Cosmology in $f(R)$ gravity with massive neutrinos

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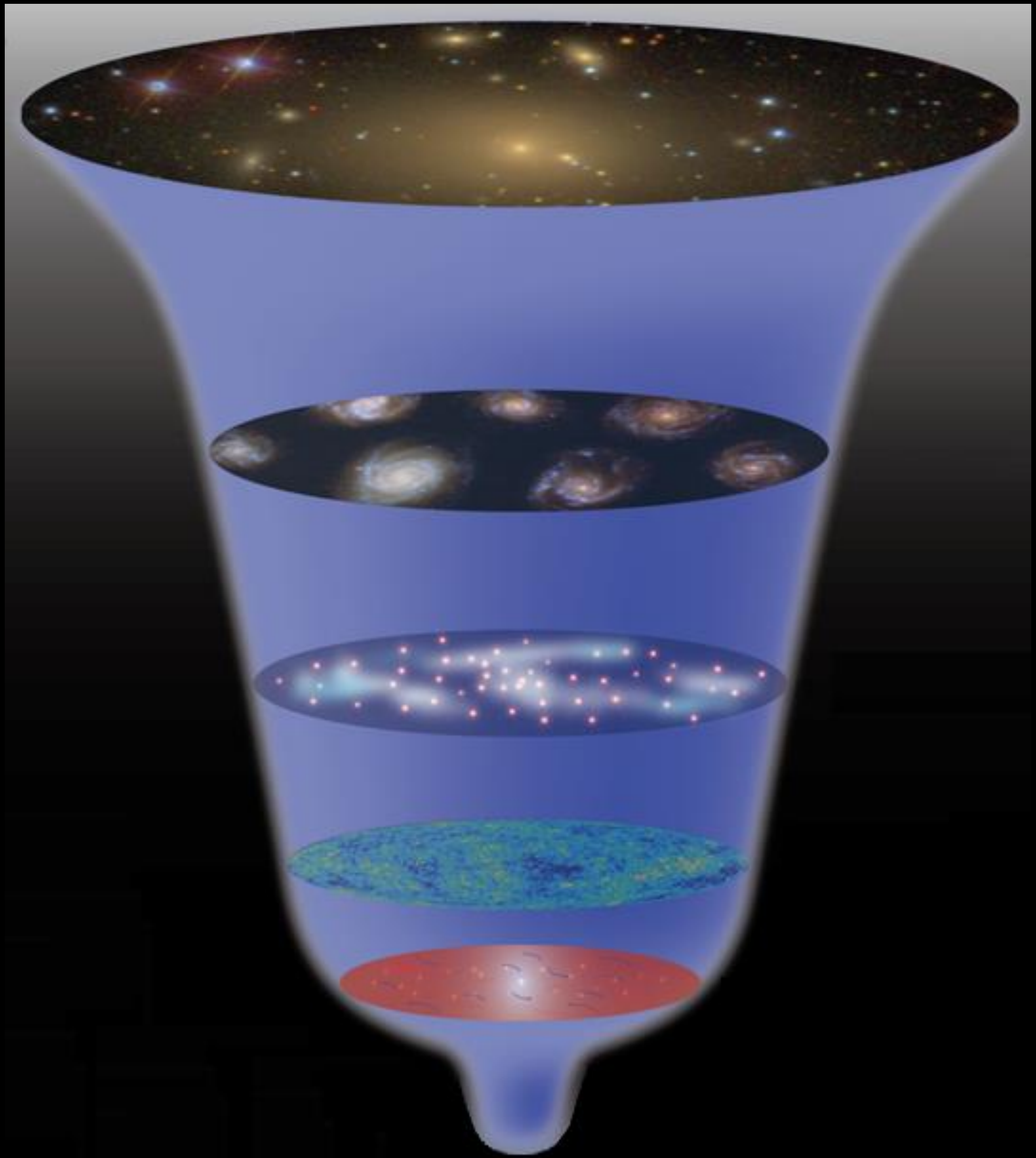
Accelerating Universe



Late-time acceleration

- Λ
- ϕ
- Modified gravity

Inflation

$f(R)$ gravity

cf. ΛCDM model

$$f(R) = R - 2\Lambda$$

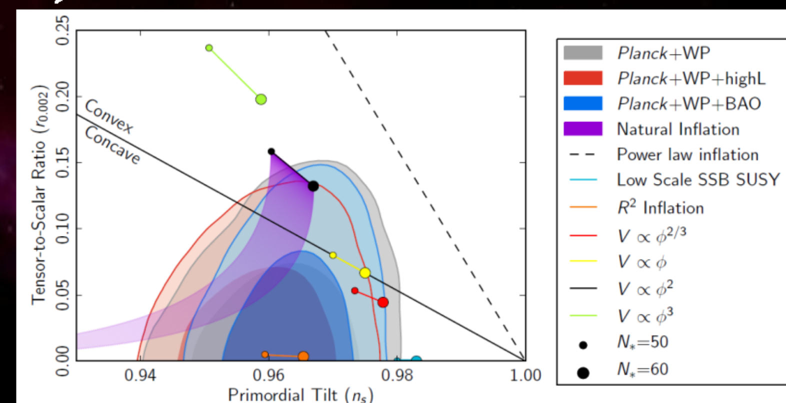
can explain accelerated expansion

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

Simple, no-ghost, and nonperturbative extension of GR.

