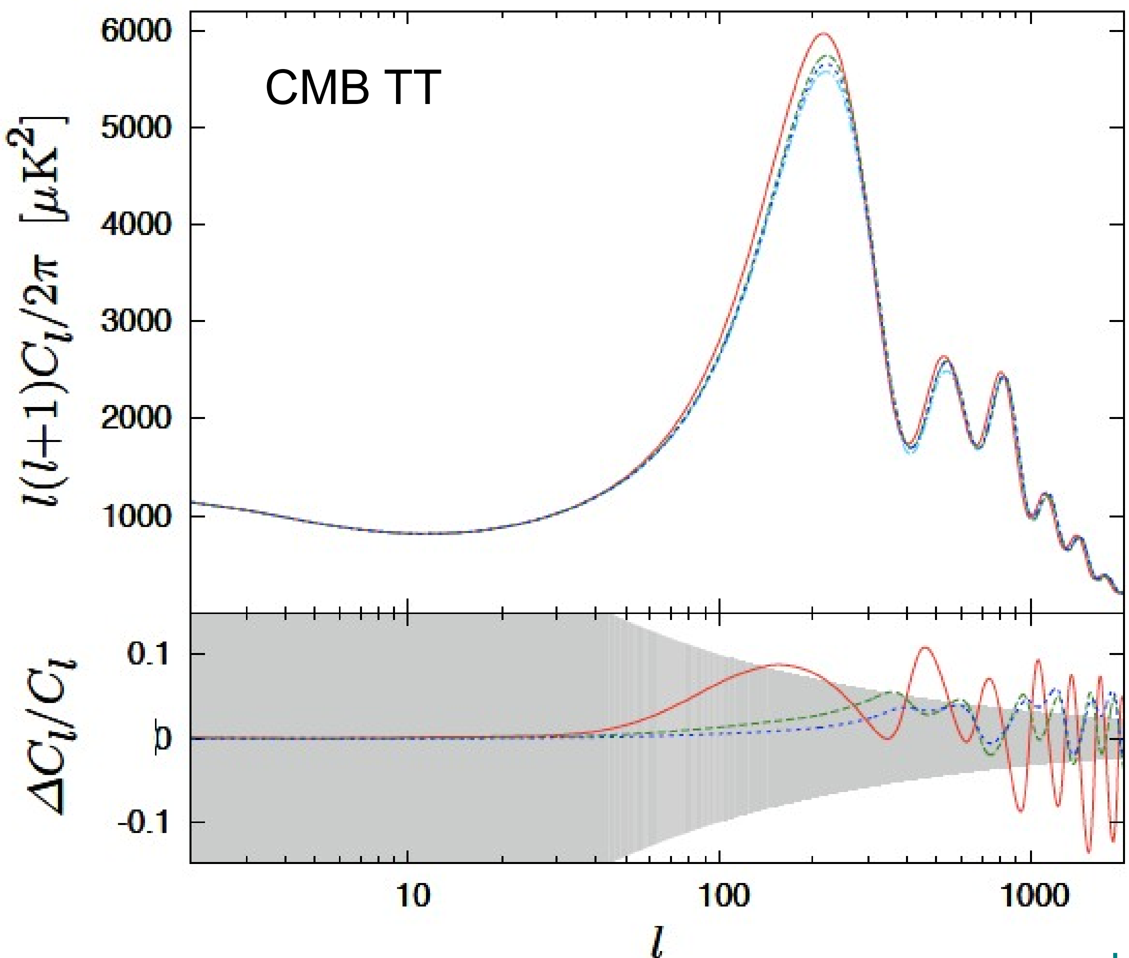
Hannestad, Mirizzi, Raffelt & Y^{3}W 2010

Data set	$\sum m_\nu$ [eV]	m_a [eV]
CMB only	1.19	—
CMB+BAO	0.85	—
CMB+HST	0.58	—
CMB+HPS	0.61	—
CMB+HPS+HST	0.44	—
CMB only	—	No constraint
CMB+BAO	—	No constraint
CMB+HST	—	No constraint
CMB+HPS	—	1.07
CMB+HPS+HST	—	0.91

HPS =
Halo power
spectrum
(SDSS DR7)

Hannestad, Mirizzi, Raffelt & Y^3W 2010

Effects on cosmological observables...



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Hannestad, Mirizzi, Raffelt & Y^3W 2010

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CMB+HST	—	No constraint
CMB+HPS	—	1.07
CMB+HPS+HST	—	0.91

Hannestad, Mirizzi, Raffelt & Y^3W 2010

Moral of the axion story...

- Free-streaming behaviour is qualitatively similar to that of the neutrinos.

- But the two scenarios differ in the details.
  - Shape of the matter power spectrum.
  - Different signatures in the CMB and the LSS power spectrum.

