Cosmological constraints on sterile neutrino mass in $f(R)$ gravity

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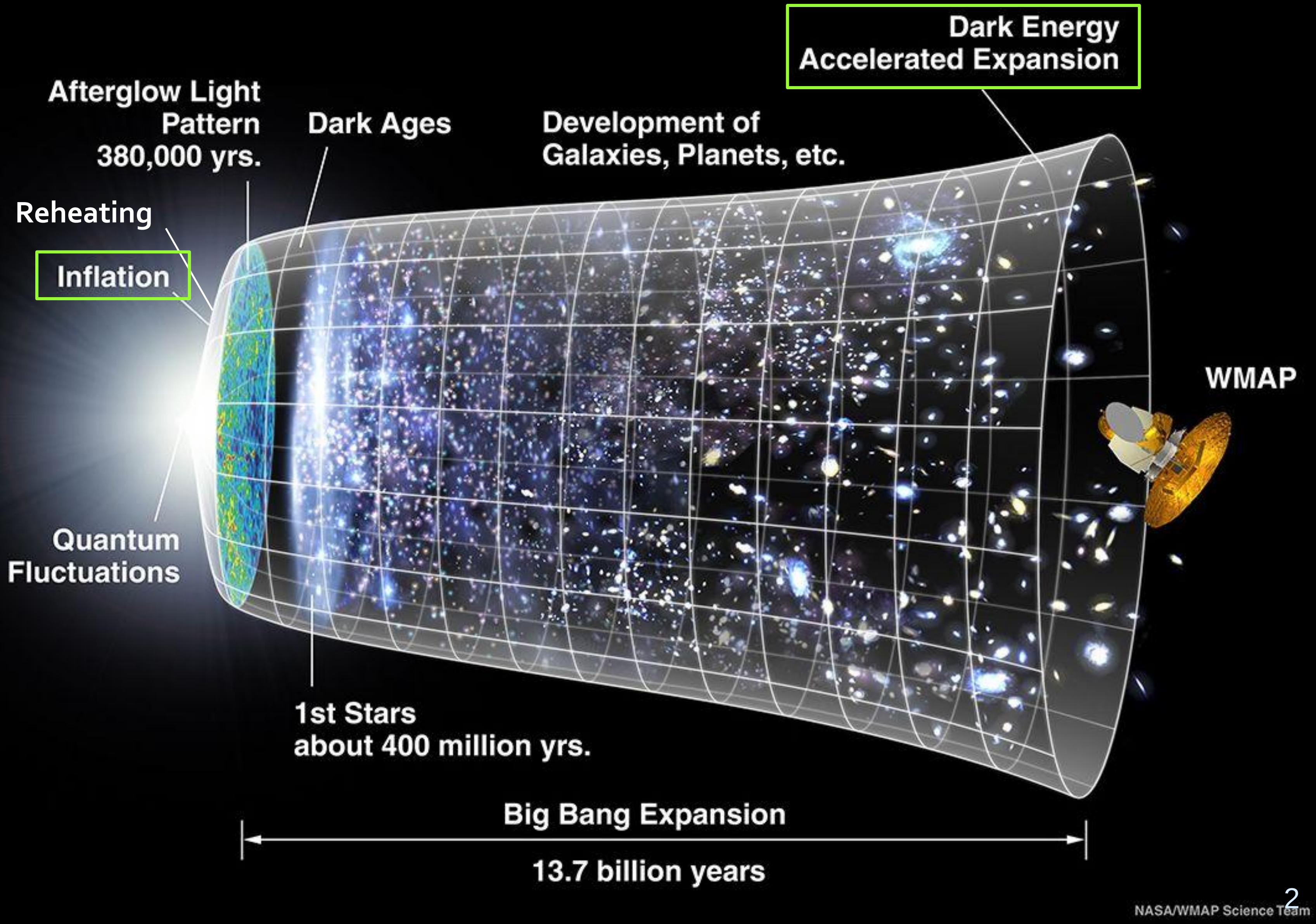
Two regimes of accelerated expansion



NASA/WMAP Science Team

$f(R)$ gravity

can describe the accelerated expansion.

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}f(R) + S_m$$

Primordial inflation

Starobinsky, Phys.Lett. B91 (1980) 99

$$f(R) = R + \frac{R^2}{6M^2}$$

Late-time acceleration

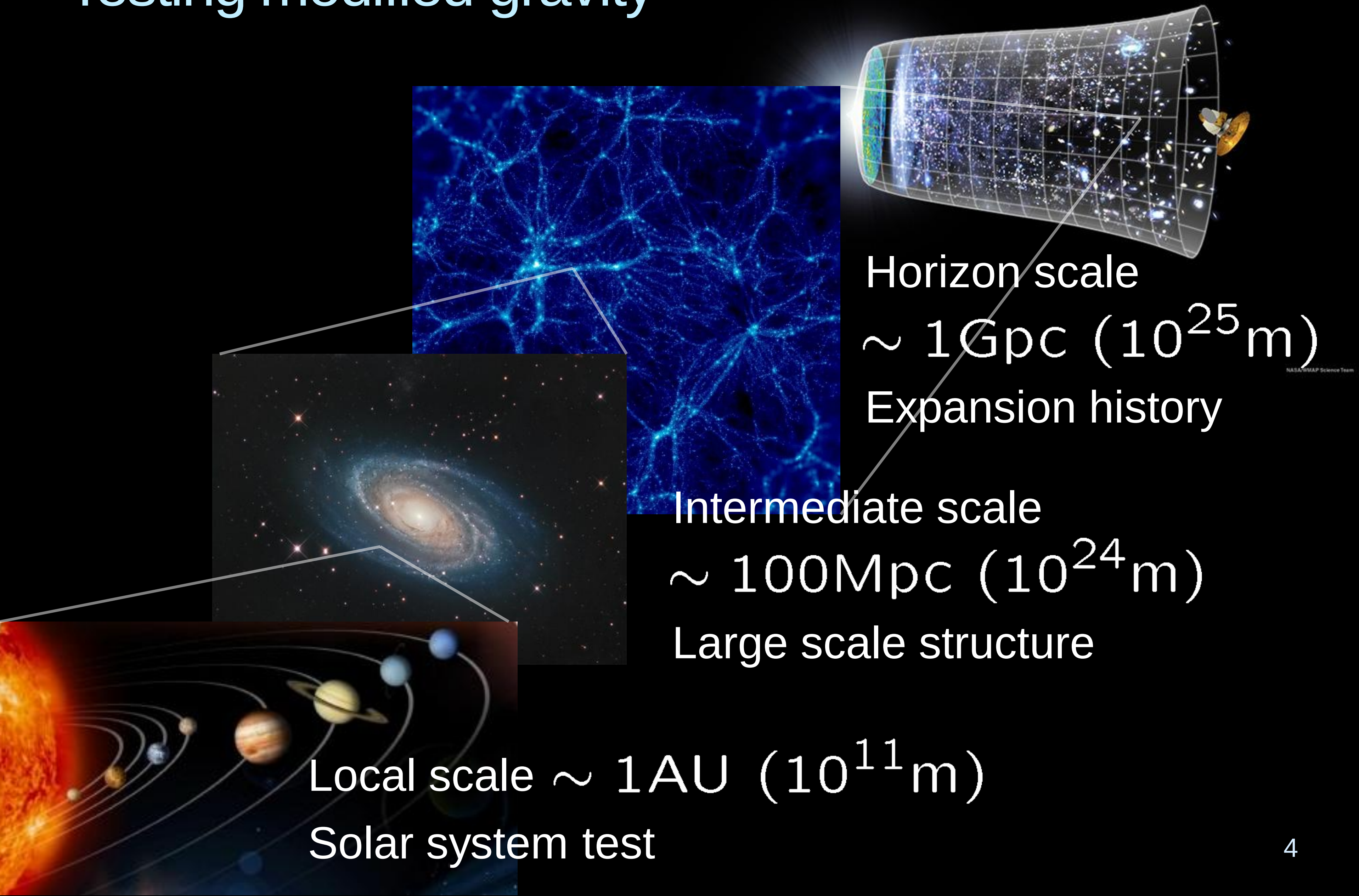
Starobinsky, JETP Lett. 86, 157 (2007)
[arXiv:0706.2041]

