Constraints on cosmological parameters from Planck and BICEP2 data

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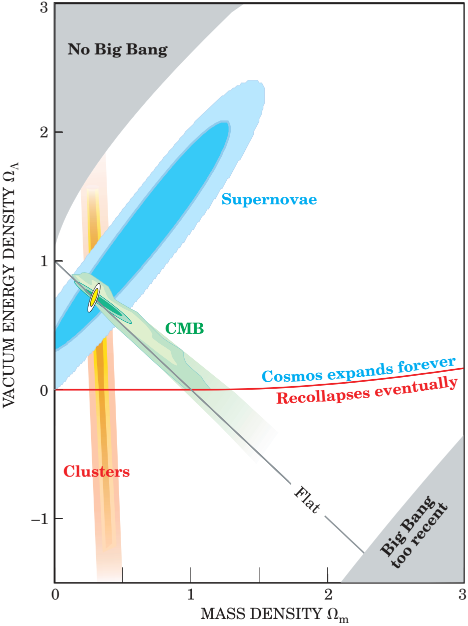
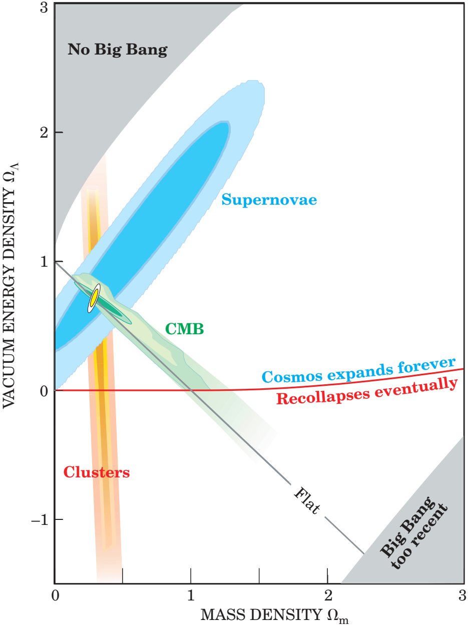
LAA, Barger, Goldberg, Huang, Marfatia, arXiv:1403.4578
LAA, Goldberg, Huang, Vlcek, arXiv:1404.1825

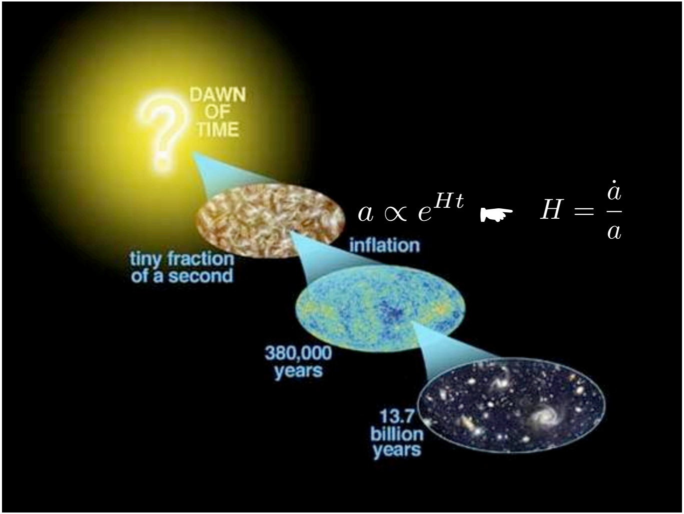

No Big Bang
Supernovae
CMB
Cosmos expands forever
Recollapses eventually
Clusters
Flat
Big Bang too recent
VACUUM ENERGY DENSITY Ω_Λ
MASS DENSITY Ω_m
3
2
1
0
−1
0
1
2
3



