Inflation, Dark matter, Dark Energy, models

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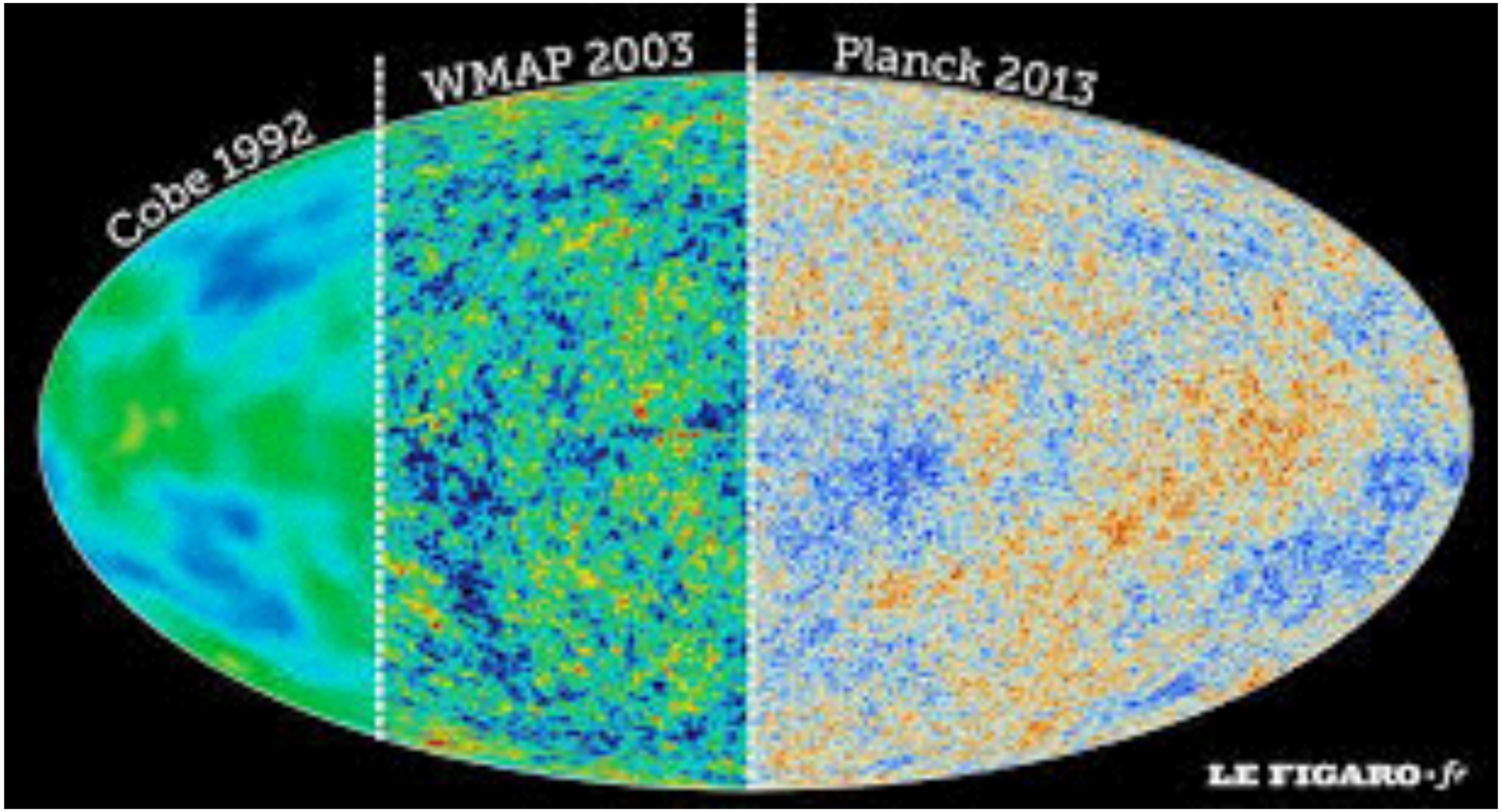
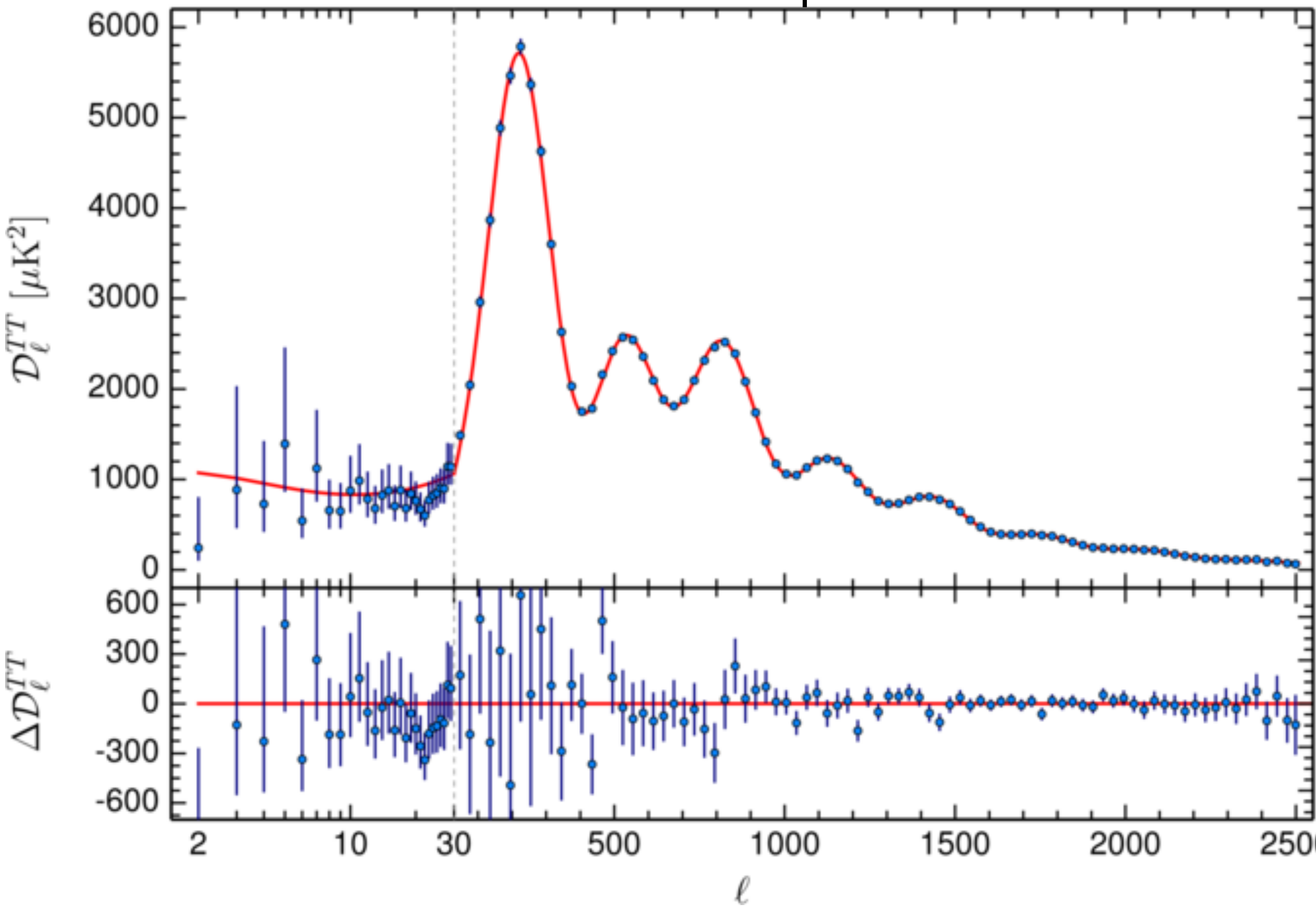
CMB Anisotropy