$$f(R) = R + \lambda R_s\left[\left(\frac{R^2}{R_s^2}+1\right)^{-n} - 1\right]$$

cf. $f(R)$ model for both accelerated expansion

Appleby, Battye, Starobinsky, JCAP 1006, 005 (2010) [arXiv:0909.1737]
H.M., Nishizawa, PRD 86 (2012) 093514 [arXiv:1204.1472]

Testing modified gravity



Horizon scale

$\sim 1\text{Gpc}\ (10^{25}\text{m})$

Expansion history

Intermediate scale

$\sim 100\text{Mpc}\ (10^{24}\text{m})$

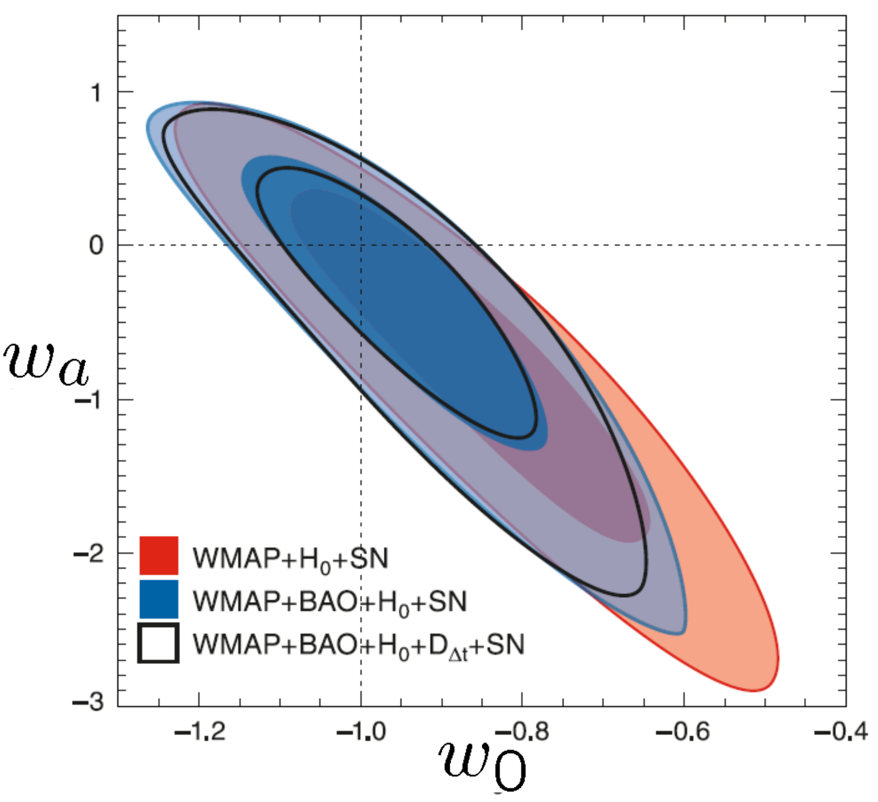