$\Omega_b \sim 0.04$

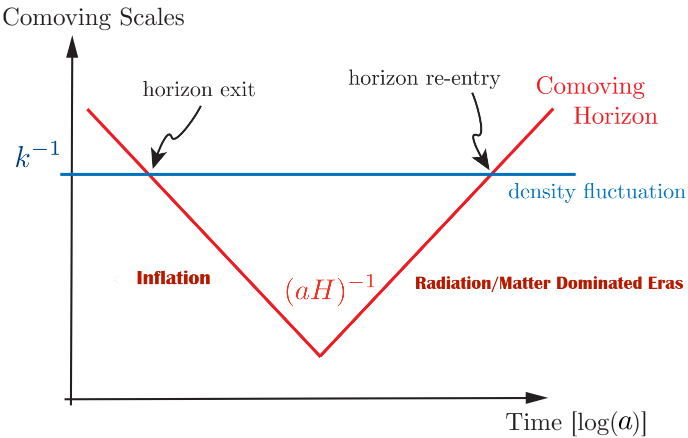
$\Omega_{\rm CDM} \sim 0.26$

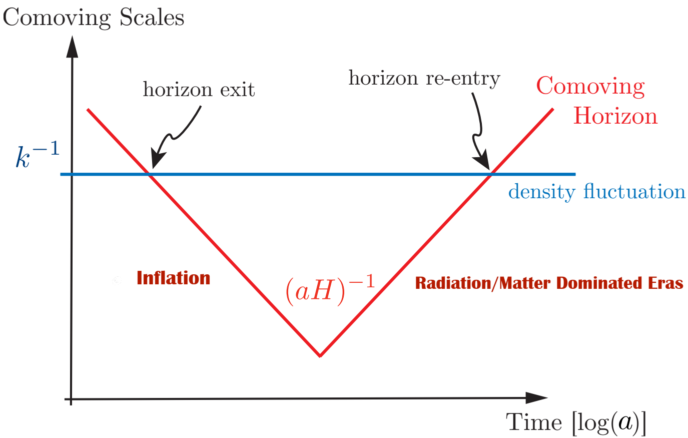
$\Omega_\Lambda \sim 0.70$



$$a \propto e^{Ht} \quad ☛ \quad H = \frac{\dot{a}}{a}$$

$$\text{If } \Delta t \gtrsim \frac{60}{H} \quad ☛ \quad \Omega \equiv \frac{8\pi\rho}{3M_{\rm Pl}H^2} \to 1$$


Comoving Scales
horizon exit
horizon re-entry
Comoving Horizon
k^{-1}
density fluctuation
Inflation
$(aH)^{-1}$
Radiation/Matter Dominated Eras
Time [$\log(a)$]



$$\mathcal{P}_\chi(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*) + \cdots}$$

- Spatially-flat 6-parameter model ☞ $\{\Omega_b h^2, \Omega_{\rm CDB} h^2, \Theta_s, \tau, n_s, A_s\}$

  - $\Omega_b = 0.02207 \pm 0.00033$ baryon density
  - $\Omega_{\rm CDM} h^2 = 0.1196 \pm 0.0031$ cold dark matter density
  - $\Theta_s = (1.04132 \pm 0.00068) \times 10^{-2}$ angular size of sound horizon at recombination
  - $\tau = 0.097 \pm 0.038$ Thomson scattering optical depth due to reionization
  - $n_s = 0.9616 \pm 0.0094$ scalar spectral index
  - $\ln(10^{10} A_s) = 3.103 \pm 0.072$ power spectrum of curvature perturbations

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$H_0 = 100\, h\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$

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- Indirect constraints ☞ $h = 0.674 \pm 0.012$ and $\Omega_\Lambda = 0.686 \pm 0.020$ are highly model dependent
- Hubble Space Telescope ☞ $h = 0.738 \pm 0.024$ more than 2σ away from Planck result

$H_0 = 100\ h\ {\rm km\ s^{-1}\ Mpc^{-1}}$

- *B*-mode power spectrum,

$$\mathcal{P}_h = A_t \left(\frac{k}{k_*}\right)^{n_t + \frac{1}{2}\alpha_t \ln\left(\frac{k}{k_*}\right) + \cdots}$$

Planck Collaboration, arXiv:1303.5082
WMAP Collaboration, arXiv:1212.5226

- B-mode power spectrum,

$$\mathcal{P}_h = A_t \left(\frac{k}{k_*} \right)^{n_t + \frac{1}{2}\alpha_t \ln\left(\frac{k}{k_*}\right) + \cdots}$$