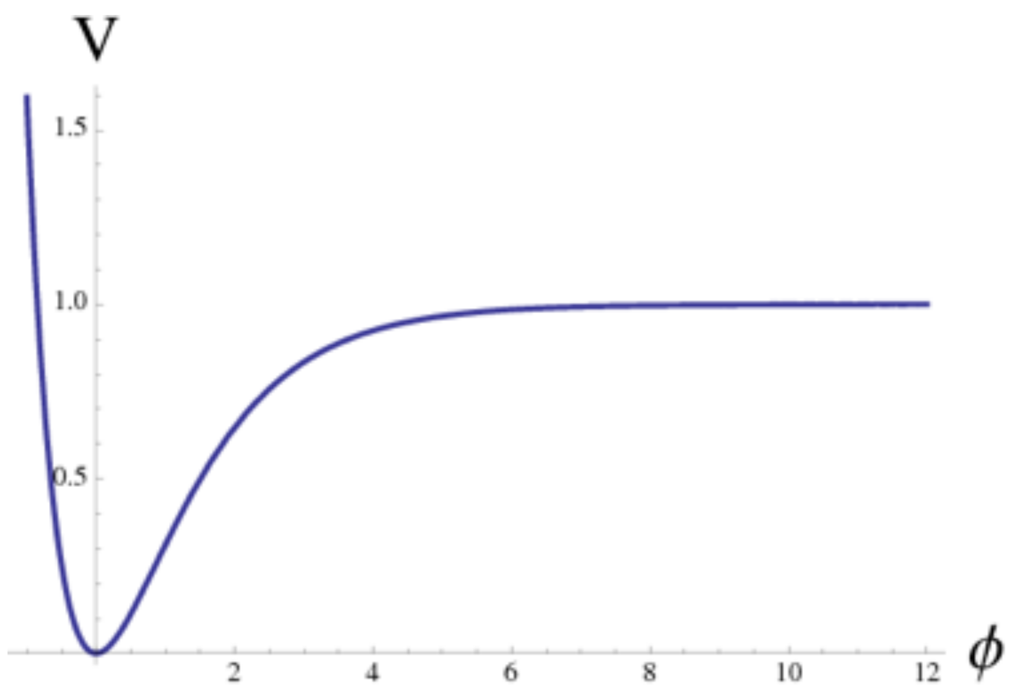


Planck TT spectrum



Inflaton potential

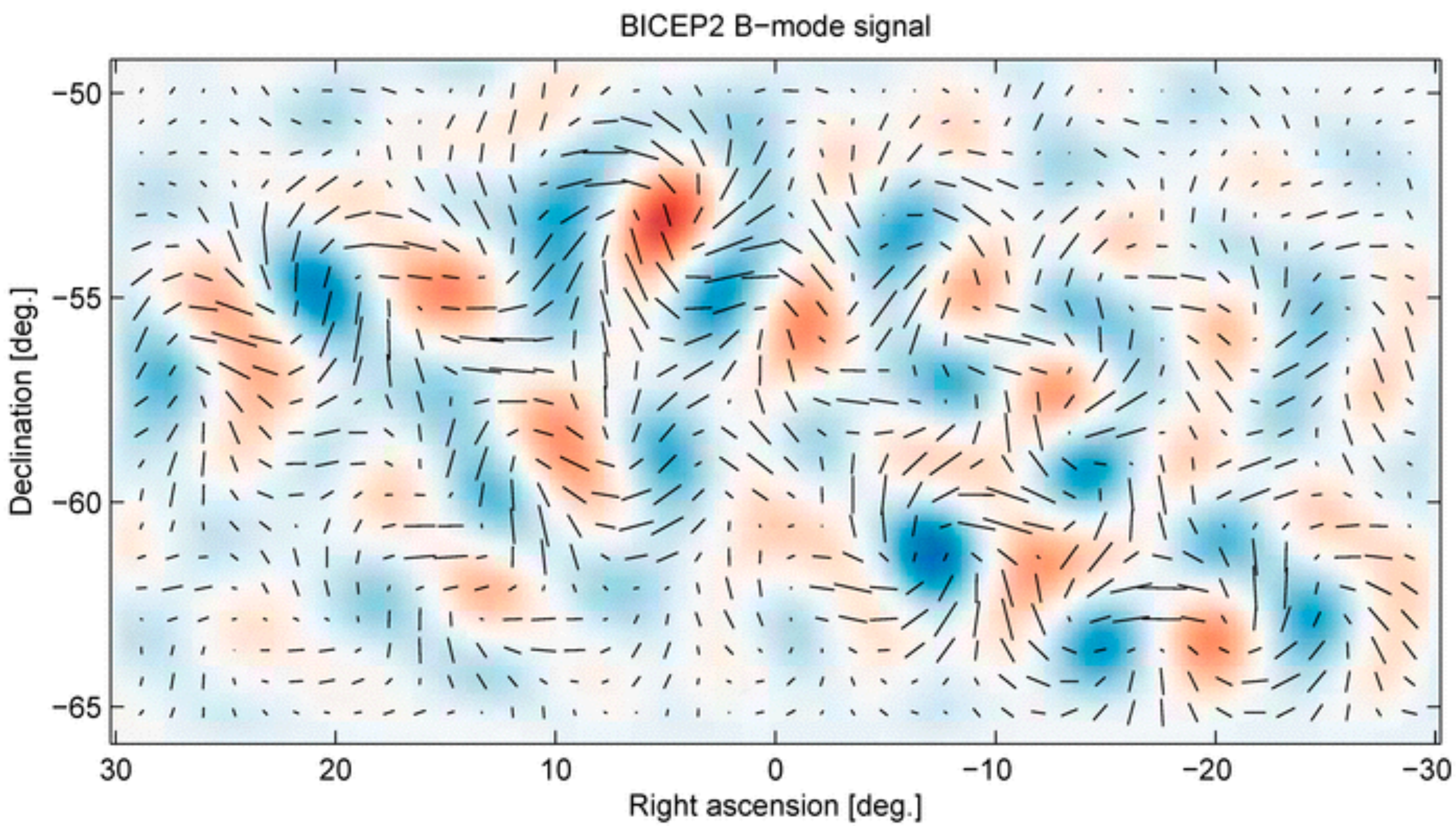
✓ $$A_S(k) = \frac{2}{5}\mathcal{P}_R^{1/2}(k) \approx \frac{\epsilon^{-1/2}}{5\pi\sqrt{3}} \frac{V^{1/2}(\phi)}{M_{\rm Pl}^2} = 1.91 \times 10^{-5}$$



✓ $$n_S \equiv 1 + \frac{d \ln A_S^2(k)}{d \ln k} \approx 1 + 2\eta - 6\epsilon$$