Large scale structure

Local scale $\sim 1\text{AU}\ (10^{11}\text{m})$

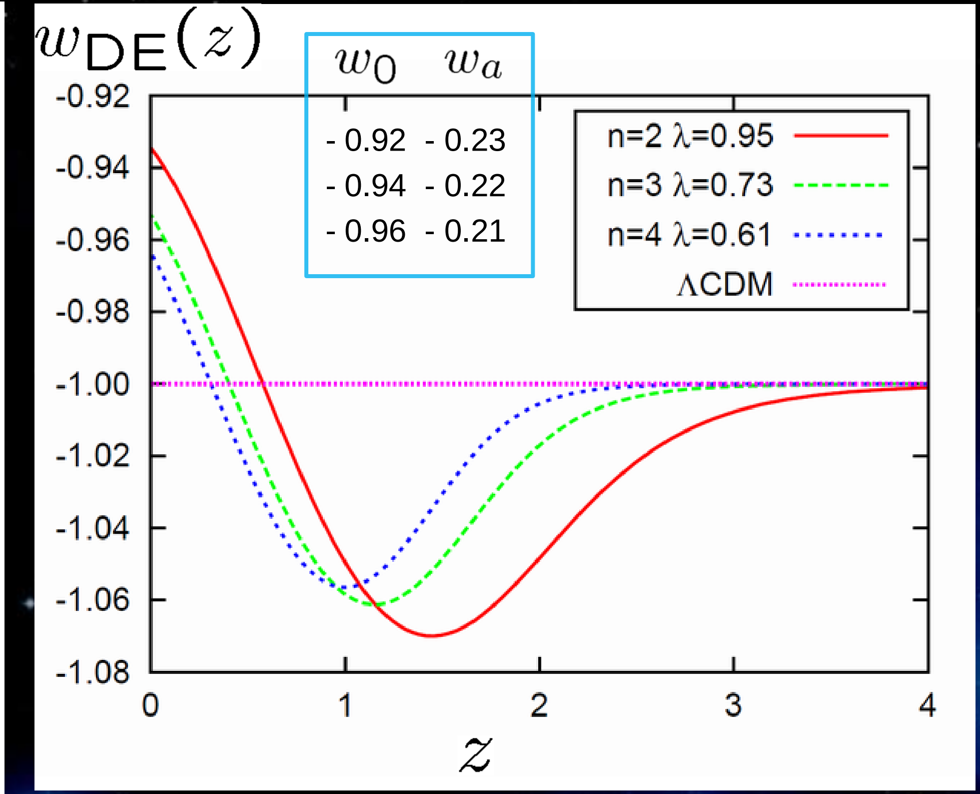
Solar system test

Time variation of EoS parameter $w \equiv P/\rho$

$$w_{\rm DE} = w_0 + \frac{w_a z}{1+z}$$



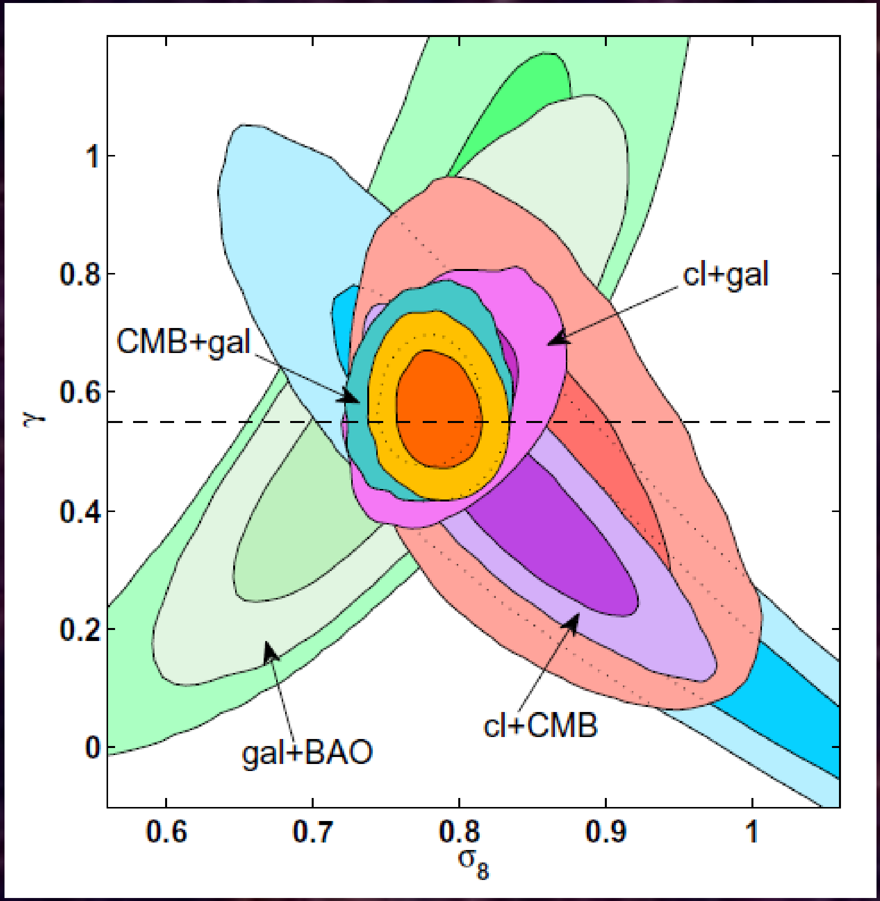
Komatsu et al.,
APJ Suppl. 192, 18 (2011)
[arXiv:1001.4538]

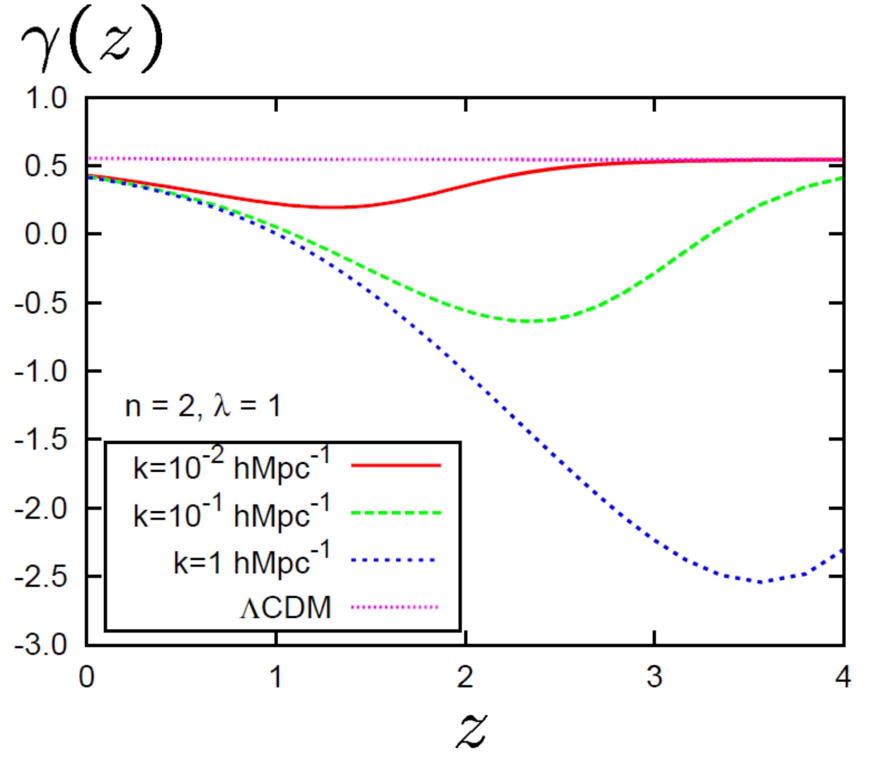


H.M., Starobinsky, Yokoyama
PTP 123 (2010) 887 [arXiv:1002.1141]