New scalar dof: scalaron with mass $(3f'')^{-1/2}$.

Planck 2013 results XXII



- Inflation Starobinsky (1980)

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

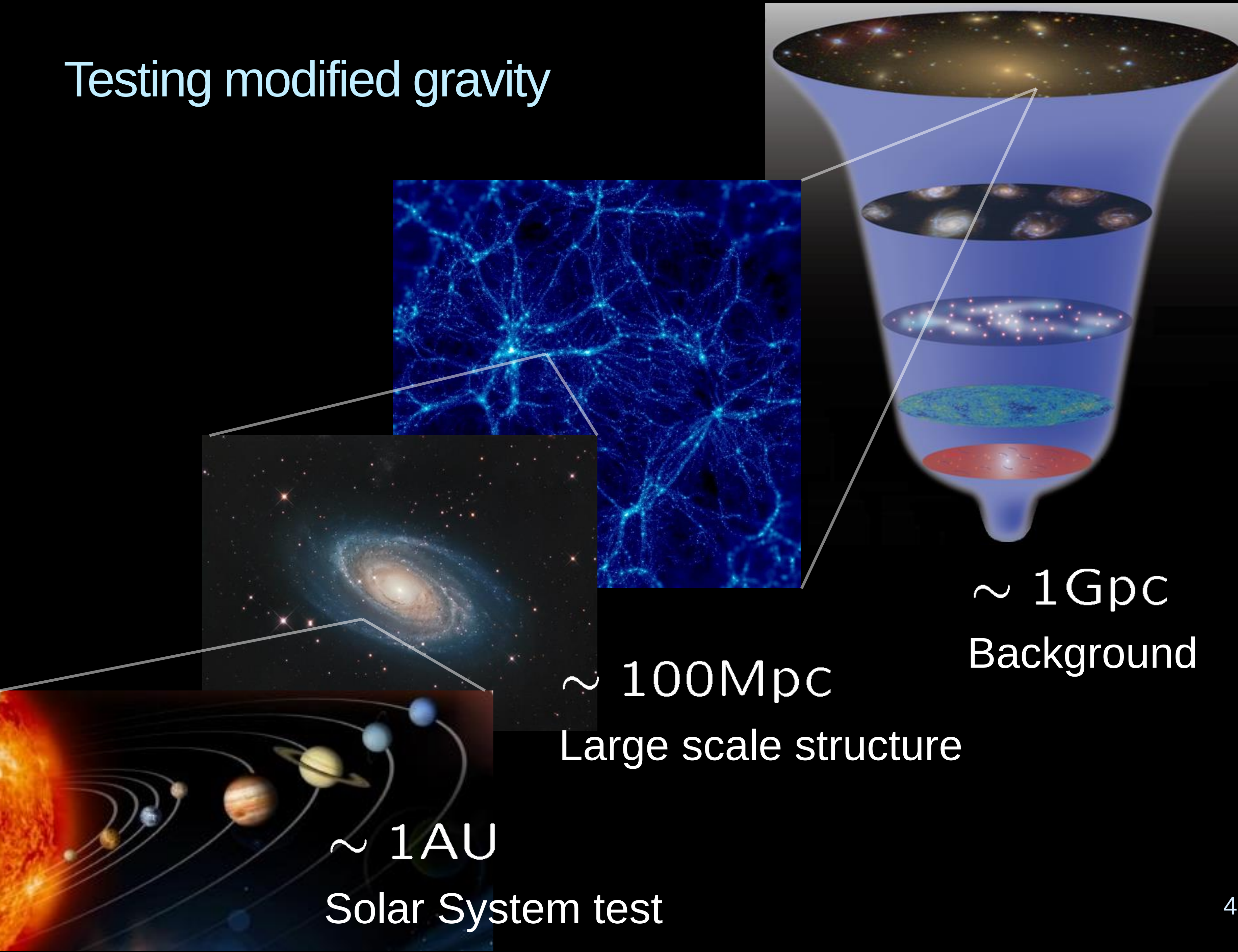
- Late-time acceleration Starobinsky (2007)

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

cf.
Hu, Sawicki (2007)
Appleby, Battye (2007)

- Combined $f(R)$ model Appleby, Battye, Starobinsky (2007)
H.M., Nishizawa (2012)