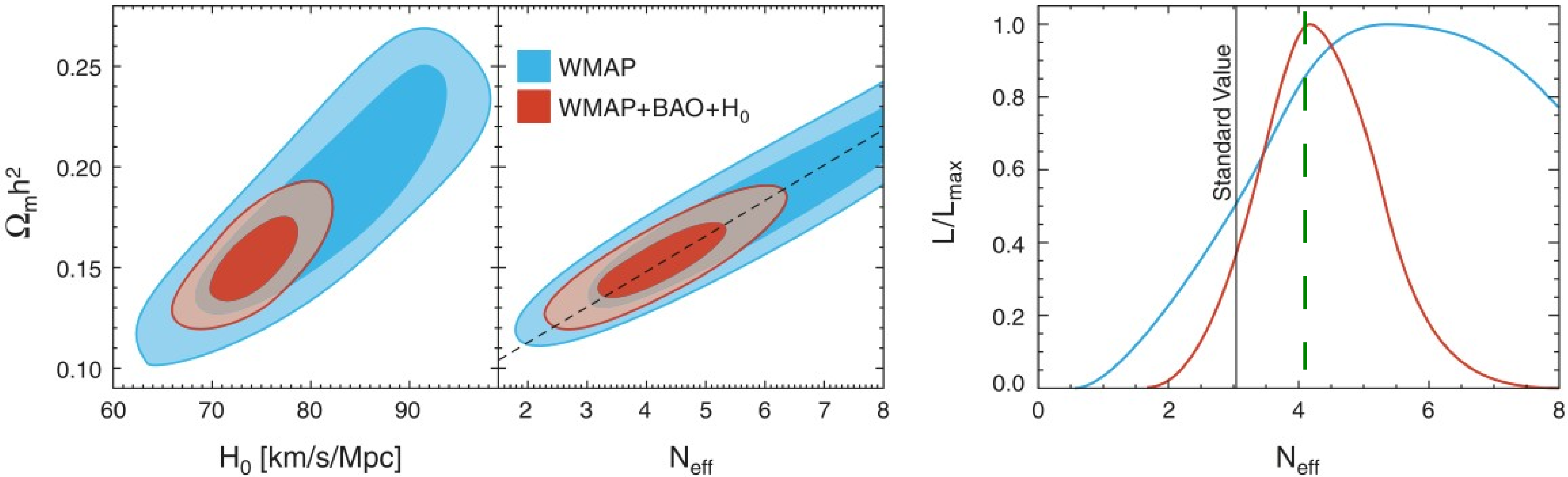
- Can we eventually use these to distinguish between different hot relics??

2b. Searching for non-standard hot relics...

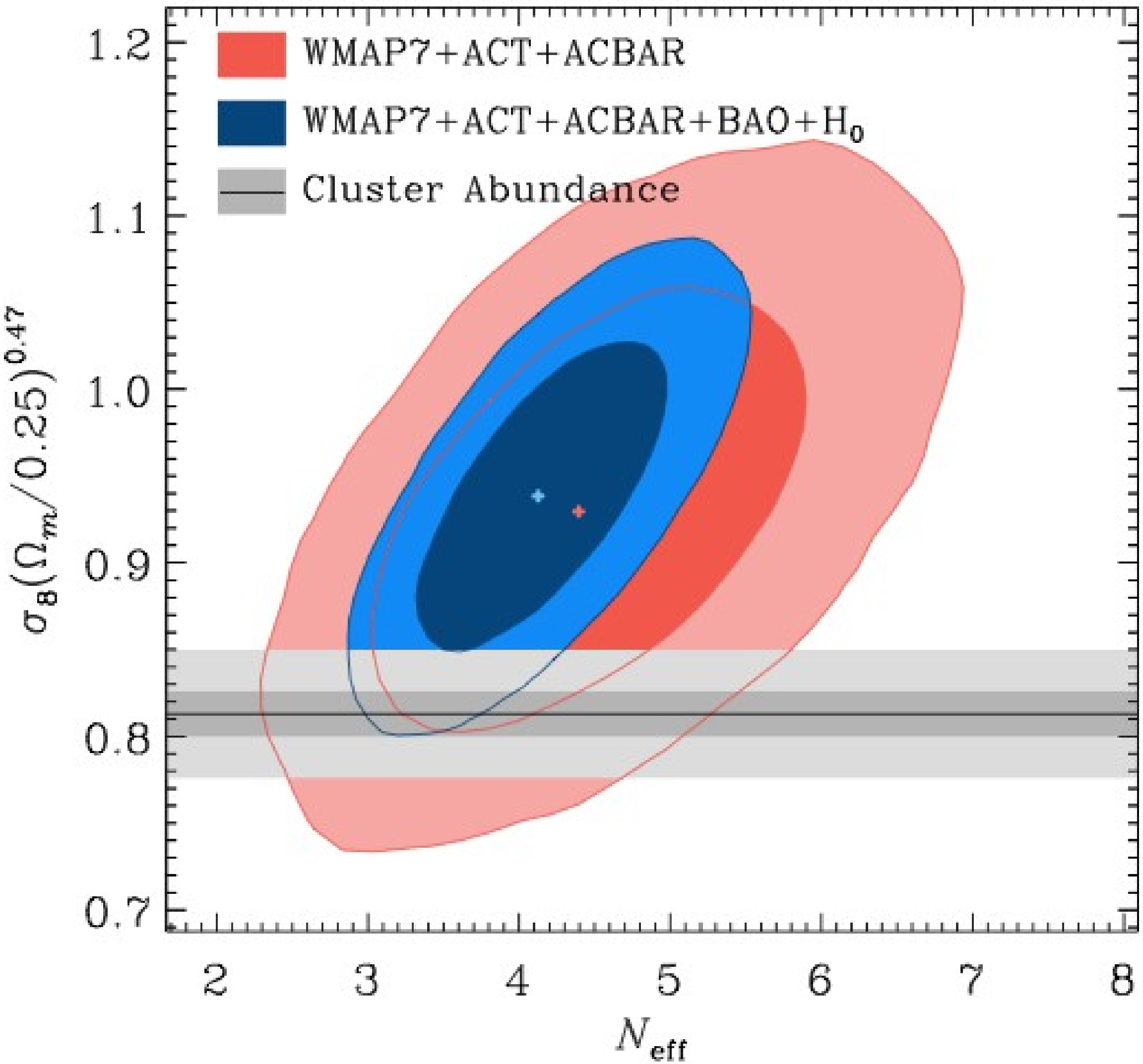
Searching for extra hot relics in precision cosmology...