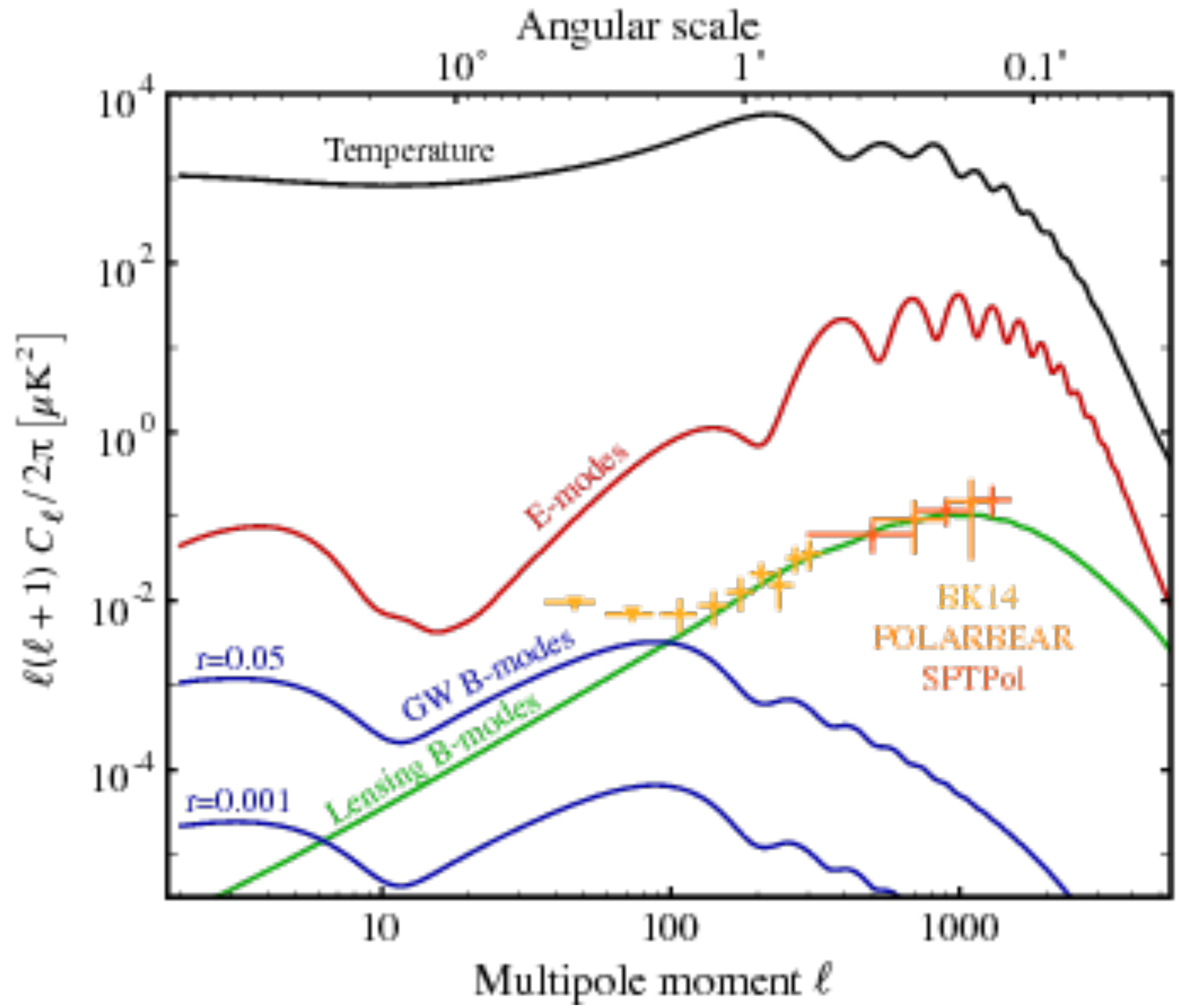
$$A_T(k) \equiv \frac{1}{5\sqrt{2}}\mathcal{P}_{gw}^{1/2} \approx \frac{1}{5\pi\sqrt{3}} \frac{V^{1/2}(\phi)}{M_{\rm Pl}^2}$$

$$\text{B} - \text{Mode Polarization} \Leftarrow \quad r = T/S \equiv \frac{\mathcal{P}_{gw}}{\mathcal{P}_R} = 16\frac{A_T^2}{A_S^2} \approx 16\,\epsilon$$

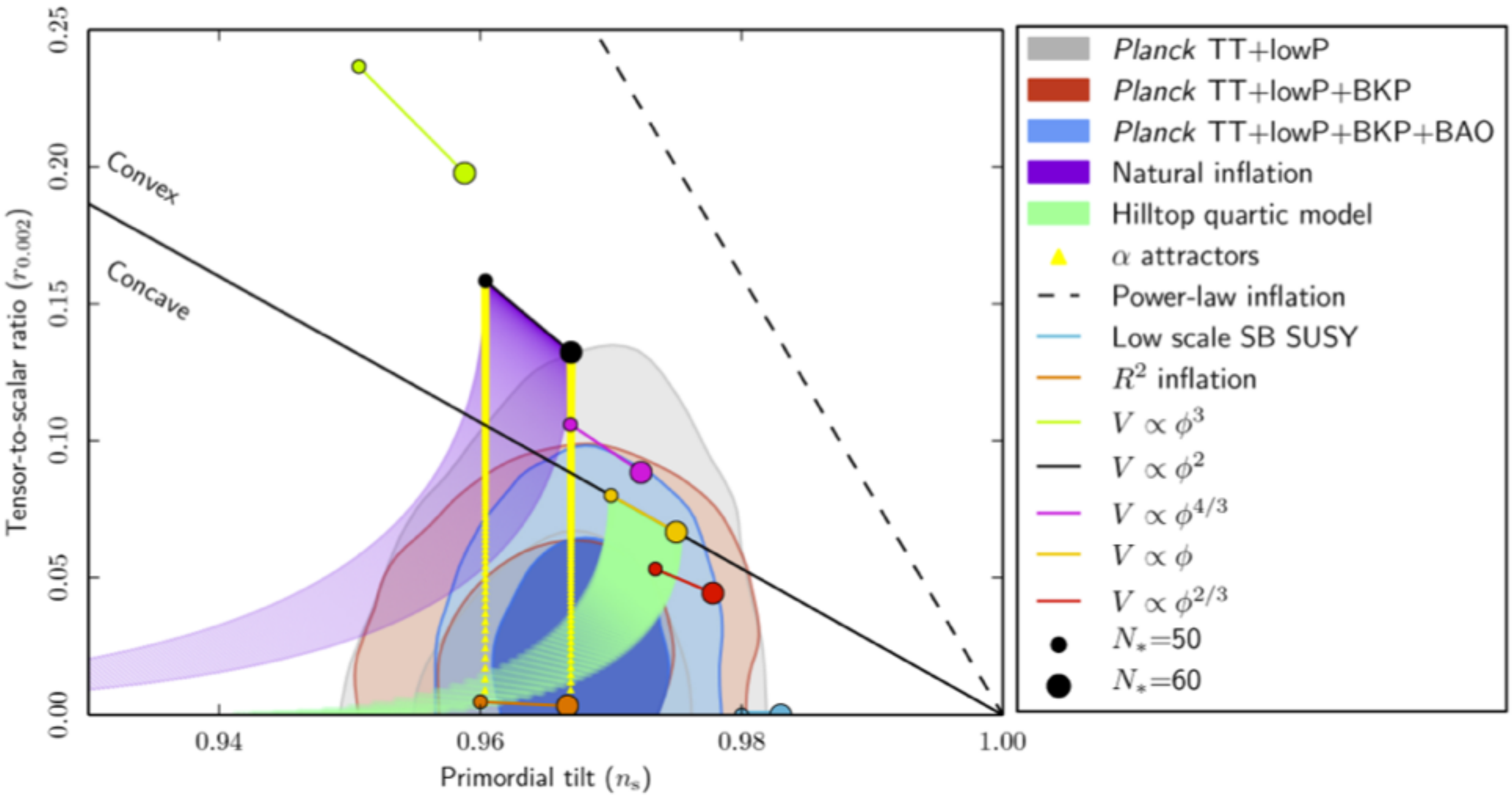


BICEP2 B−mode signal
−50
−55
−60
−65
Declination [deg.]
30
20
10
0
−10
−20
−30
Right ascension [deg.]