Growth index $\gamma(z)$

$$\frac{d\log\delta}{d\log a} = \Omega_m(z)^{\gamma(z)}$$

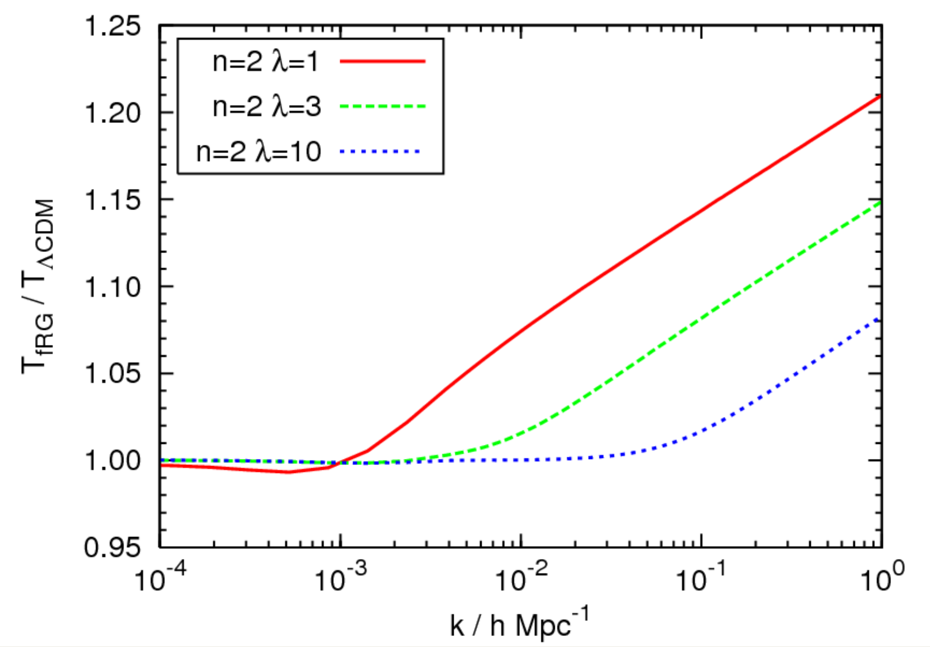


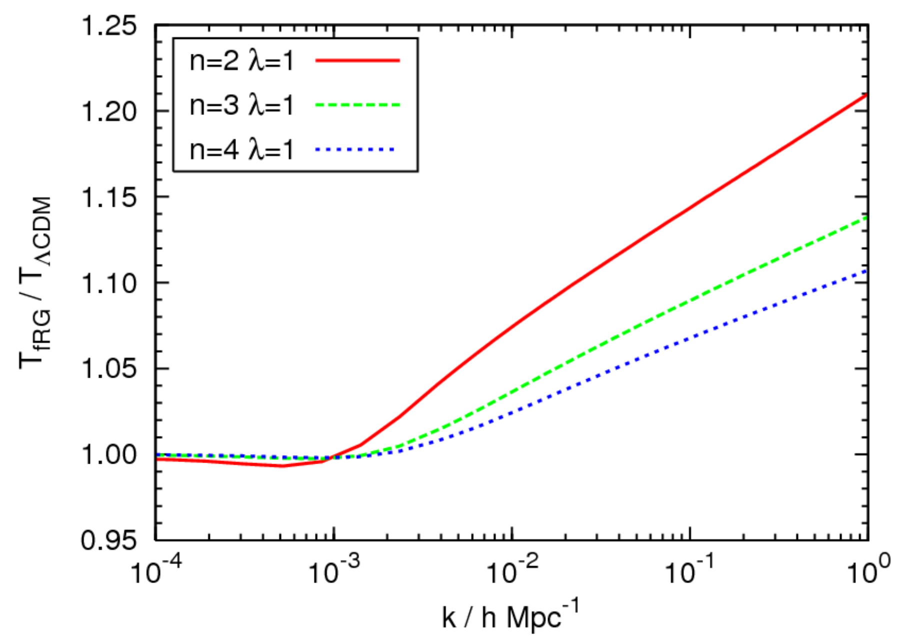


H.M., Starobinsky, Yokoyama
PTP 123 (2010) 887 [arXiv:1002.1141]

Rapetti et al., arXiv: 1205.4679

Additional transfer function in $f(R)$ gravity





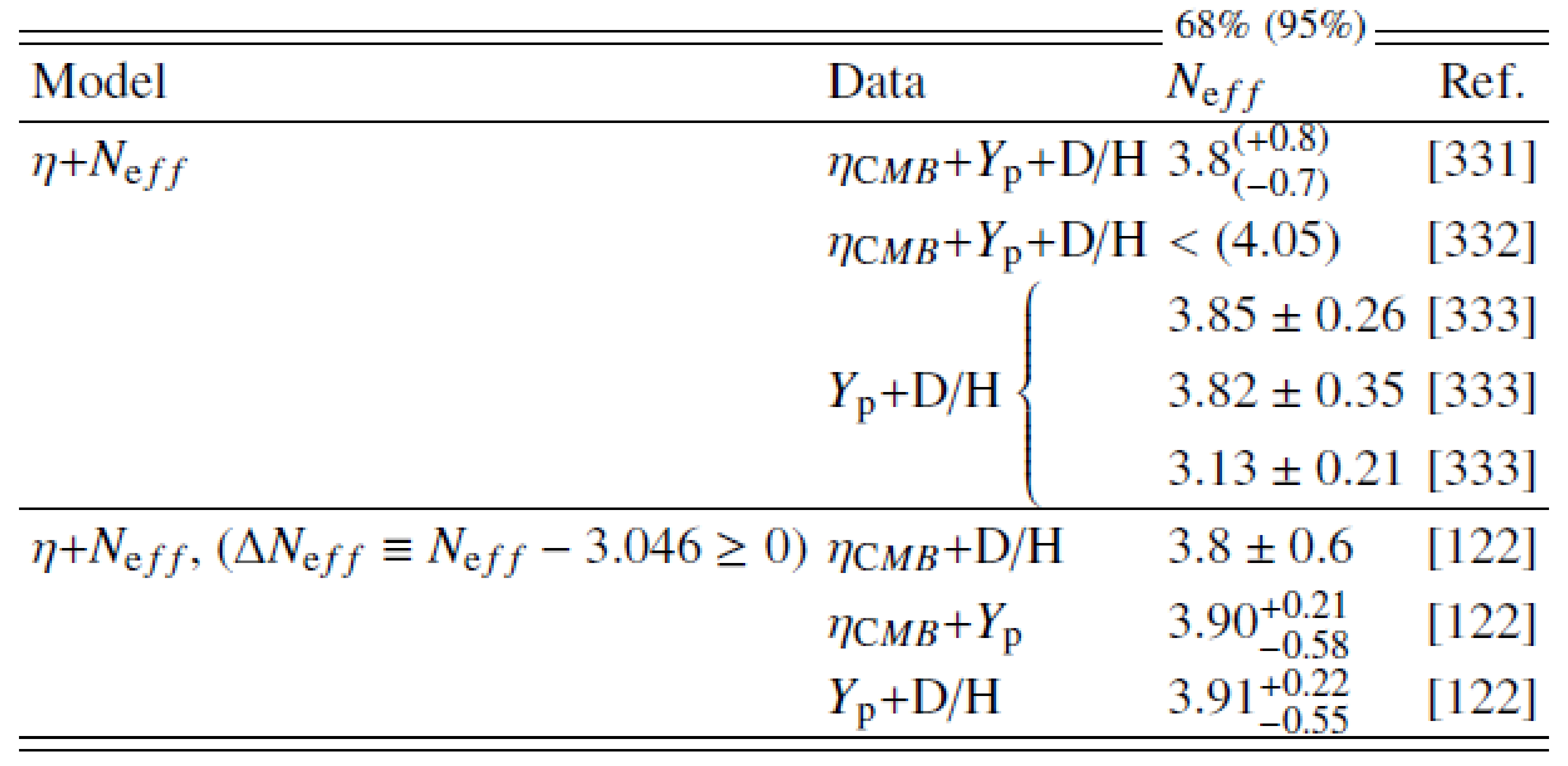
$f(R)$ gravity enhances matter power spectrum.