- The simplest phenomenological model is to represent any excess relativistic energy density in terms of extra species of massless neutrinos.

$$\rho_\nu + \rho_X = \underline{N_{\mathrm{eff}}}\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right) = (3.04 + \underline{\Delta N_{\mathrm{eff}}})\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right)$$



Komatsu [WMAP7] et al. 2010

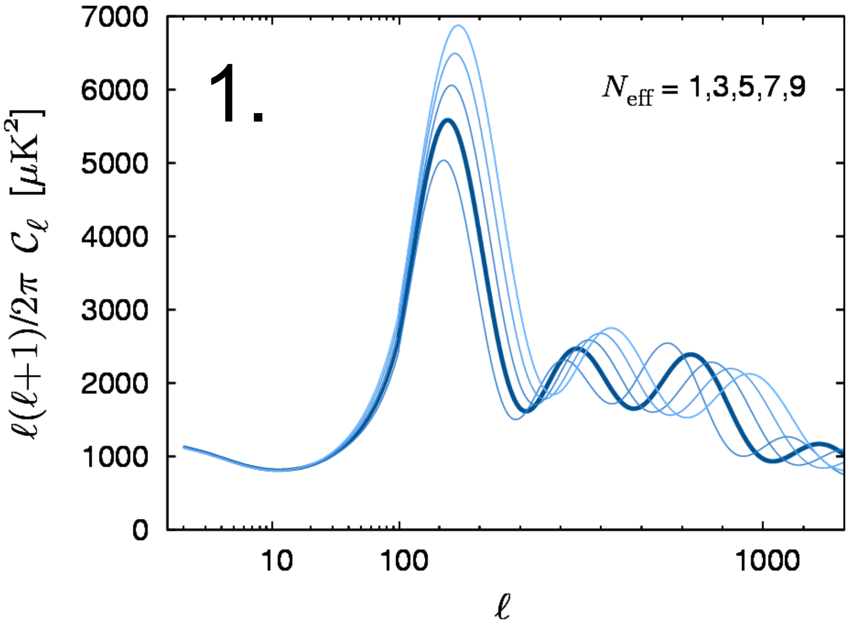


- The most recent analysis using WMAP7+ACT+ ACBAR+BAO+H_0 finds N_{eff} = 3.04 is disfavoured at 98.4% confidence.