B-modes still unseen



Inflation models compatible with CMB data



Starobinsky model

A. A. Starobinsky, Phys. Lett. B **91**, 99 (1980).

$$S_\mathrm{S} = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\,\left(M_\mathrm{p}^2 R + \frac{1}{6M^2}R^2\right)$$

Jordan frame

$$S_\mathrm{S} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_\mathrm{p}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{3}{4}M_\mathrm{p}^4 M^2\left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_\mathrm{p}}\right)^2\right]$$

Einstein frame

$$n_s - 1 \approx -\frac{2}{N},\ \ r \approx \frac{12}{N^2}$$

$$M \simeq 10^{-5}\,, \quad N = 55$$

Higgs Inflation

F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008)

$$S_{\rm HI} = \int d^4x \sqrt{-g} \left(\frac{M_{\rm p}^2}{2} R + \frac{1}{2} \xi h^2 R - \frac{\lambda}{4} h^4 \right)$$ Jordan frame

Potential in the Einstein frame

$$V(\phi) = \frac{\lambda M_P^4}{4\xi^2} \left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_{\rm p}} \right)^2$$

$$\xi \sim 49000$$

SUGRA Inflation

J. Ellis, D. V. Nanopoulos and K. A. Olive, Phys. Rev. Lett. **111**, 111301 (2013)

Kahler potential $K(\phi_i, \phi_i^*)$

Superpotential $W(\phi_i)$

$$\mathcal{L}_{kin} = -K_{ij^*} g^{\mu\nu} \partial_\mu \phi^i \partial_\nu \phi^{*j}$$

$$K_{ij^*} = \frac{\partial^2 K}{\partial \phi^i \partial \phi^{*j}}.$$

Scalar potential

$$V(\phi_i, \phi_i^*) = V_F(\phi_i, \phi_i^*) + V_D(\phi_i, \phi_i^*).$$

F term potential

$$V_F = e^K \left[D_{\phi_i} W K^{ij^*} D_{\phi_j^*} W^* - 3|W|^2 \right]$$

$$M_P = 1$$

$$K^{ij^*} \equiv K^{-1}_{ij^*}$$

$$D_{\phi_i} W = \frac{\partial W}{\partial \phi_i} + \frac{\partial K}{\partial \phi_i} W.$$

D-term potential

$$V_D = \frac{1}{2} \left[Re f^{-1}_{ab}(\phi_i) \right] D^a D^b$$

$$D^a = -g \frac{\partial G}{\partial \phi_k} (\tau^a)^l_k \phi_l$$

$$G(\phi_i, \phi_i^*) \equiv K(\phi_i, \phi_i^*) + \ln W(\phi_i) + \ln W^*(\phi_i^*),$$

SUGRA Model of Starobinsky potential

Ellis, Nanopoulos, Olive , PRL, 2013

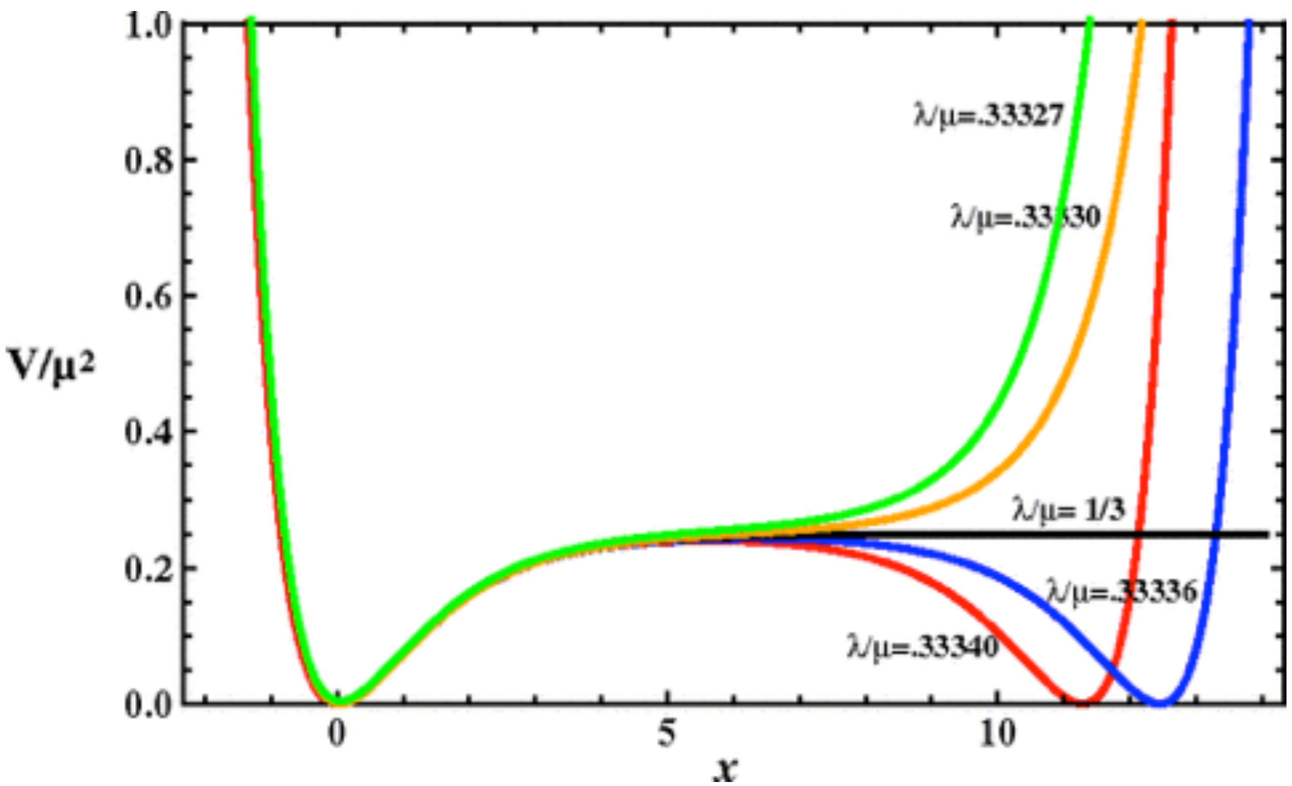
$$K = -3\ln\left[T + T^* - \frac{\phi\phi^*}{3}\right]$$

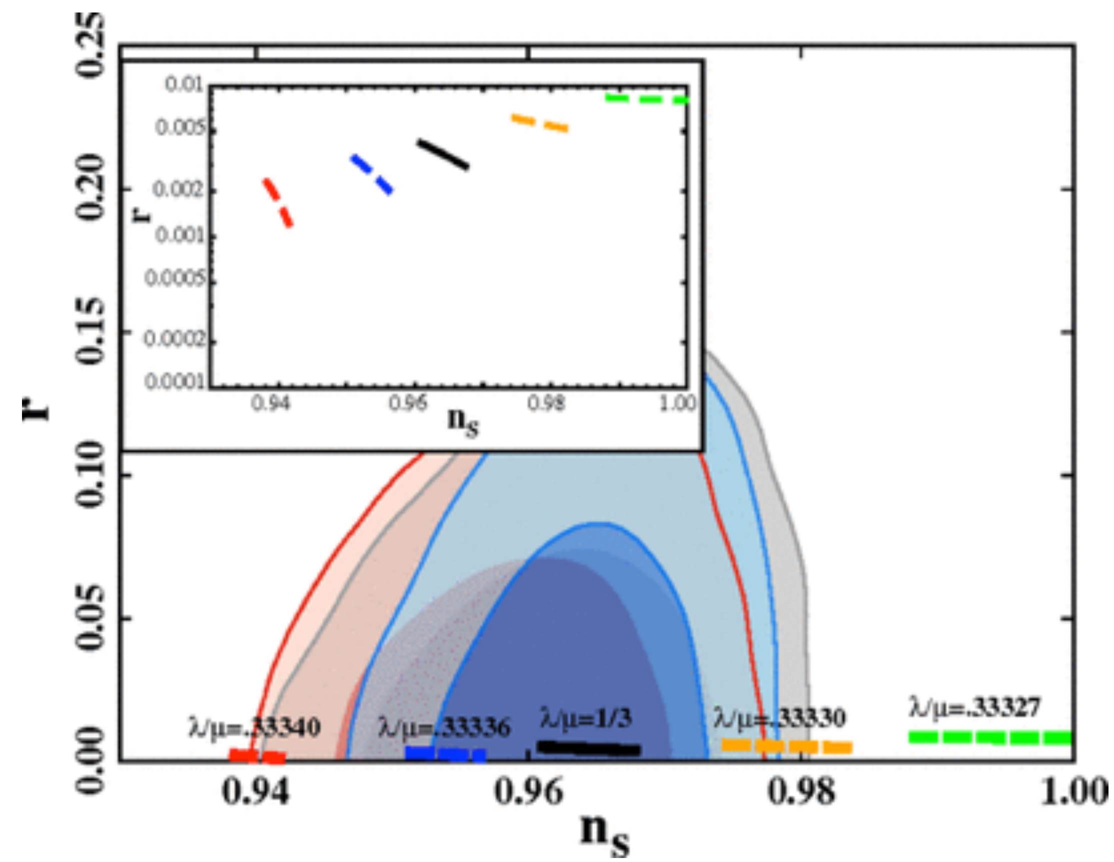
$$W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