↕ cancel

Massive neutrino suppresses matter power spectrum.

Constraint on N_{eff} from BBN

Abazajian et al [arXiv:1204.5379]



Model	Data	68% (95%) N_{eff}	Ref.
η+N_{eff}	η_{CMB}+$Y_{\rm p}$+D/H	$3.8^{(+0.8)}_{(-0.7)}$	[331]
	η_{CMB}+$Y_{\rm p}$+D/H	$<(4.05)$	[332]
	$Y_{\rm p}$+D/H	3.85 ± 0.26	[333]
		3.82 ± 0.35	[333]
		3.13 ± 0.21	[333]
η+N_{eff}, $(\Delta N_{eff} \equiv N_{eff} - 3.046 \geq 0)$	η_{CMB}+D/H	3.8 ± 0.6	[122]
	η_{CMB}+$Y_{\rm p}$	$3.90^{+0.21}_{-0.58}$	[122]
	$Y_{\rm p}$+D/H	$3.91^{+0.22}_{-0.55}$	[122]

[331] Izotov, Thuan, Astrophys.J. 710, L67 (2010) [arXiv:1001.4440]

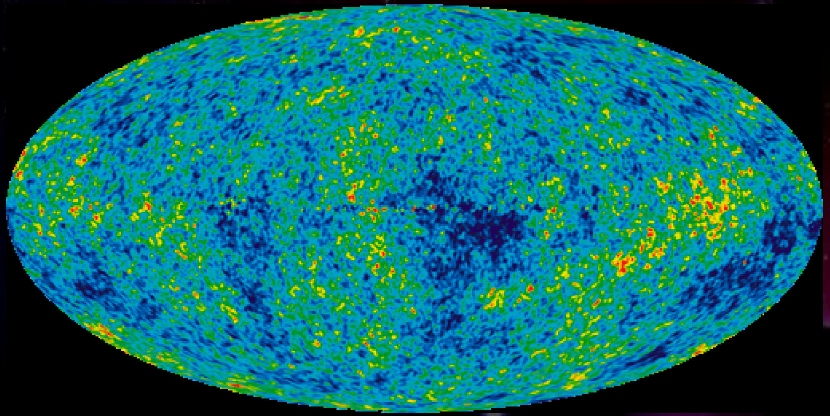
[332] Mangano,Serpico, Phys.Lett. B701, 296 (2011) [arXiv:1103.1261]

[333] Nollett, Holder [arXiv:1112.2683]

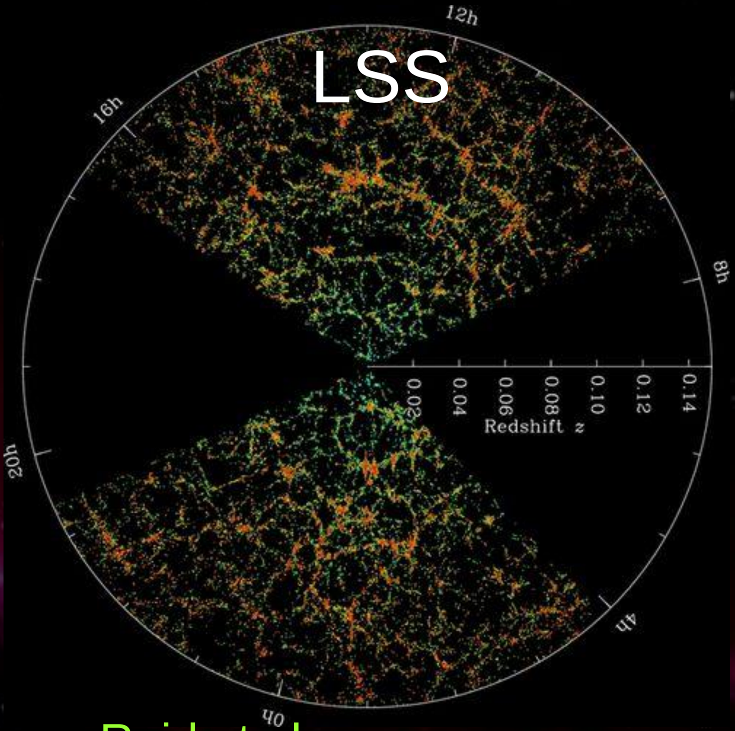
[122] Hamann et al, JCAP 1109, 034 (2011) [arXiv:1108.4136]