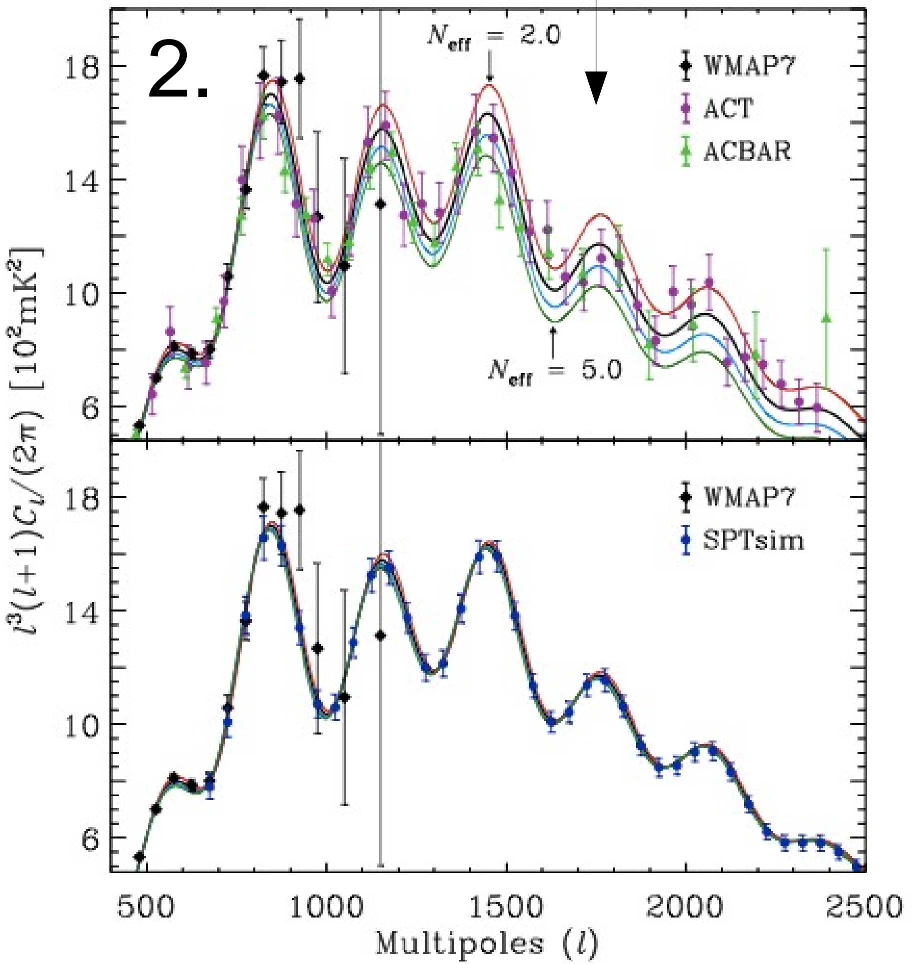
Hou, Keisler, Knox et al. 1104.2333

How it works...

- **Primary effect** of N_{eff}: shifts epoch of equality.
- **Secondary effect**: enhances expansion rate at equality and hence Silk damping.



Fixed z_{eq}, ρ_b, θ_s



Hou, Keisler, Knox et al. 1104.2333

Light (eV) sterile neutrinos as a candidate...

- Oscillation signals in LSND and MiniBooNE (anti-neutrino channel) **conflict** with the standard 3-neutrino interpretation of global neutrino oscillation data.

- The simplest solution: introduce a fourth neutrino flavour.

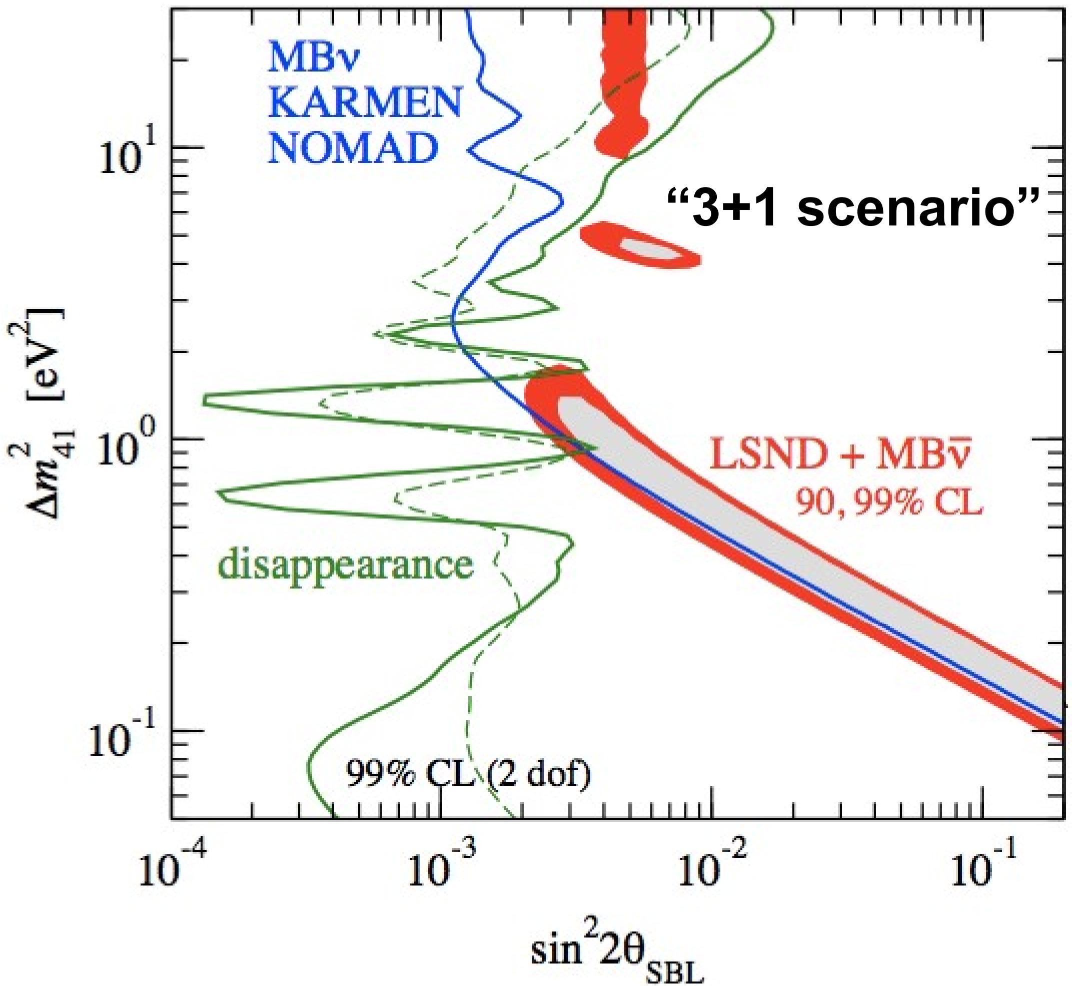
  - Must not couple to W, Z, or LEP would have seen it.