$$\mathcal{L}_{eff} = \frac{1}{(c - |\phi|^2/3)^2}\left[c|\partial_\mu \phi|^2 - \hat{V}\right]$$

$$\phi = c\sqrt{3}\tanh\frac{\chi}{\sqrt{3}}$$

$$V_F = \frac{\mu^2}{4}\left(1 - e^{-\sqrt{\frac{2}{3}}x}\right)^2$$





Power law Starobinsky model

G.K.Chakravarty, SM ,2015

$$S_J = \frac{-M_p^2}{2}\int d^4x\sqrt{-g}\left(R + \frac{1}{6M^2}\frac{R^\beta}{M_p^{2\beta-2}}\right)$$

is equivalent to

$$S_J = \int d^4x\sqrt{-g}\left(-\frac{M_p^2 R}{2} - \frac{\xi\Phi^a R^b}{2M_p^{a+2b-4}} + \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi + \frac{\lambda\Phi^{4(1+\gamma)}}{4M_p^{4\gamma}}\right)$$

SUGRA $\quad K = -3\ln\left[T + T^* - \frac{(\phi+\phi^*)^n}{12}\right]$

No scale SUGRA SO(10) derived Starobinsky Model of Inflation

Ila Garg and SM , Phys Lett B751 (2015)

$$W = \frac{m_\Phi}{4!}\Phi^2 + \frac{\lambda}{4!}\Phi^3 + \frac{m_\Sigma}{5!}\Sigma\overline{\Sigma} + \frac{\eta}{4!}\Phi\Sigma\overline{\Sigma} + m_H H^2 + \frac{1}{4!}\Phi H(\gamma\Sigma + \bar{\gamma}\overline{\Sigma})$$

$$K = -3\ln(T + T^* - \frac{1}{3}(\frac{1}{4!}\Phi^\dagger\Phi + \frac{1}{5!}\Sigma^\dagger\Sigma + \frac{1}{5!}\overline{\Sigma}^\dagger\overline{\Sigma} + H^\dagger H))$$

$SO(10)$ scalar representations

$\mathbf{210}(\Phi_{ijkl})$ $\mathbf{126}(\Sigma_{ijklm})$ $\mathbf{10}(H_i)$,

Some intermediate symmetries like Pati-Salam do not give successful plateau inflation

No-scale sugra inflation and Type-I see-saw

Ila Garg, SM, 1711.01979

$$W = Y_\nu^{ij} L_i H_u N_j + \frac{1}{2} M_N^{jj} N_j N_j + \mu H_u H_d$$

$$K = -3 \ln \left(T + T^* - \frac{1}{3}(|L_i|^2 + |N_j|^2 + |H_u|^2) \right)$$

D-flat directions $$L_i = \begin{pmatrix} \tilde{\nu}_i \\ 0 \end{pmatrix}; \quad H_u = \begin{pmatrix} 0 \\ h_u \end{pmatrix}; \quad H_d = \begin{pmatrix} h_d \\ 0 \end{pmatrix}$$

$$\tilde{N} = \tilde{\nu} = h = \varphi$$

$$W = Y_\nu^{13}\phi^3 + M_N^{33}\frac{\phi^2}{2},$$
$$K = -3\ln(T + T^* - |\phi|^2)$$

$$V = \frac{1}{(1-|\phi|^2)^2}\left|\frac{\partial W}{\partial \phi}\right|^2$$

$$L_{K.E.} = \frac{3}{(1-|\phi|^2)^2}|\partial^\mu \phi|^2$$

$$\phi = \tanh\frac{\chi}{\sqrt{3}}$$

Starobinsky Potential

$$V = M_N^{33^2}(1 - e^{-\frac{2\chi}{\sqrt{3}}})^2$$

$$P_R = \frac{V}{24\pi^2\epsilon} = \frac{M_N^{33^2}\sinh^4\left(\frac{\chi}{\sqrt{3}}\right)}{4\pi^2}$$

$$Y_\nu = \begin{pmatrix} 6.46\times10^{-6}+7.16\times10^{-6}i & 2.11\times10^{-5}-6.29\times10^{-8}i & -1.68\times10^{-7} \\ 6.67\times10^{-5}+2.09\times10^{-6}i & -1.84\times10^{-4}+1.71\times10^{-4}i & -3.24\times10^{-4}+2.62\times10^{-8}i \\ -2.67\times10^{-3}-1.13\times10^{-9}i & -2.11\times10^{-2}+2.37\times10^{-7}i & 1.44\times10^{-3}+5.58\times10^{-5}i \end{pmatrix},$$

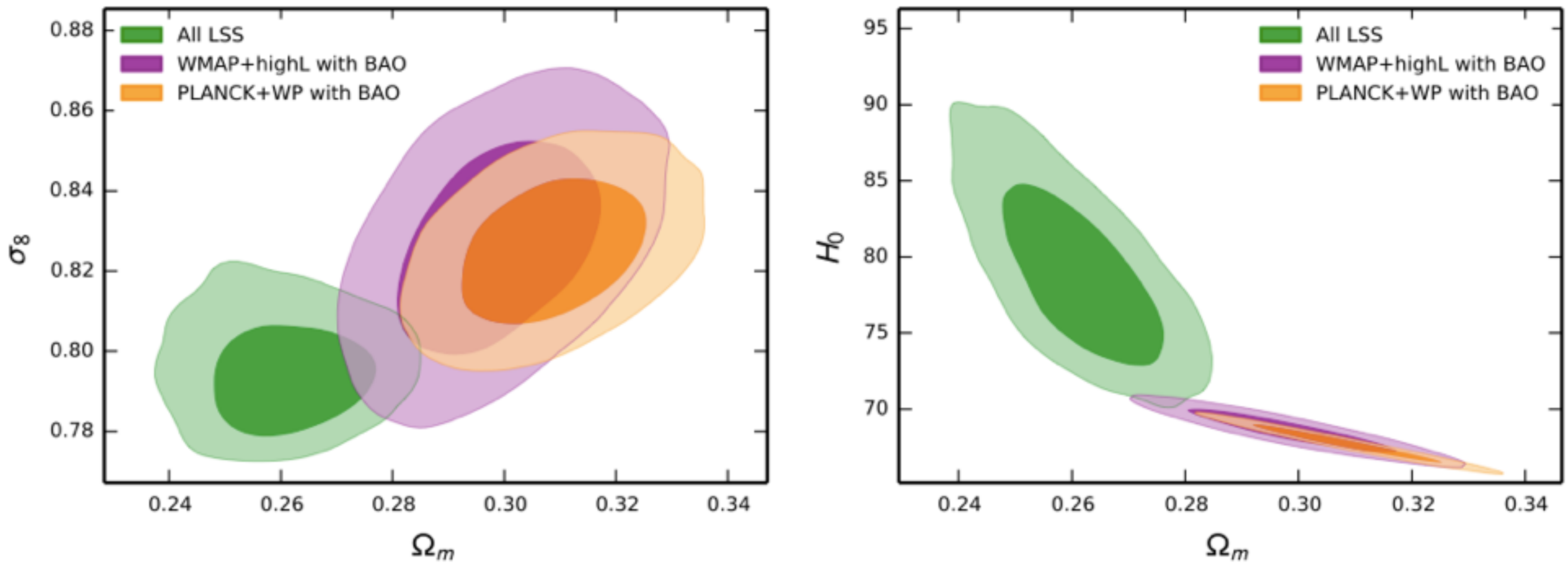
$$M_N = \begin{pmatrix} 1.16\times10^{6} & 0 & 0 \\ 0 & 1.05\times10^{8} & 0 \\ 0 & 0 & 4.08\times10^{12} \end{pmatrix} \text{ GeV}$$