- Define tensor-to-scalar amplitude ratio

$$r = \frac{A_t}{A_s}$$

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- Define tensor-to-scalar amplitude ratio

$$r = \frac{A_t}{A_s}$$

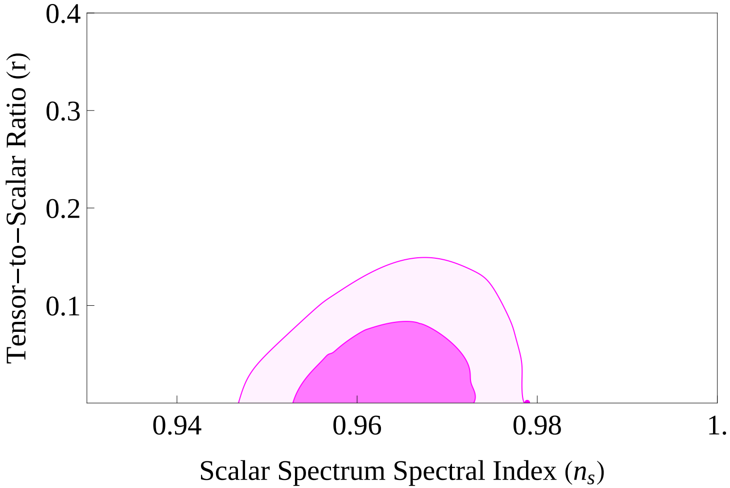
- Planck temperature map

$$r < 0.11 \ @\, 95\%\mathrm{CL}$$

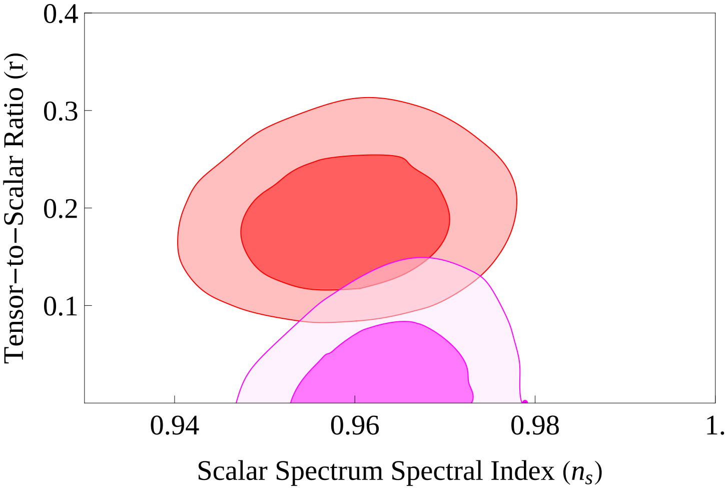
- WMAP temperature map

$$r < 0.13 \ @\, 95\%\mathrm{CL}$$

Planck Collaboration, arXiv:1303.5082
WMAP Collaboration, arXiv:1212.5226



Planck Collaboration, arXiv:1303.5082
BICEP2 Collaboration, arXiv:1403.3985



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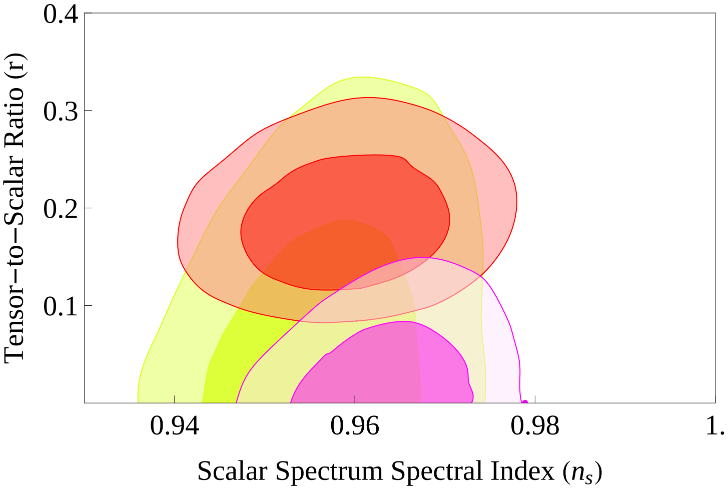