Constraints on $N_{\rm eff}$ and $\sum m_\nu$ in ΛCDM

CMB



LSS



Komatsu et al.,
APJ Suppl. 192, 18 (2011)
[arXiv:1001.4538]

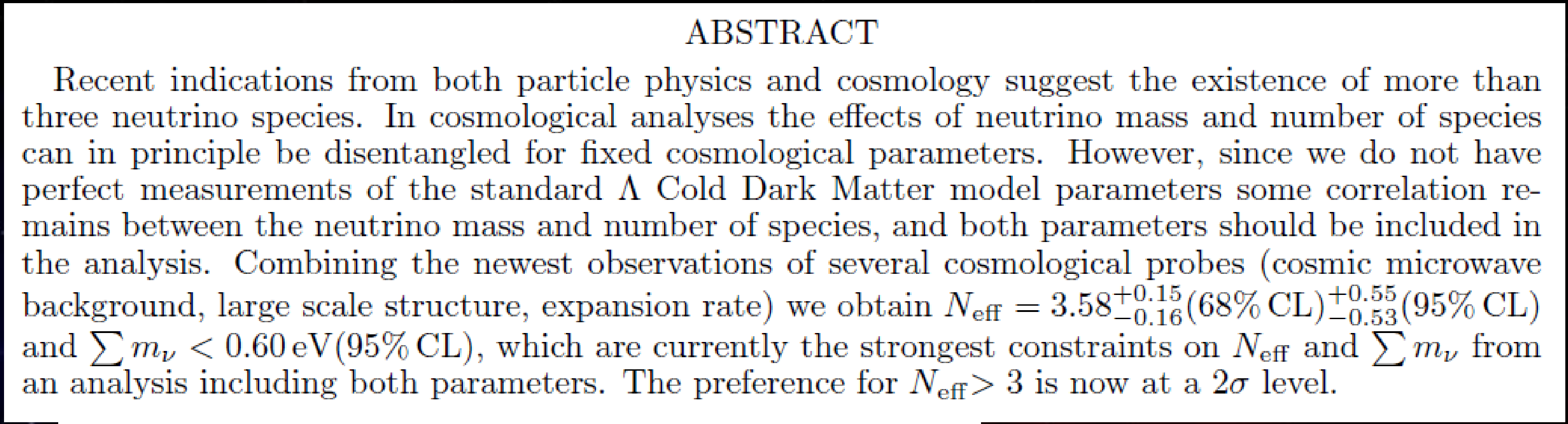
+
ΛCDM
⇓

Reid et al,
Mon.Not.Roy.Astron.Soc. 404
(2010) 60 [arXiv:0907.1659]

$$\sum m_\nu < 0.44\mathrm{eV} \quad (95\%\ \mathrm{CL})$$

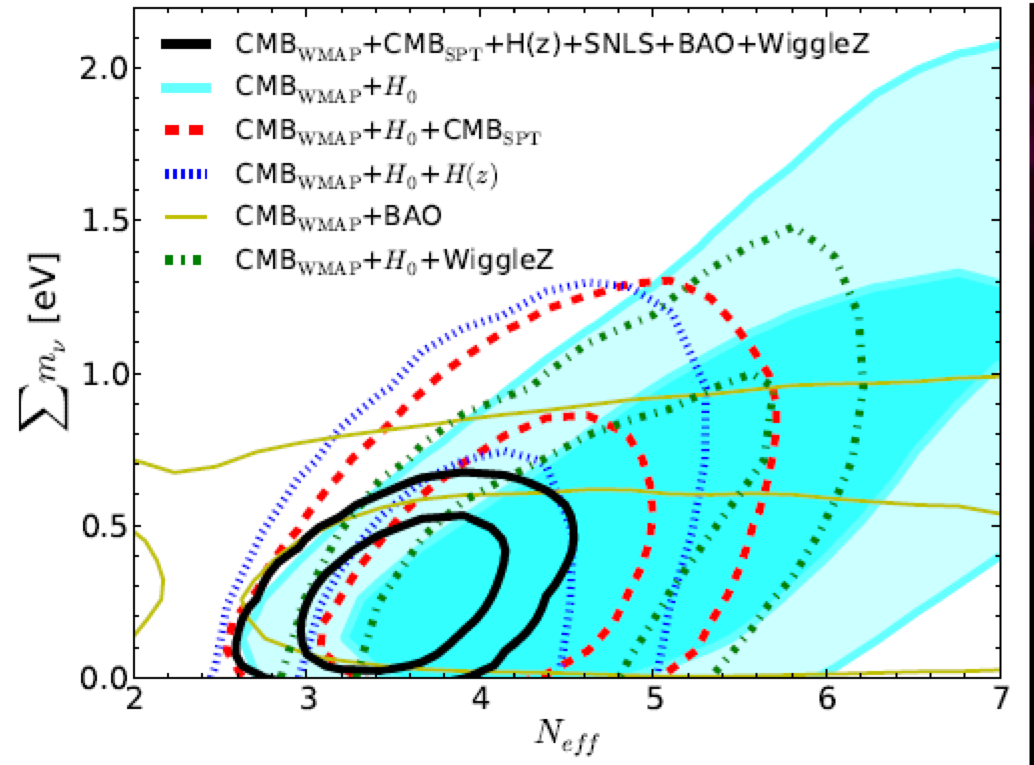
$$N_{\rm eff} = 4.34^{+0.86}_{-0.88} \quad (68\%\ \mathrm{CL})$$

Constraints on N_{eff} and $\sum m_\nu$ in ΛCDM



ABSTRACT

Recent indications from both particle physics and cosmology suggest the existence of more than three neutrino species. In cosmological analyses the effects of neutrino mass and number of species can in principle be disentangled for fixed cosmological parameters. However, since we do not have perfect measurements of the standard Λ Cold Dark Matter model parameters some correlation remains between the neutrino mass and number of species, and both parameters should be included in the analysis. Combining the newest observations of several cosmological probes (cosmic microwave background, large scale structure, expansion rate) we obtain $N_{\mathrm{eff}} = 3.58^{+0.15}_{-0.16}(68\%\,\mathrm{CL})^{+0.55}_{-0.53}(95\%\,\mathrm{CL})$ and $\sum m_\nu < 0.60\,\mathrm{eV}(95\%\,\mathrm{CL})$, which are currently the strongest constraints on N_{eff} and $\sum m_\nu$ from an analysis including both parameters. The preference for $N_{\mathrm{eff}} > 3$ is now at a 2σ level.