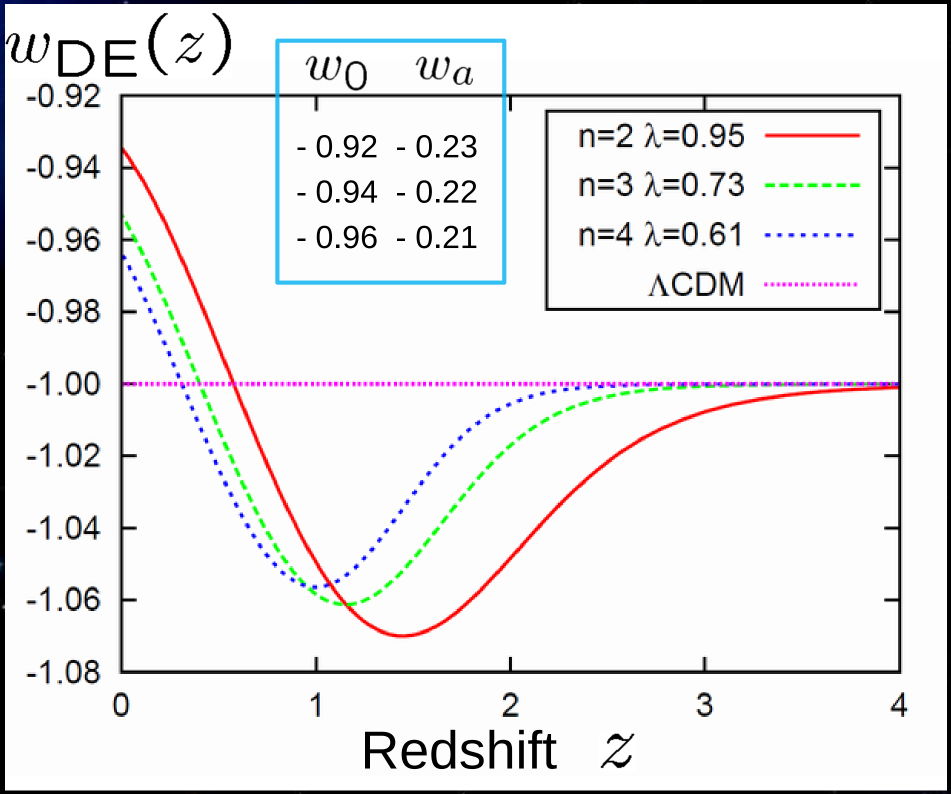
Testing modified gravity



Time evolution of EoS parameter

$f(R)$ gravity exhibits phantom crossing.

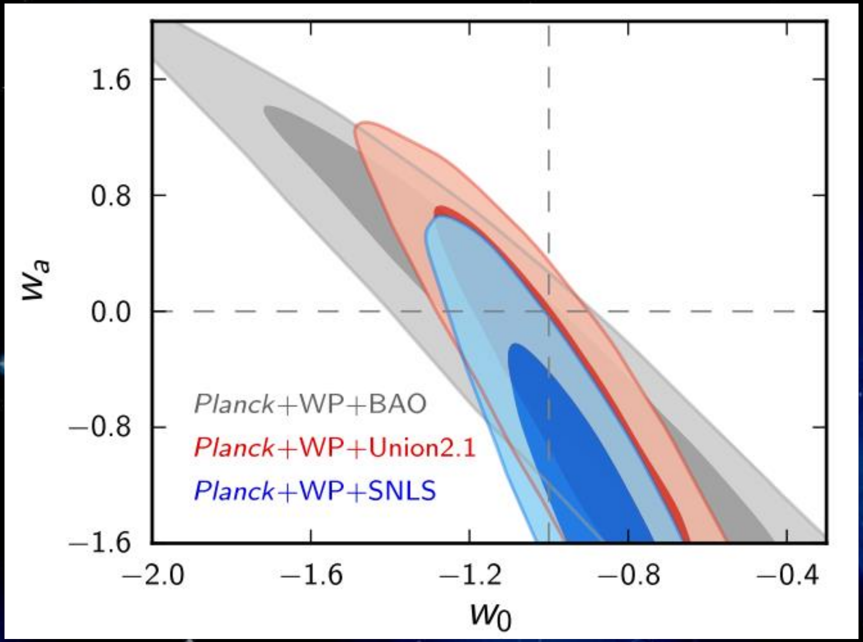
At this moment, we cannot distinguish it with the ΛCDM model.



H.M., Starobinsky, Yokoyama (2010)
H.M., Starobinsky, Yokoyama (2011)

Chevallier, Polarski (2001)
Linder (2003)