Planck Collaboration, arXiv:1303.5082
BICEP2 Collaboration, arXiv:1403.3985

- Slow-roll inflation is essentially based in two parameters

$$\epsilon = \frac{M_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \quad \text{and} \quad \eta = \frac{M_{\rm Pl}^2}{8\pi}\left|\frac{V''}{V} - \frac{1}{2}\left(\frac{V'}{V}\right)^2\right|$$

- Amplitudes are related to ϵ, η and V by

$$A_s = \frac{8V}{3M_{\rm Pl}^4\epsilon}\left[1-(4C+1)\epsilon + \left(2C - \frac{2}{3}\right)\eta\right] \qquad \text{and} \qquad A_t = \frac{128V}{3M_{\rm Pl}^4}\left[1 - \left(2C + \frac{5}{3}\right)\epsilon\right]$$

- Spectral indices and their running to $\mathcal{O}(\epsilon^2)$ are

$$\begin{aligned} n_s &\simeq 1 - 4\epsilon + 2\eta + \left(\frac{10}{3} + 4C\right)\epsilon\eta - (6+4C)\epsilon^2 + \frac{2}{3}\eta^2 - \frac{2}{3}(3C-1)\left(2\epsilon^2 - 6\epsilon\eta + \xi^2\right) \\ n_t &\simeq -2\epsilon + \left(\frac{8}{3} + 4C\right)\epsilon\eta - \frac{2}{3}(7+6C)\epsilon^2 \\ \alpha_s &\equiv \frac{dn_s}{d\ln k} \simeq -8\epsilon^2 + 16\epsilon\eta - 2\xi^2 \\ \alpha_t &\equiv \frac{dn_t}{d\ln k} \simeq -4\epsilon(\epsilon - \eta) \end{aligned}$$

with $\quad C = \gamma_{\rm E} + \ln 2 - 2 \approx -0.7296 \qquad \xi^2 \equiv (M_{\rm Pl}^4 V' V''')/(64\pi^2 V^2) \qquad k_* = 0.002\ {\rm Mpc}^{-1}$

- Hypothesize potential be invariant to the *S*-duality constraint

$$g \to 1/g \qquad \text{or} \qquad \phi \to -\phi$$

$$\phi \equiv \text{dilaton/inflaton} ☞ g \sim e^{\phi/M}$$

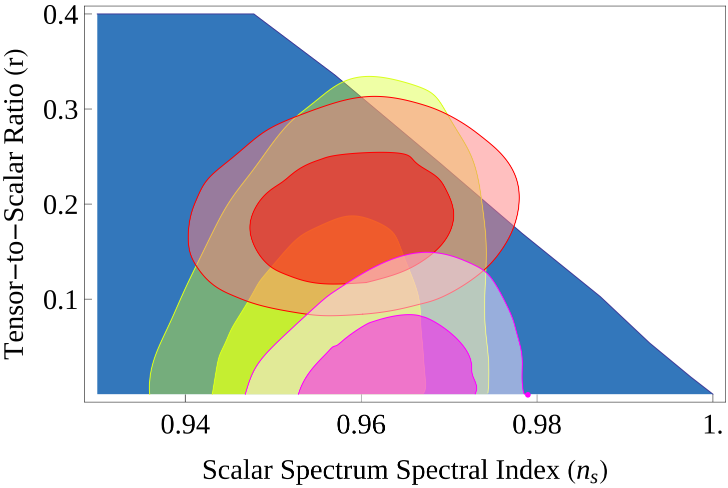
- *S*-duality forces functional form on potential