Neutrino masses and mixings

$(m^2_{12})/10^{-5}(eV)^2$	7.8005
$(m^2_{23})/10^{-3}(eV)^2$	2.6040
$\sin^2\theta^L_{12}$	0.3238
$\sin^2\theta^L_{23}$	0.3888
$\sin^2\theta^L_{13}$	0.0229
δ_{PMNS}	3.1416
ϕ_1, ϕ_2	3.3875, 0.0133

Dark Matter Dark Energy from CMB and LSS

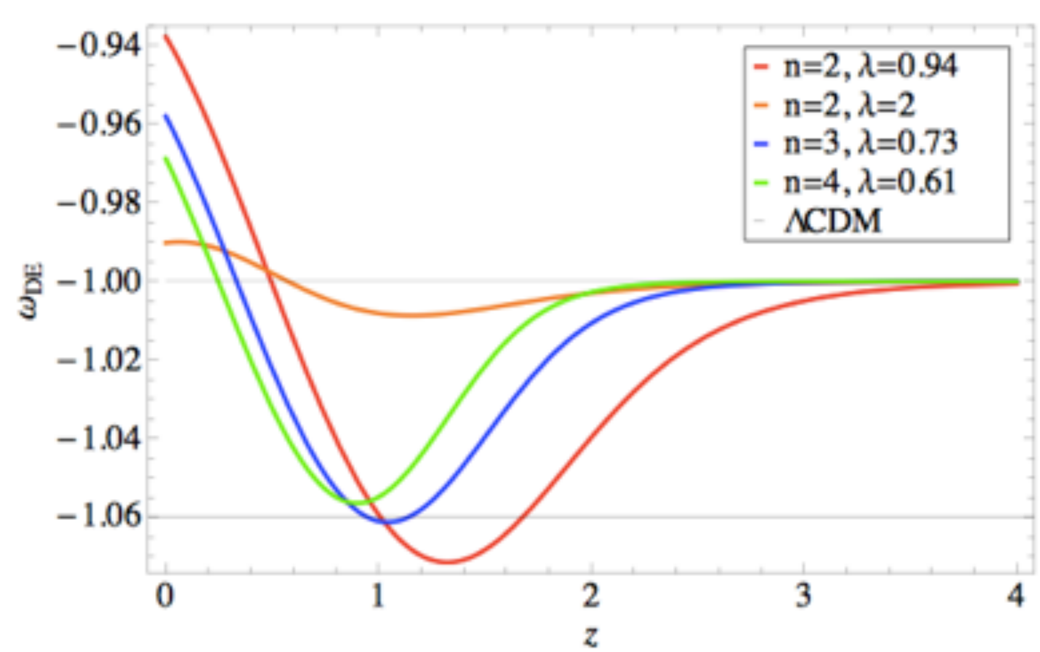
Problems with the LambdaCDM model ?



Battye et al Phys Rev D 2015,
Macaulay et al Phy Rev Lett 2013.