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



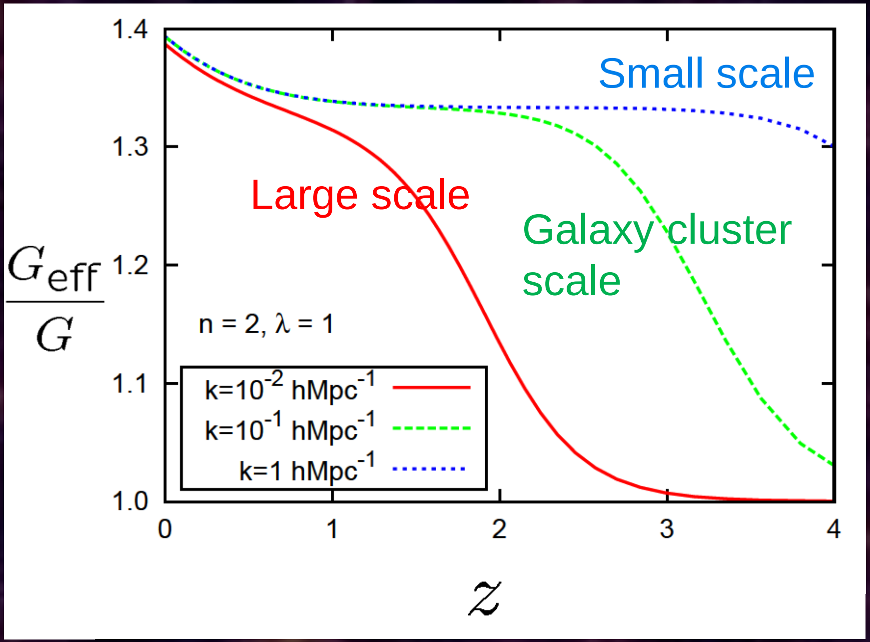
Ade et al., Planck 2013 results XVI

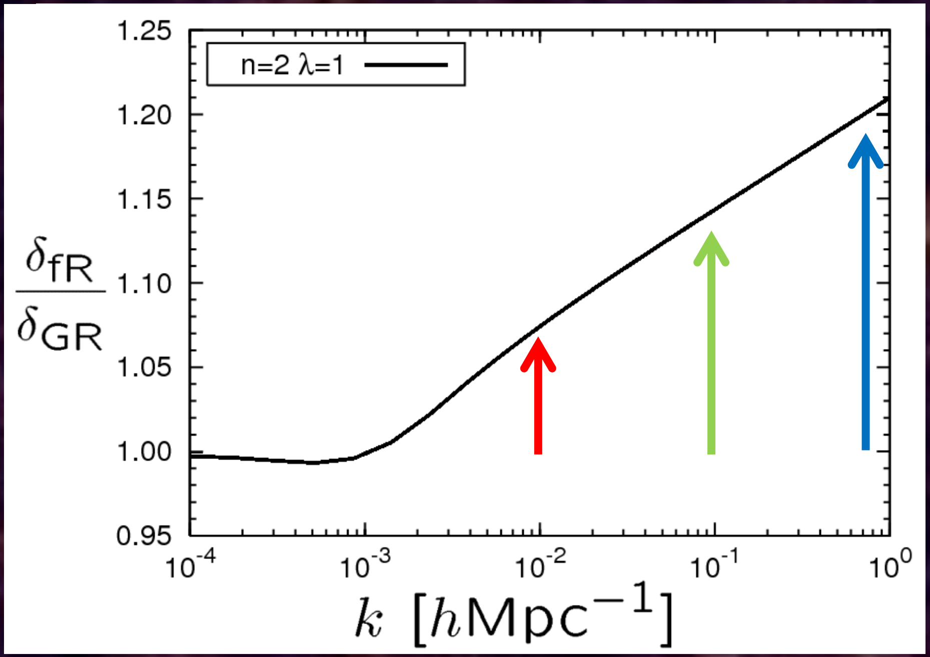
Evolution of small scale density perturbations

$f(R)$ gravity enhances evolution of density perturbations on small scales.