$$N_\nu = 2.9840 \pm 0.0082$$

Z invisible decay width
Particle Data Group 2010

→ Fourth flavour = “Sterile neutrino”.

(e, μ, τ neutrinos = “Active neutrinos”.)



Kopp, Maltoni & Schwetz 1103.4570

New reactor fluxes

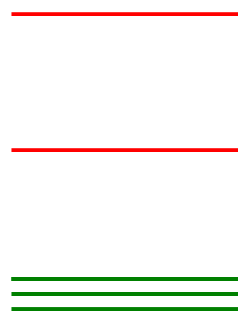
Old reactor fluxes

- Tension between LSND/ MiniBooNE and reactor disappearance experiments.
- New analysis of reactor fluxes finds 3% higher mean flux.
  → disappearance @98.6% confidence (old: 68% CL).
  Mention et al. 1101.2755
- "3+1" best-fit: $\Delta m^2_{41} \sim 1 \ \text{eV}^2$

→ $m_s \sim 1 \ \text{eV}$

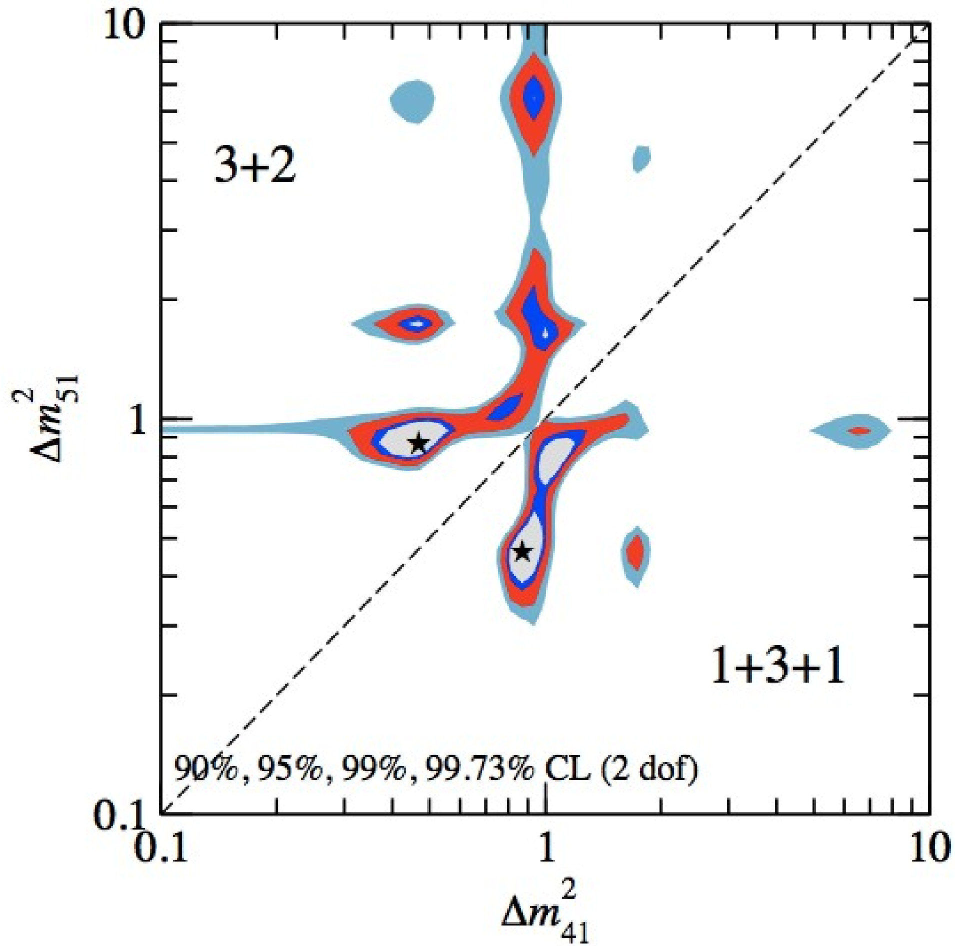
If lightest neutrino mass ~ 0 eV

- 3 active + 2 sterile scenarios fit even better.