Riemer-Sorensen et al
[arXiv:1210.2131]

ΛCDM cosmology

⇓

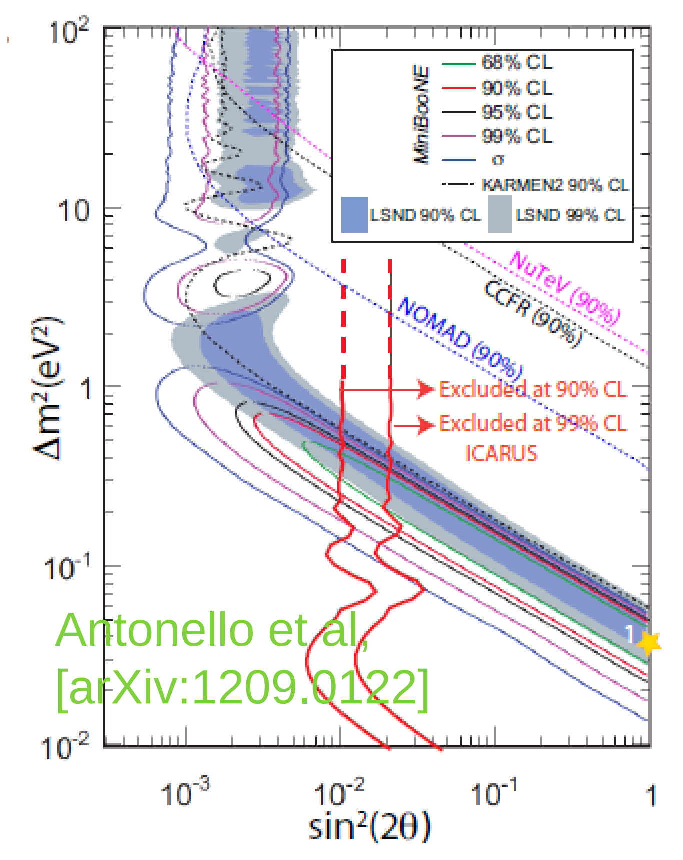
sub-eV

sterile neutrino

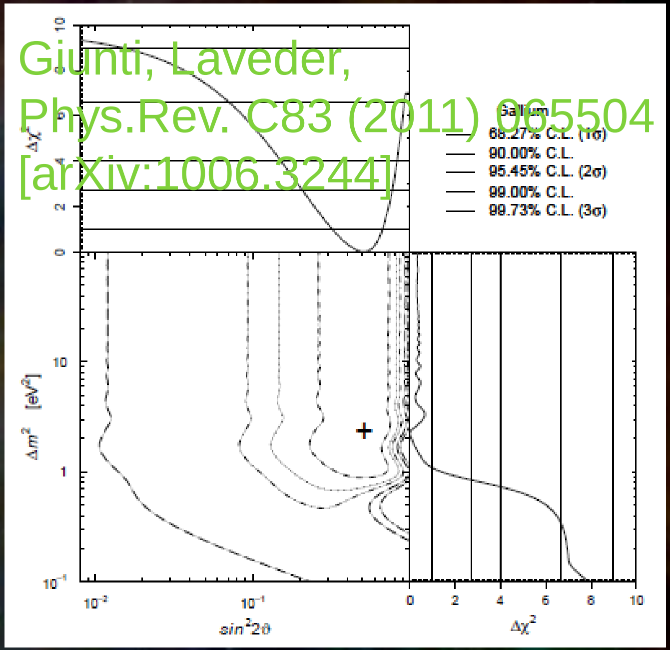
Neutrino oscillation

Sterile neutrino mass $\gtrsim$ 1 eV

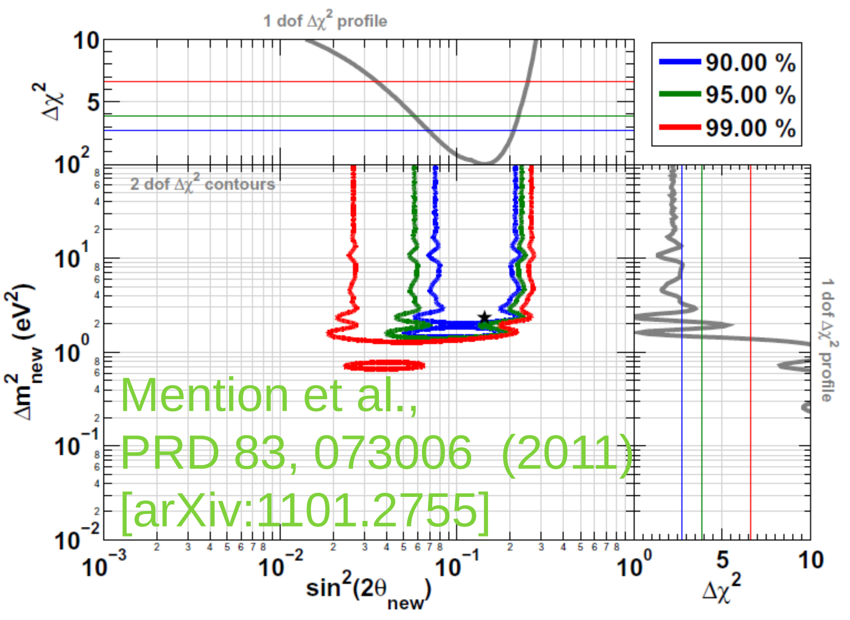
⇔ ΛCDM model



Antonello et al, [arXiv:1209.0122]



Giunti, Laveder, Phys.Rev. C83 (2011) 065504 [arXiv:1006.3244]