$\Longleftrightarrow$ Evolution of growth index γ

Opposite to the effect of massive neutrinos $\sum m_\nu$





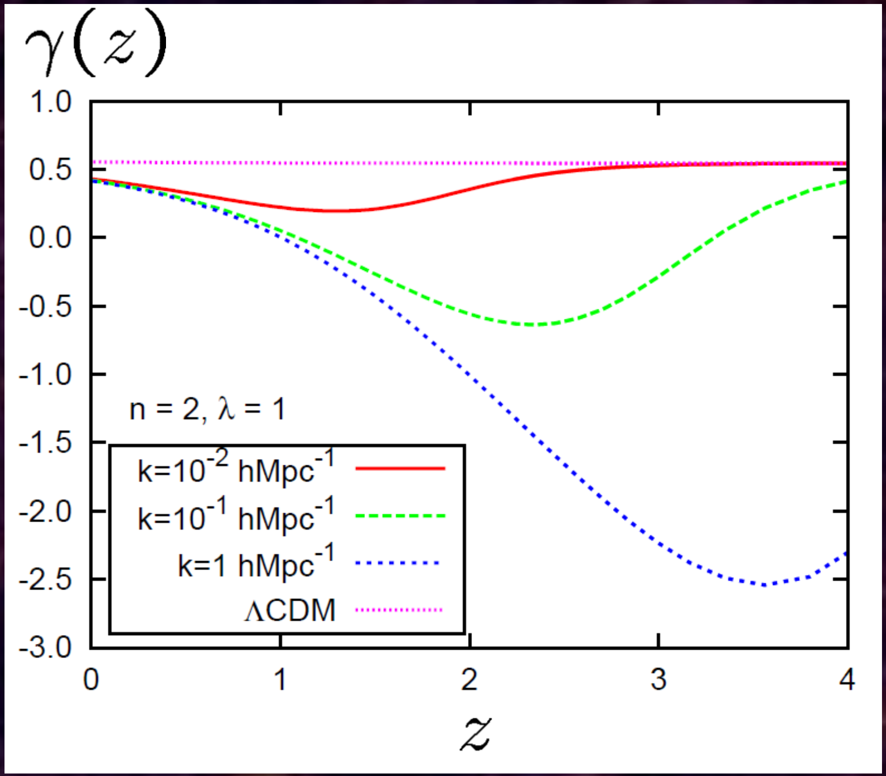
cf. ΛCDM
$\gamma \simeq 0.55$

Growth index $\gamma(z)$

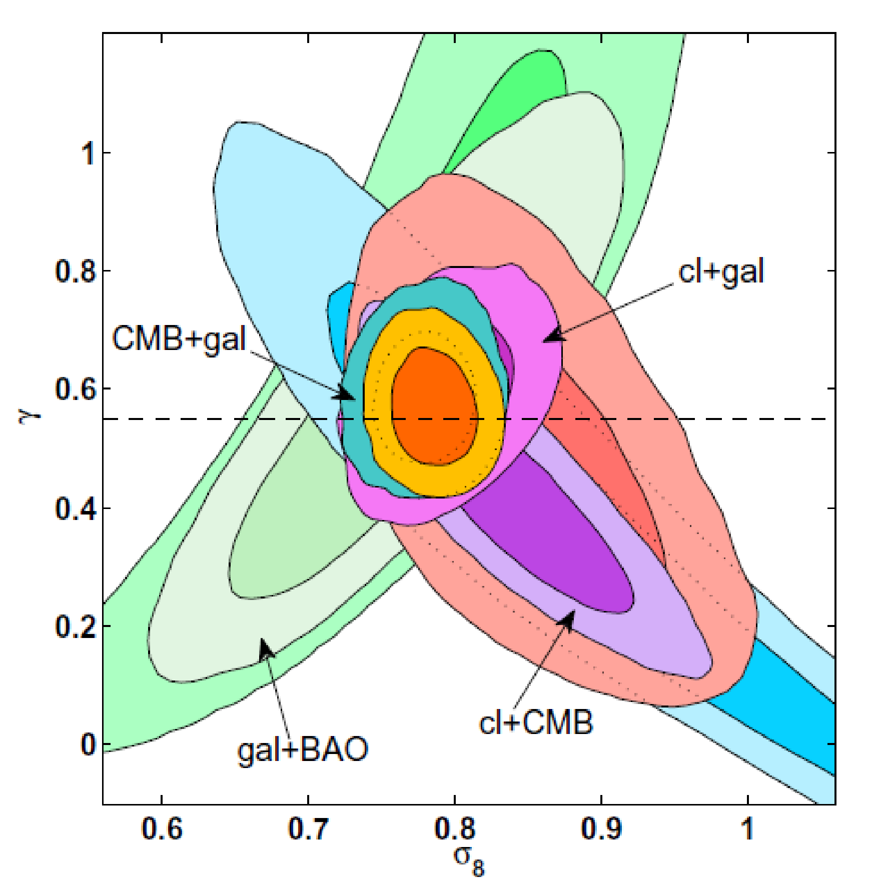
Peebles (1984)

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

Growth index depends on time and scale in $f(R)$ gravity.



H.M., Starobinsky, Yokoyama (2010)

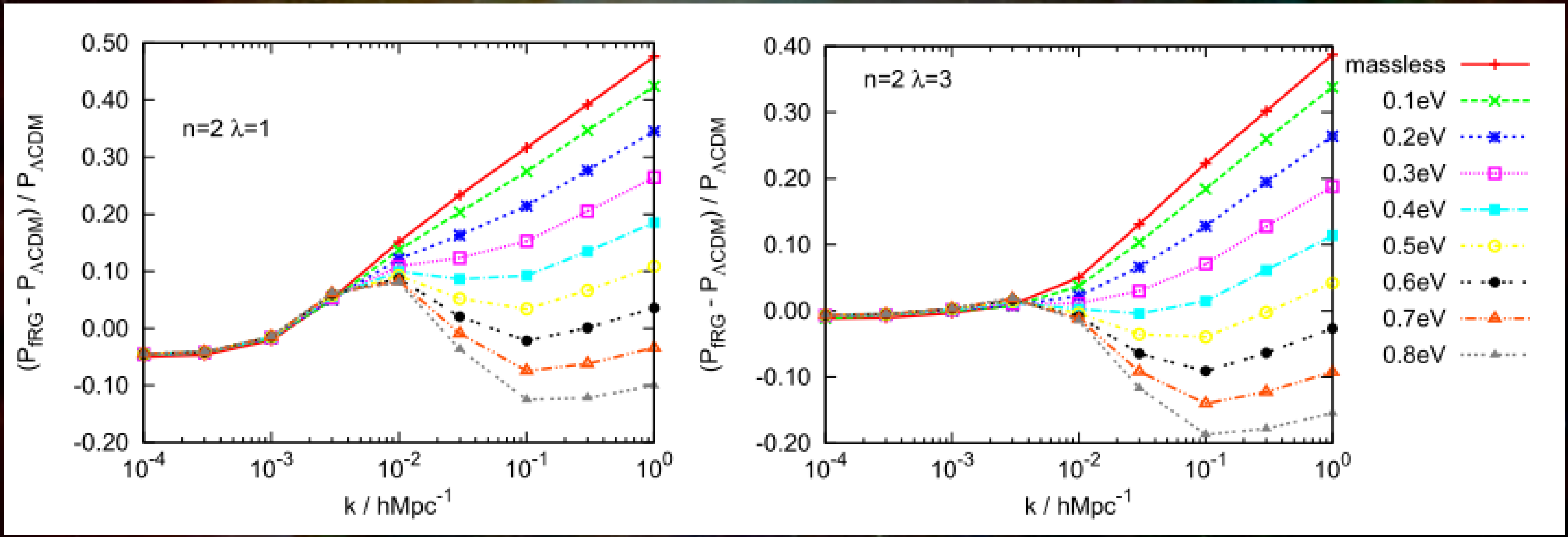


Rapetti et al. (2012)

Free streaming damping by massive neutrinos

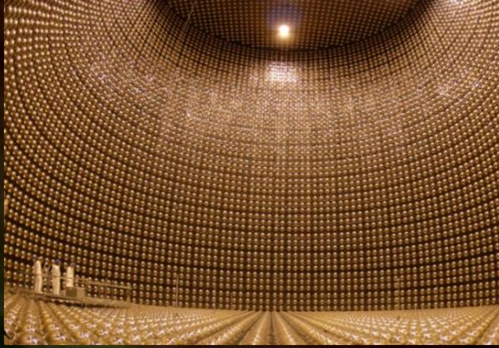
H.M., Starobinsky, Yokoyama (2010)

Effects of massive neutrino and $f(R)$ gravity on small-scale perturbations cancel.