$$\Delta m_{41}^2 \sim 0.47 \quad eV^2$$
$$\Delta m_{51}^2 \sim 0.87 \quad eV^2$$
$$\chi^2 / \text{dof} = 110.1/130$$

$$m_1 \sim m_2 \sim m_3 \quad 0 \quad eV$$
$$m_{s1} \sim 0.7 \quad eV$$
$$m_{s2} \sim 0.9 \quad eV$$



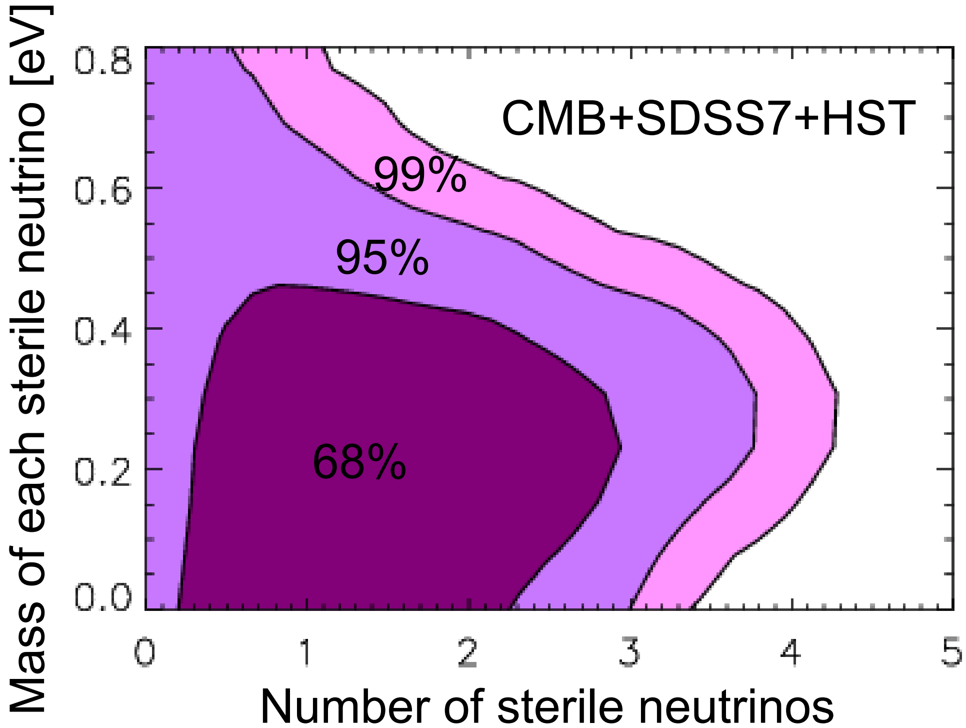
Kopp, Maltoni & Schwetz 1103.4570

Sterile neutrino thermalisation...

- Production process is a combination of active-sterile neutrino oscillations and weak scattering of the active neutrinos.
  - Extent of sterile neutrino thermalisation depends sensitively on the square-mass splitting and the mixing matrix.
  - $\Delta m^2 > 1\ eV^2 \rightarrow$ complete thermalisation: same temperature and abundance as active neutrinos.*

- **Caution**: A full-scale 3+1 or 3+2 flavour oscillation+scattering thermalisation calculation is a very computationally demanding exercise.
  - No one has ever done it...
  - * based on old momentum-averaged 2-flavour analyses.

Compatibility of 3+1 and 3+2 with cosmology...



- 3+1 thermalised sterile:

$$m_s < 0.48 \ \ \text{eV} \ \ (95\% \, C.I.)$$

Lab best-fit: $m_s \sim 1 \ \ \text{eV}$

- 3+2 thermalised sterile:

$$m_{s1} + m_{s2} < 0.9 \ \ \text{eV} \ \ (95\% \, C.I.)$$

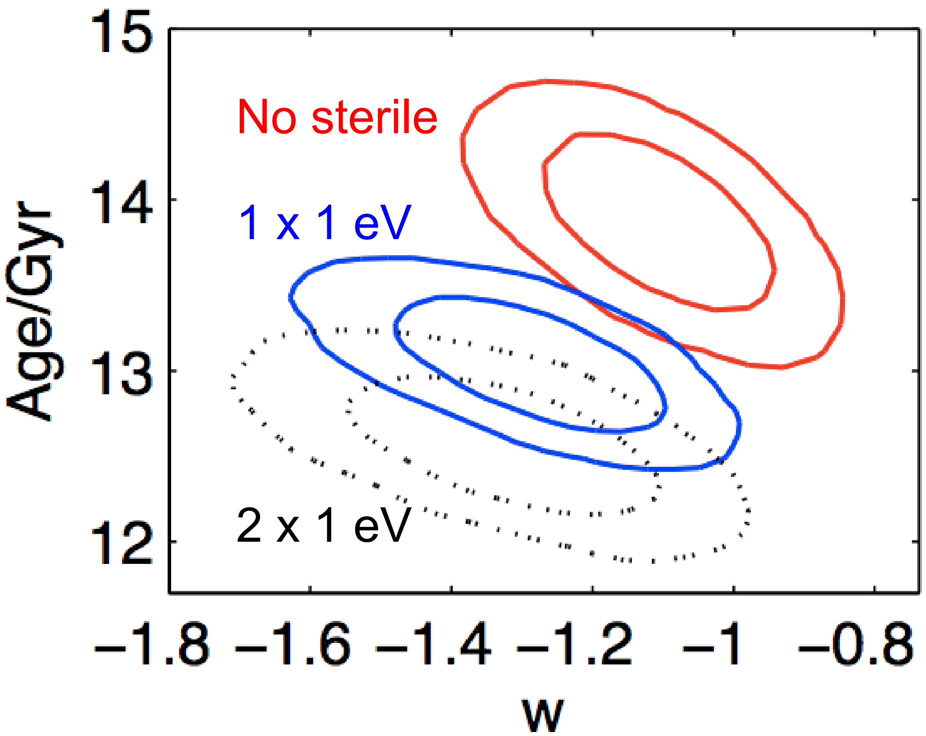
Lab best-fit: $m_{s1} \sim 0.7 \ \ \text{eV}$, $m_{s2} \sim 0.9 \ \ \text{eV}$

Hamann, Hannestad, Raffelt, Tamborra & Y[3]W 2010

→ Tension between experiment results and cosmology!

Suppose 1eV sterile neutrinos are for real...

- How would other cosmological parameters have to change in order to accommodate two sterile neutrinos?



→ Cosmolgical constant disfavoured at > 95% confidence!

(wCDM+k+sterile)
(CMB+LSS+SN)

Kristiansen & Elgaroy 1104.0704

3. How to know more...

Planck and N_{eff}...

- The question of whether or not N_{eff} ~ 4 will be settled almost immediately with Planck!

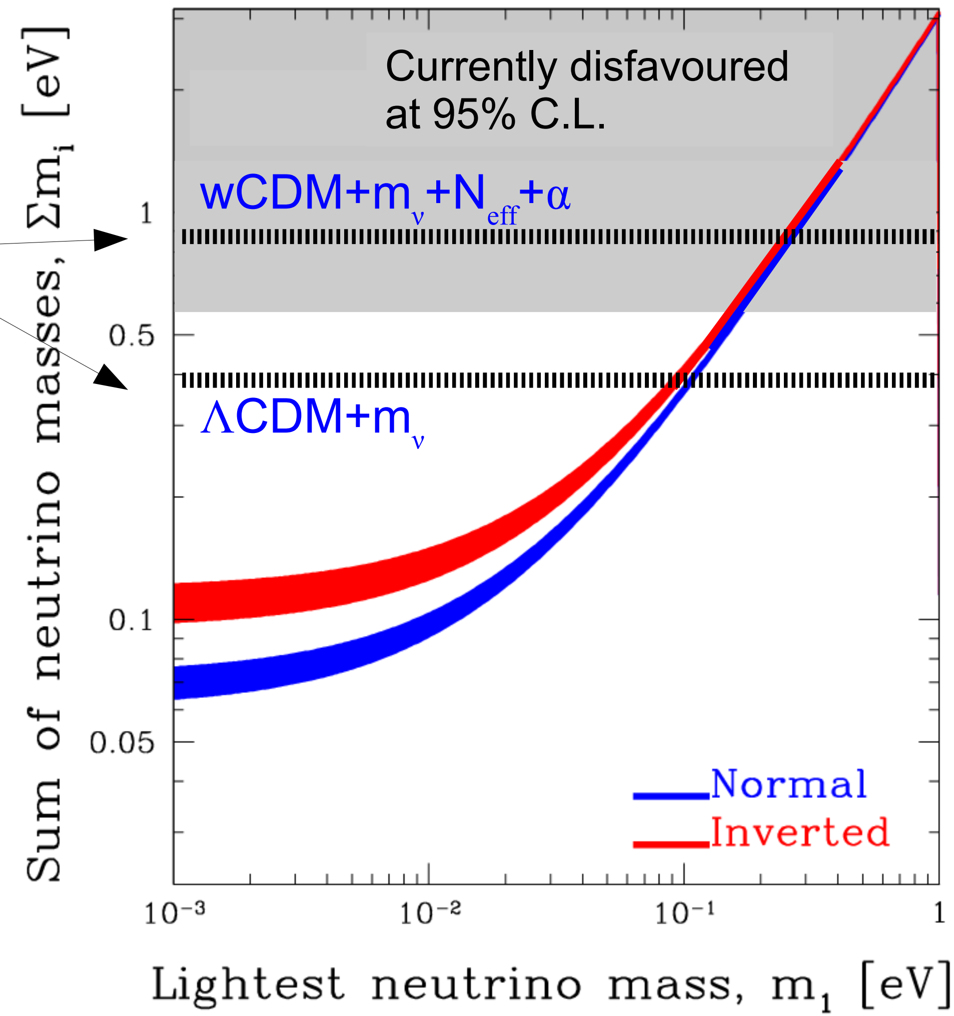
Experiment	$f_{\rm sky}$	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Bashinsky & Seljak 2004