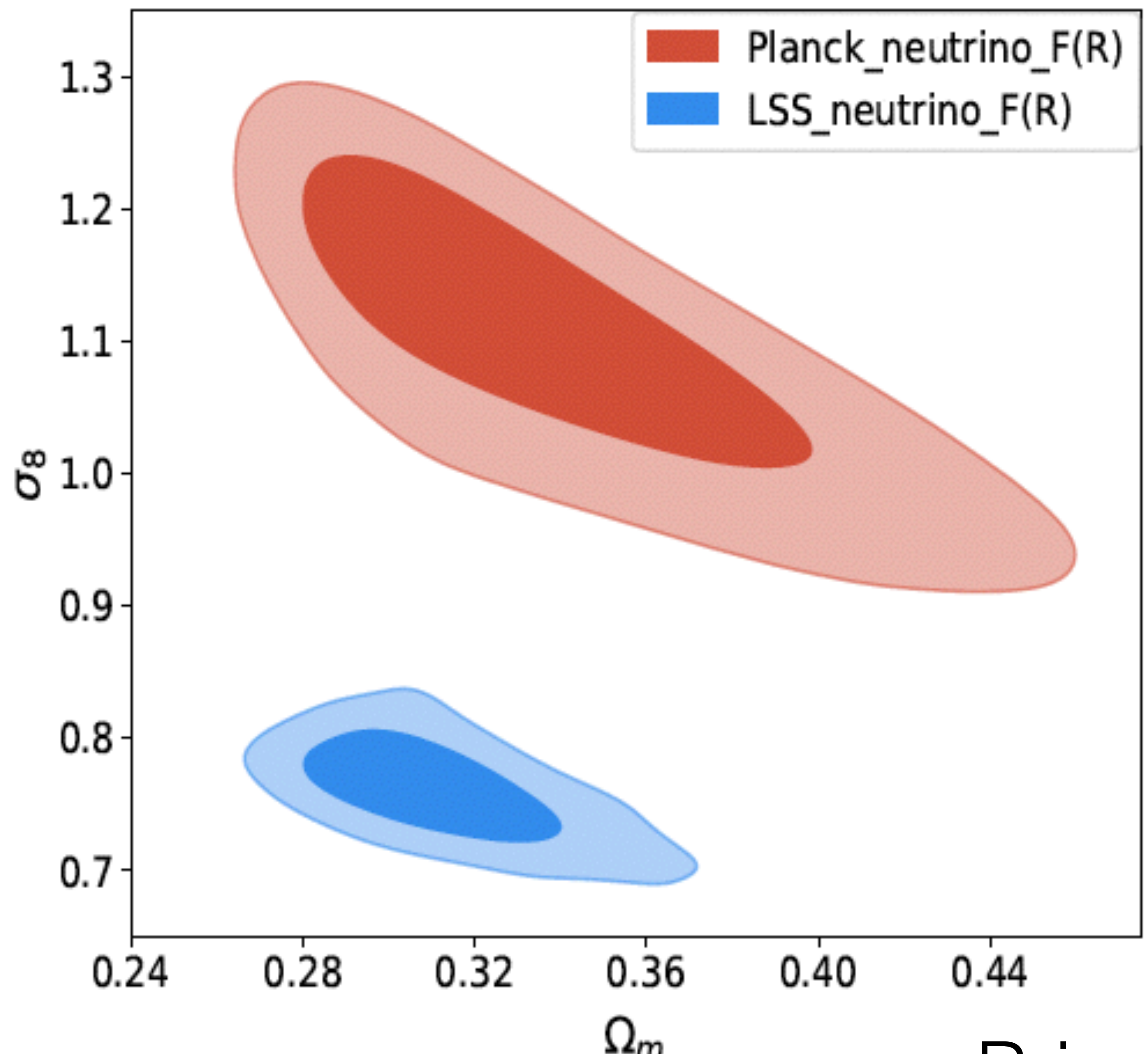
Starobinsky model of dark energy

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



Allows eV sterile neutrinos

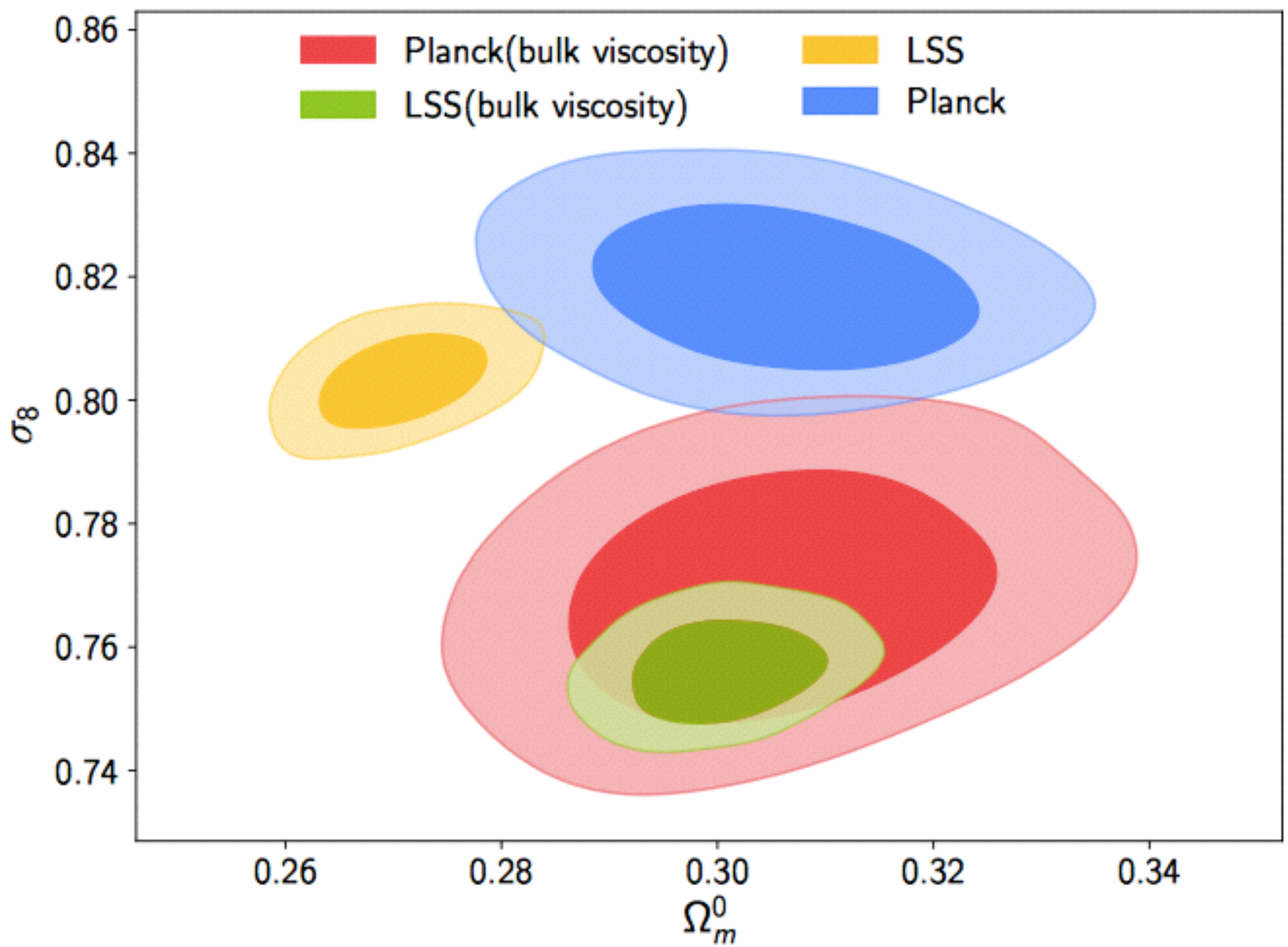
$\sigma_8 - \Omega_m$ tension worsens



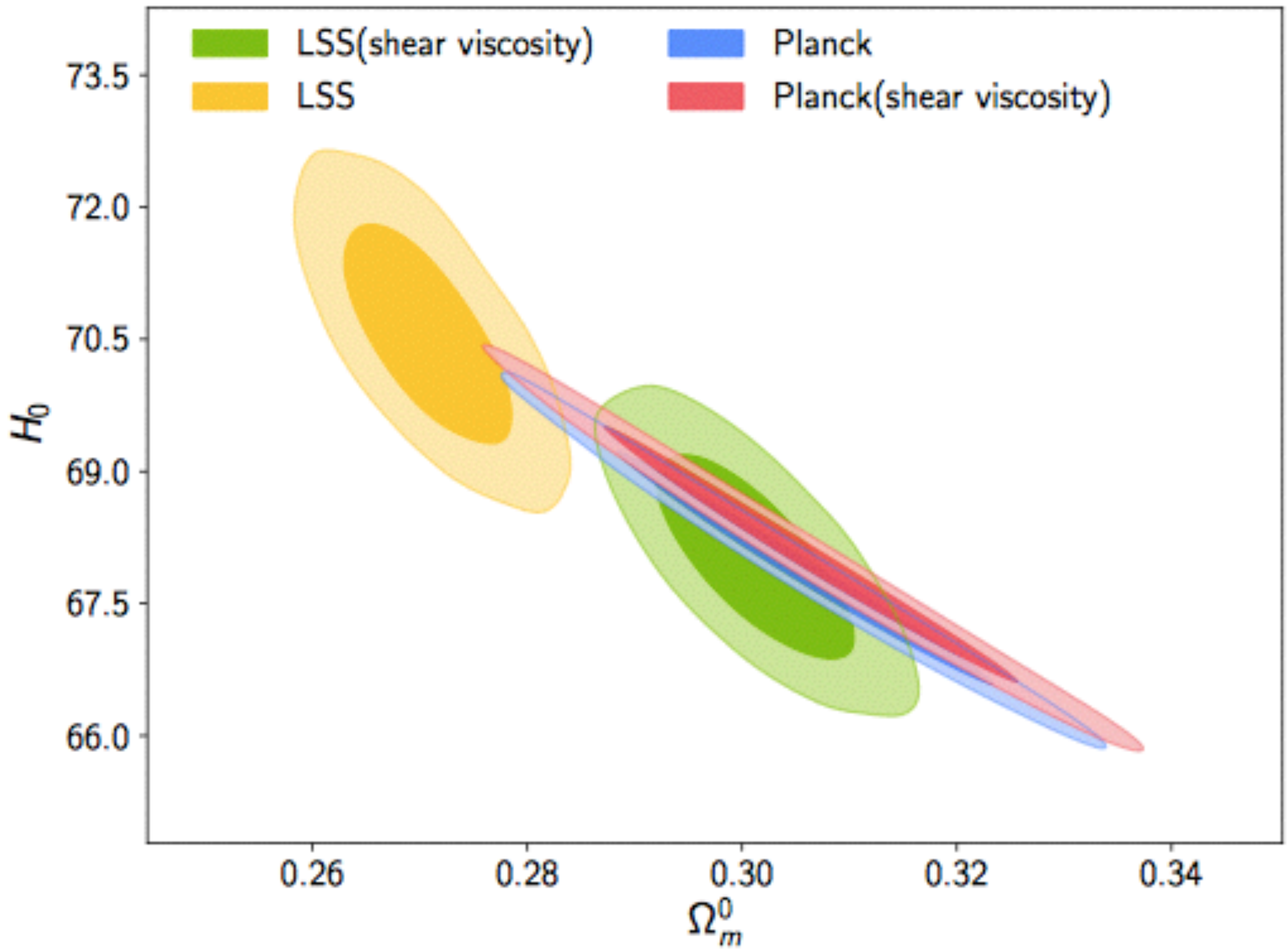
Hu-Sawicki model , n=0.5

Priyank Parashari, Ashish Narang

Viscous DM- Self interacting DM

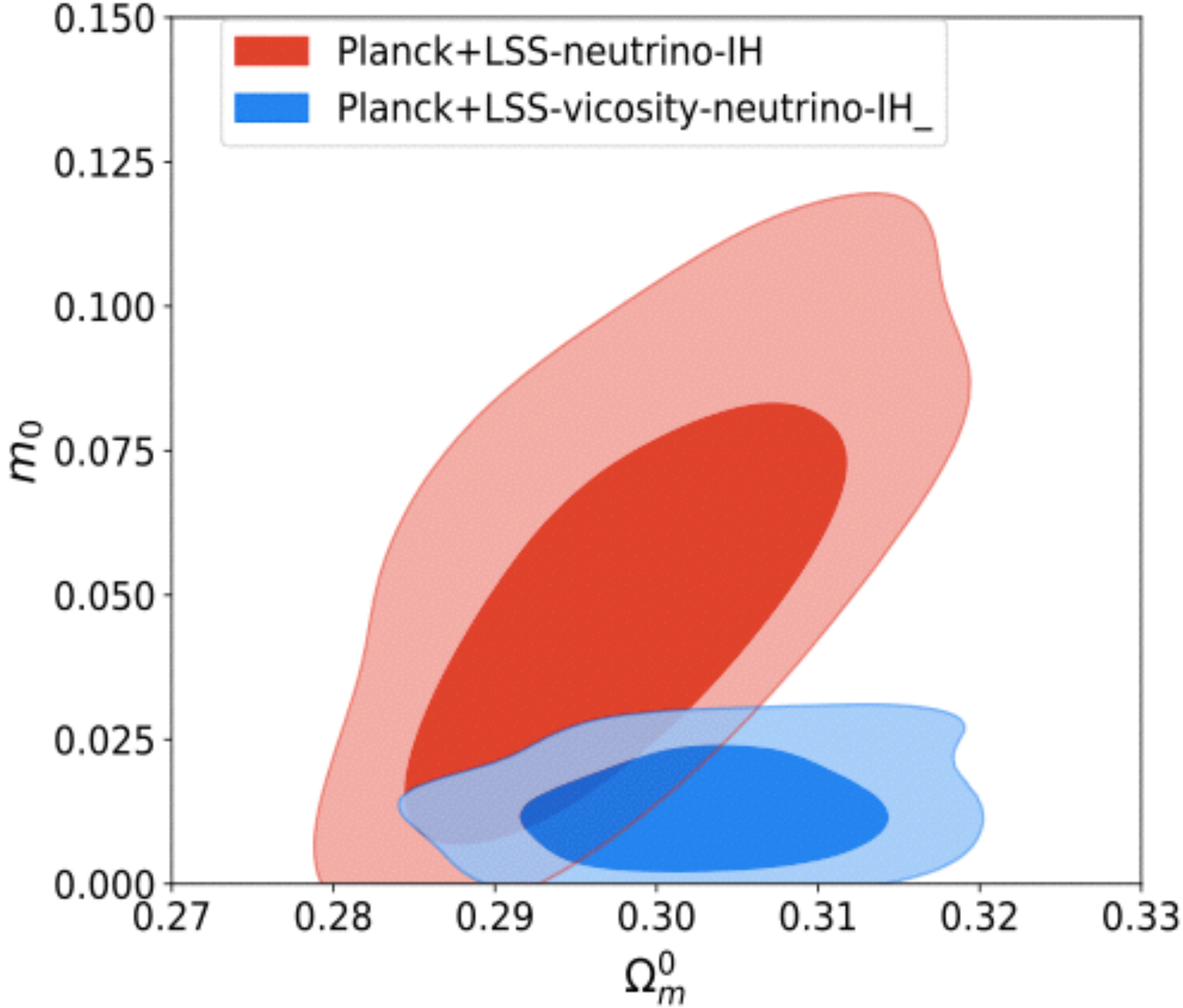


S. Anand, P.Chaubal , A. Mazumdar, SM -JCAP-2017