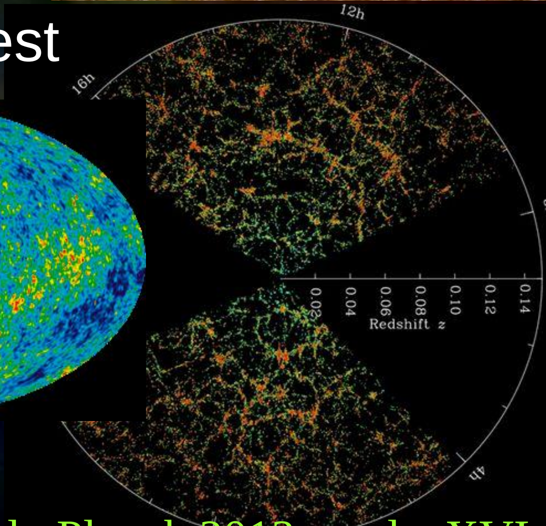
- Massive neutrino relaxes constraint on $f(R)$ gravity.
- $f(R)$ gravity admits heavier neutrino than ΛCDM model.

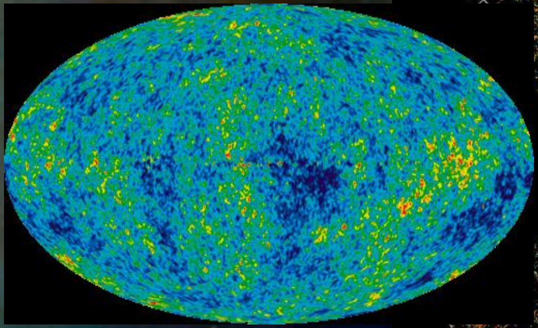
Mass and effective number of neutrino



- Particle Physics

- Standard Model: massless 3 generation
- Solar and atmospheric neutrino oscillation suggest neutrino has a small mass.

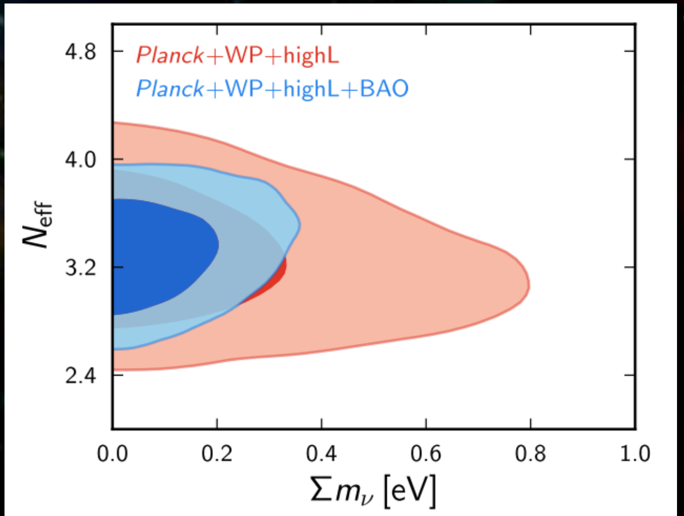




- Cosmology

- Contribute to the expansion rate
  ⇨ BBN, CMB
- Free streaming
  ⇨ Massive neutrino suppresses matter perturbations on small scales.