Free Helium fraction

Planck and neutrino masses...

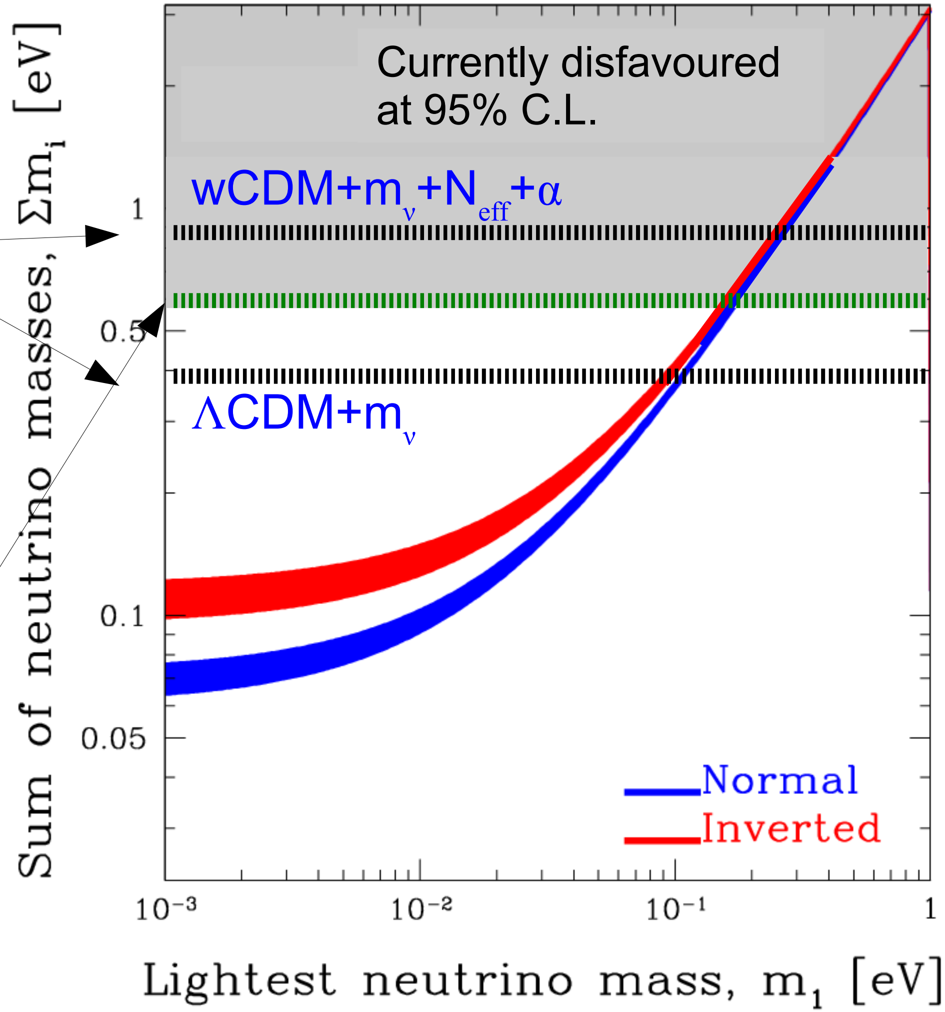
Planck 95% sensitivities to neutrino masses



Perotto et al. 2006

Planck and neutrino masses...

Planck 95% sensitivities to neutrino masses



Reach of KATRIN

KATRIN main spectrometer

Perotto et al. 2006

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	0.2 – 0.05	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST [100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS [81], TMT [99], GMT [89]
21 cm	∞	0.1 – 0.006	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

+Planck; 95% sensitivities

Abazajian et al. 1103.5083

Summary...

- Hot relics are still fun.
  - With present data: $\sum m_\nu < O(1)\ \mathrm{eV}$
  - We can do **even better** in the future with forthcoming probes/new techniques.

- Question of the moment: are there extra hot relics beyond 3 standard model neutrinos?
  - **Planck** will answer this soon!