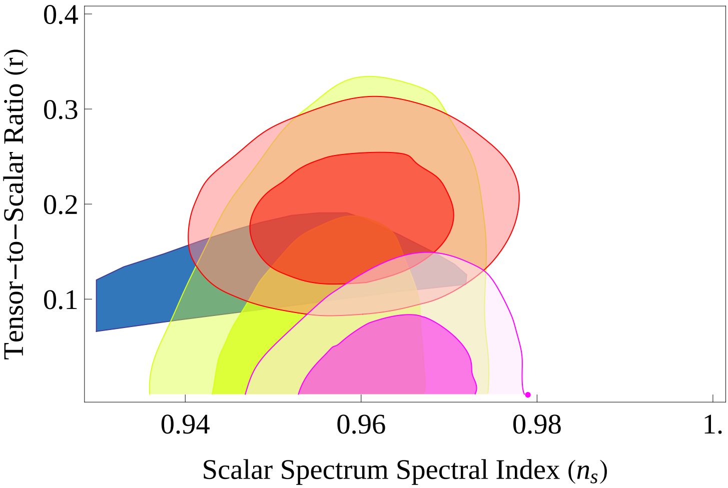
$$V(\phi) = f[\cosh(\phi/M)]$$

- Two illustrative examples

$$V = V_0 \,\mathrm{sech}(\phi/M)$$

$$V = V_0 \,\left[\mathrm{sech}(3\phi/M) - \frac{1}{4}\mathrm{sech}^2(\phi/M)\right]$$


Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.94
0.96
0.98
1.
Scalar Spectrum Spectral Index (n_s)



0.4
0.3
0.2
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Tensor–to–Scalar Ratio (r)
0.94
0.96
0.98
1.
Scalar Spectrum Spectral Index (n_s)

- Planck + BICEP2 data favor $\alpha_s < 0$ @ 3σ
- BICEP2 best fit ☞ $\alpha_s = -0.028 \pm 0.009$ (68%CL)
- slow-roll ☞ $\alpha_s \sim \mathcal{O}(\epsilon^2)$

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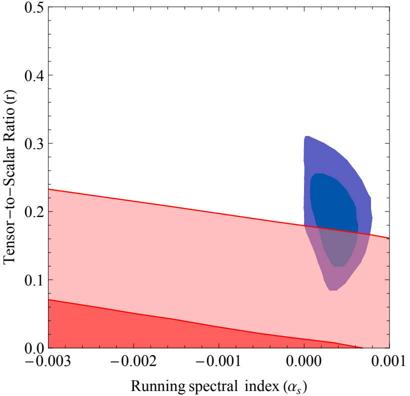
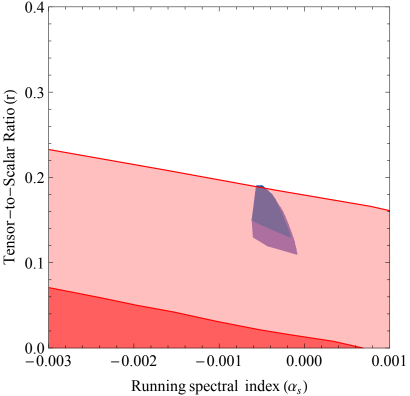
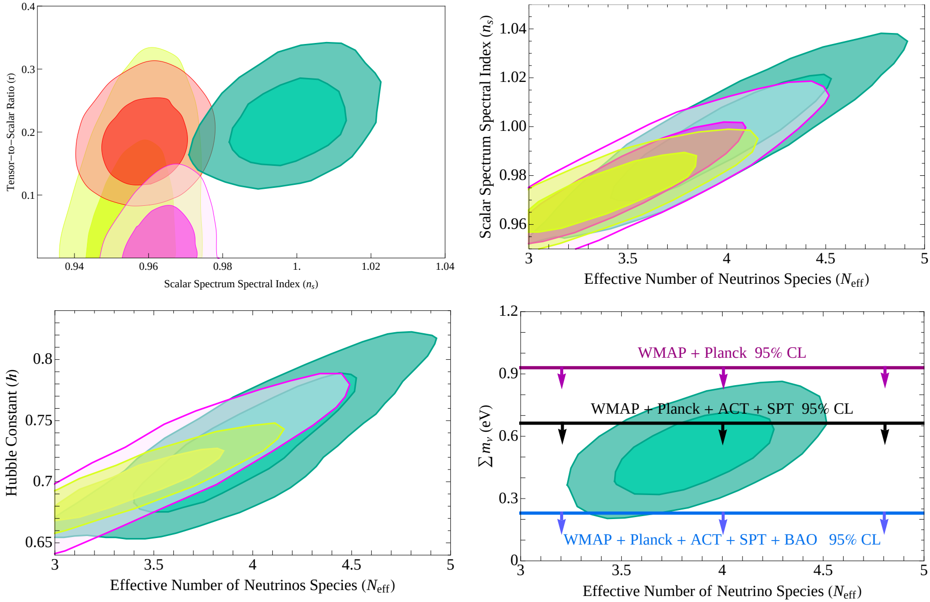
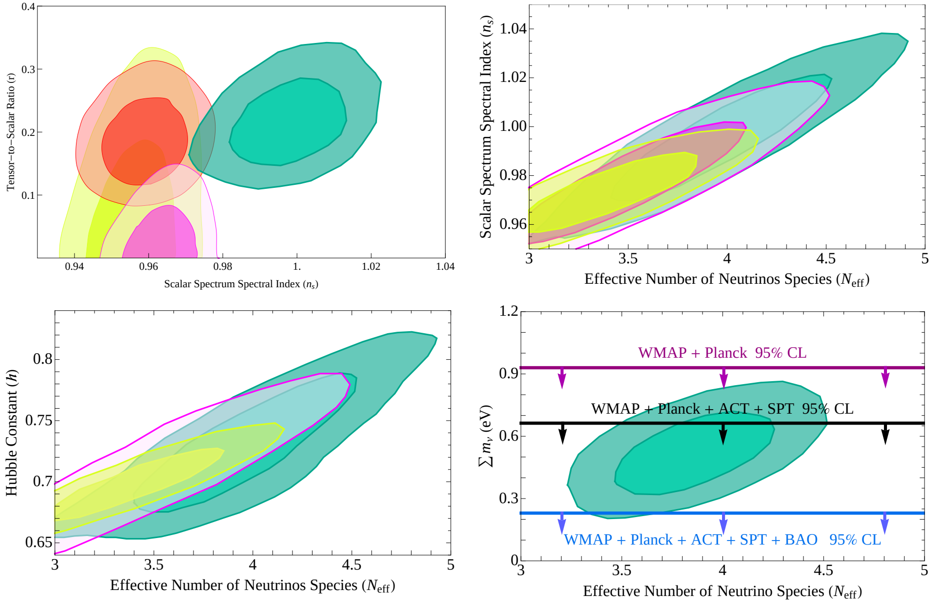