Ade et al., Planck 2013 results XVI



Constraints in GR

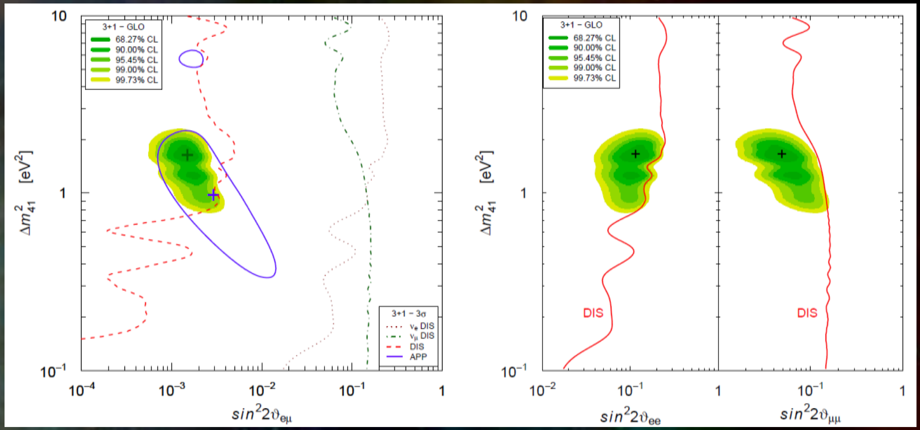
$$N_{\rm eff} = 3.30 \pm 0.27$$

$$\sum m_\nu < 0.23\ \mathrm{eV}\ \ (95\% CL)$$

Mass and effective number of neutrino

- Cosmology

Giunti et al. 1308.5288



Constraints in GR

$$N_{\rm eff} = 3.30 \pm 0.27$$

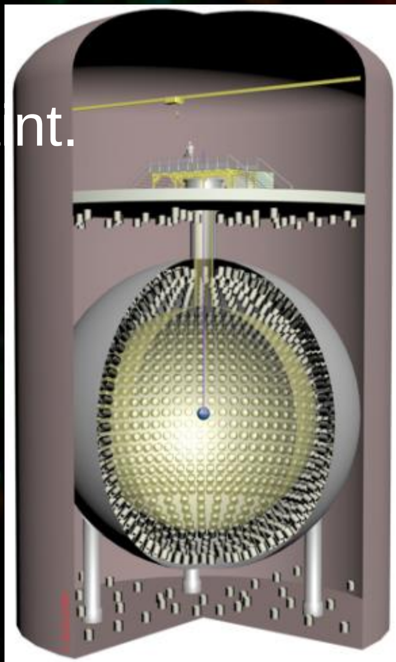
$$\sum m_\nu < 0.23 \text{ eV } (95\% CL)$$

$N_{\rm eff}$: Effective # of relativistic dof

- Particle physics

- Neutrino oscillation experiments (short baseline, reactor, gallium)

⇨ Sterile neutrino with $m_\nu \gtrsim 1$ eV



Mass seems inconsistent with the cosmological constraint.

(Still, high-precision experiments are needed.)

GR and particle physics are inconsistent?

⇩

Modified gravity admits heavier neutrino because of small-scale enhancement on δ .

“Cosmology Based on $f(R)$ Gravity Admits 1 eV Sterile Neutrinos”

H.M., A. Starobinsky, J. Yokoyama
PRL 110 (2013) 12, 121302
[arXiv:1203.6828].

MCMC analysis: ΛCDM model vs $f(R)$ gravity

H.M., Starobinsky, Yokoyama (2013)

Setup

see also Wyman et al. (2013)

- Background $=$ ΛCDM / ΛCDM
- Perturbation $=$ ΛCDM / $f(R)$ gravity

Hojjati et al. (2011)

(Implement $f(R)$ to MGCAMB and connect it to CosmoMC)

- 3 standard massless neutrino species
- + 1 sterile neutrino with a mass of 1 eV $\Omega_\nu h^2 = \frac{m_\nu}{94.1\mathrm{eV}}$

(Thermalized through neutrino oscillation before decoupling)

Kainulainen (1990)

- Parameters： $\Omega_{\mathrm{DM}}h^2, \Omega_b h^2, \theta_*, \tau, n_s, \ln(10^{10}A_s), A_{\mathrm{SZ}}, b_0$

λ $(n = 2 \text{ fix})$

Galaxy bias

- Observational data：WMAP7, SDSS DR 7 LRG

1 additional floating parameter

$(0.02h\mathrm{Mpc}^{-1} \leq k \leq 0.08h\mathrm{Mpc}^{-1})$

Nonlinear effect is negligible.

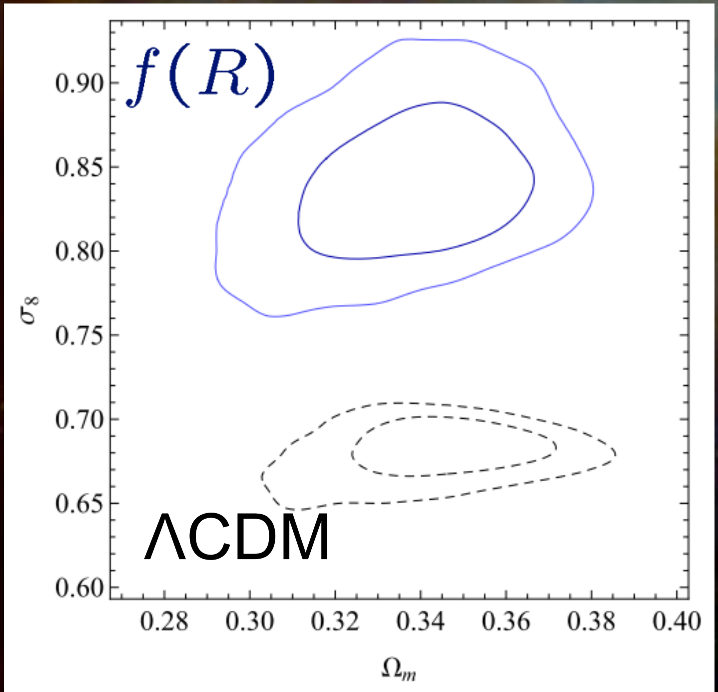
MCMC analysis: ΛCDM model vs $f(R)$ gravity