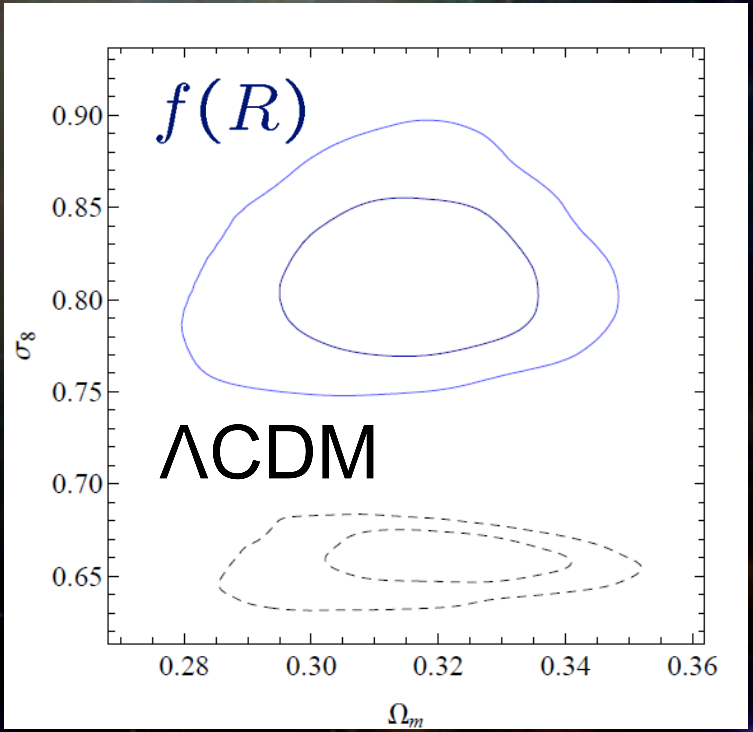


Mention et al., PRD 83, 073006 (2011) [arXiv:1101.2755]

MCMC analysis: ΛCDM vs $f(R)$ gravity

H.M., Starobinsky and Yokoyama, arXiv:1203.6828

- 3 massless and 1 massive neutrino with mass = 1 eV
- WMAP7, SDSS DR 7 $(0.02h\text{Mpc}^{-1} \le k \le 0.08h\text{Mpc}^{-1})$
- Better fit : $\Delta\chi^2 = 10.7$ (ΔAIC = 8.7)
- GR : $\sigma_8 = 0.661^{+0.023}_{-0.027}$, $f(R)$: $\sigma_8 = 0.815^{+0.105}_{-0.066}$



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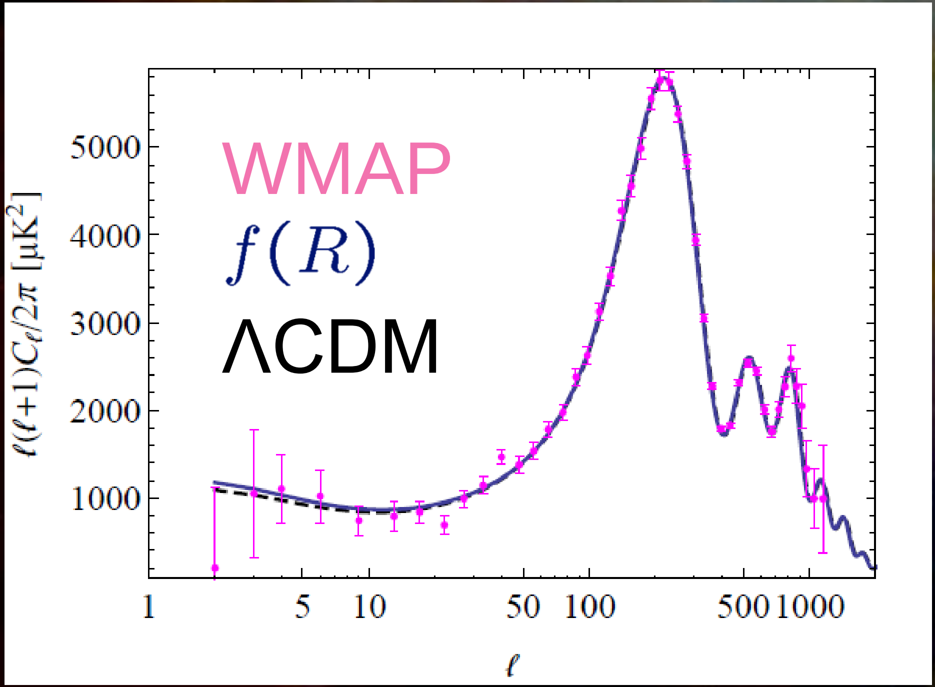

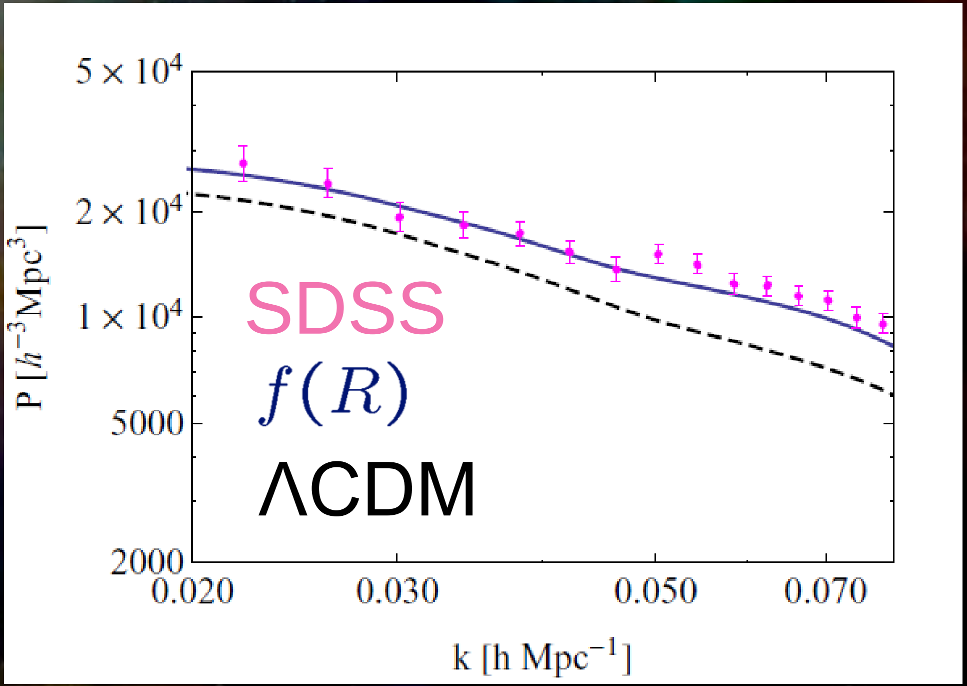

Summary

- Cosmology based on ΛCDM model

  Sterile neutrino mass $<$ 1 eV

- Neutrino oscillation experiments

  Sterile neutrino mass $\gtrsim$ 1 eV

- $f(R)$ gravity can resolve the tension.