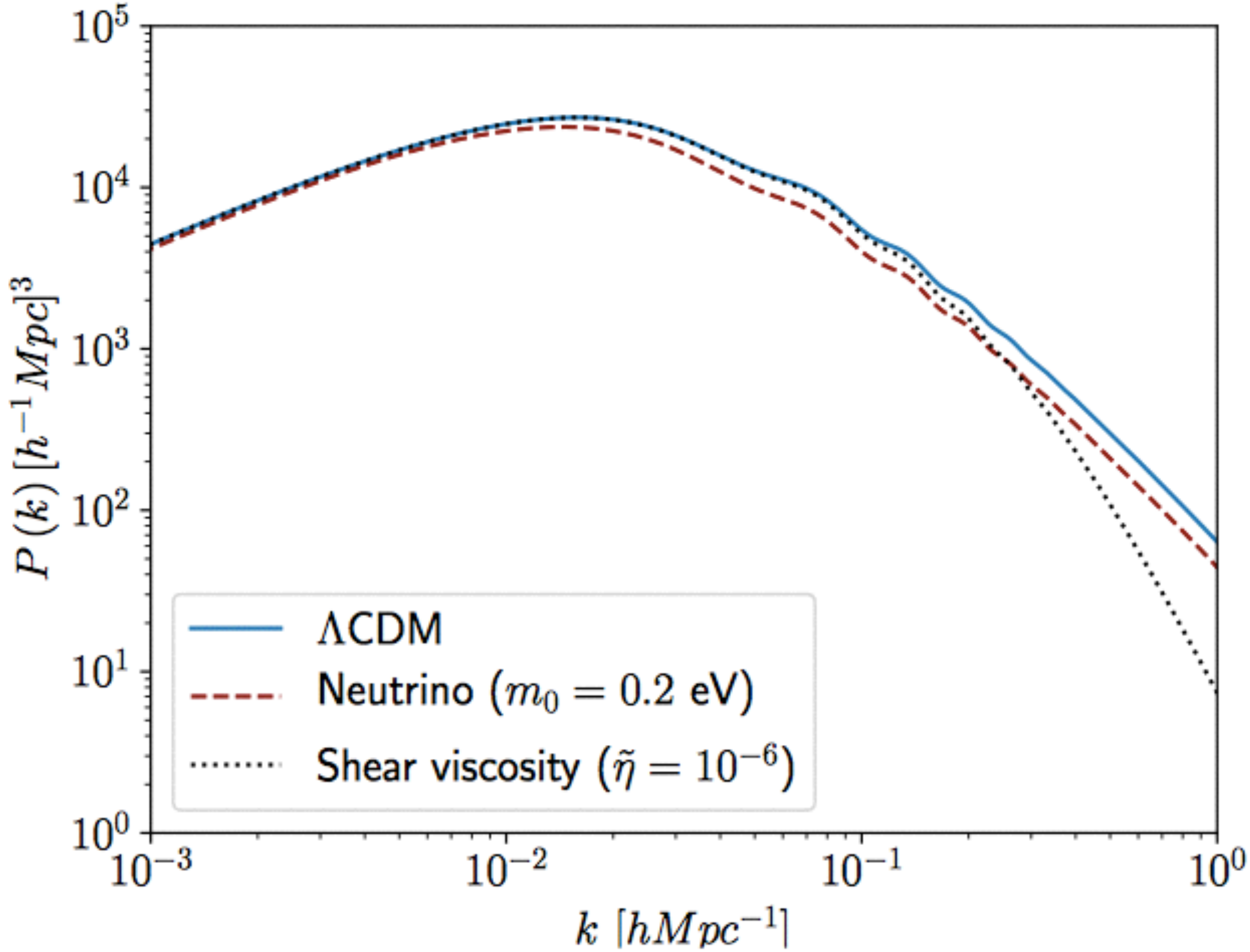


S. Anand, P.Chaubal , A. Mazumdar, SM -JCAP-2017

Bounds on Neutrino mass



Anand, Chaubal , Mazumdar, SM, Parashari 1712.01254



10^5
10^4
10^3
10^2
10^1
10^0
$P(k)\,[h^{-1}Mpc]^3$
10^{-3}
10^{-2}
10^{-1}
10^0
$k\ [hMpc^{-1}]$
ΛCDM
Neutrino ($m_0 = 0.2$ eV)
Shear viscosity ($\tilde{\eta} = 10^{-6}$)

LSS and CMB observations can test

- Dark matter self viscosity
- Varying dark energy
- f(R) gravity
- Neutrino mass
- ….

Thank You