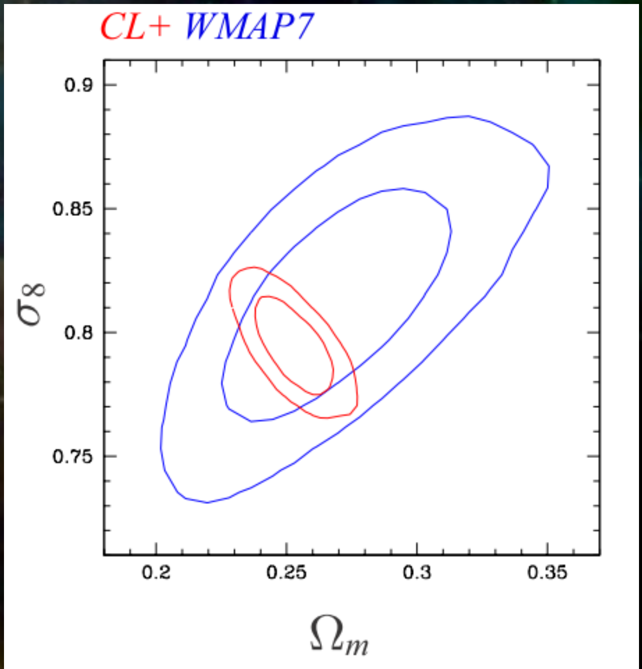
H.M., Starobinsky, Yokoyama (2013)

Results

- ΛCDM model $\sigma_8 = 0.661^{+0.023}_{-0.027}$
  $f(R)$ gravity $\sigma_8 = 0.815^{+0.105}_{-0.066}$
- For the best fit parameter, $\Delta\chi^2$ = -9.55（ΔAIC＝-7.55）

$f(R)$ gravity is favored.





Burenin, Vikhlinin (2012)

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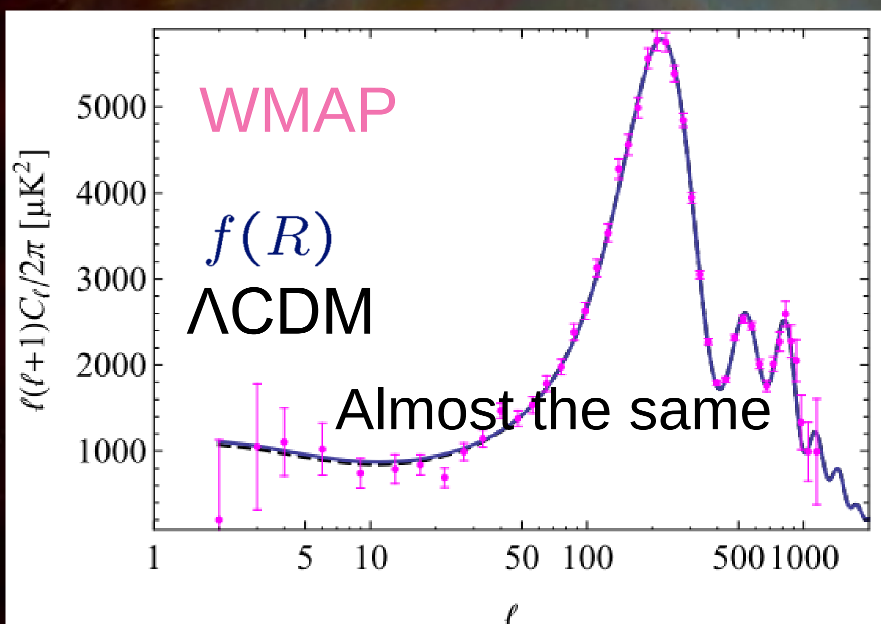

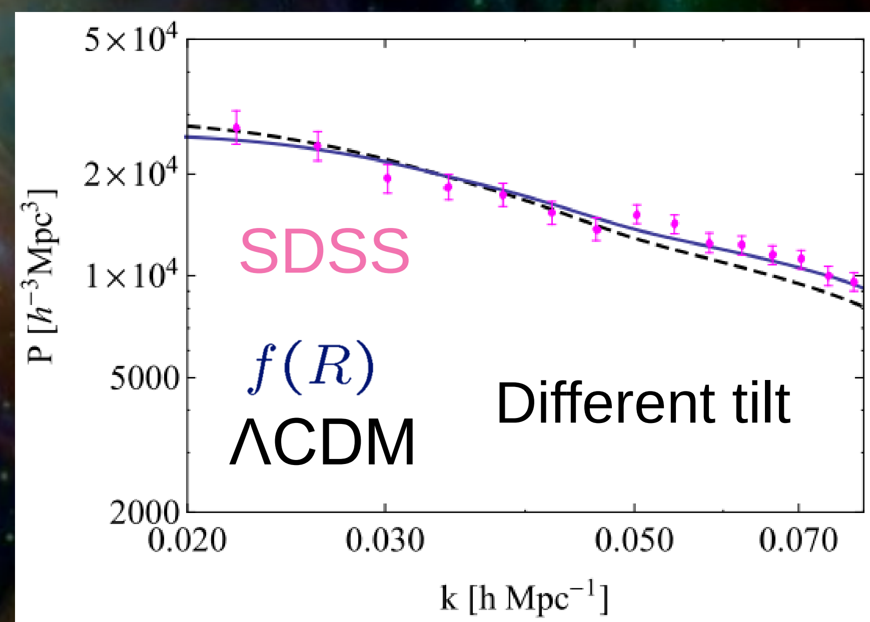

Summary

Late-time cosmic acceleration

1 eV sterile neutrino

Background

w

✖ ΛCDM model

○ $f(R)$ gravity

Perturbation

$\delta \quad \gamma \quad \sum m_\nu$

If future experiments establish 1 eV sterile neutrino, we need modification of gravity to resolve the tension between cosmology and particle physics.