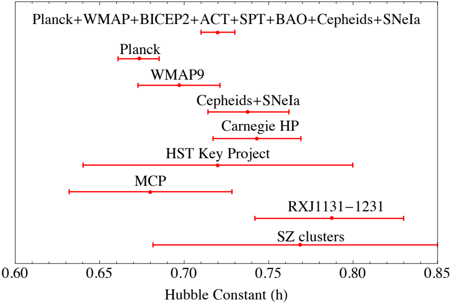


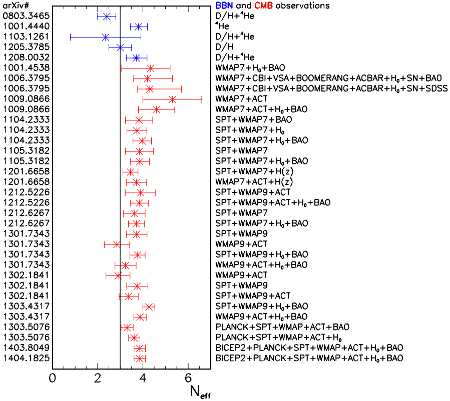
Tensor−to−Scalar Ratio (r)
Scalar Spectrum Spectral Index (n_s)
Scalar Spectrum Spectral Index (n_s)
Effective Number of Neutrinos Species ($N_{\rm eff}$)
Hubble Constant (h)
Effective Number of Neutrinos Species ($N_{\rm eff}$)
$\sum m_\nu$ (eV)
WMAP + Planck 95% CL
WMAP + Planck + ACT + SPT 95% CL
WMAP + Planck + ACT + SPT + BAO 95% CL
Effective Number of Neutrino Species ($N_{\rm eff}$)



$h = 0.72 \pm 0.01$

$N_{\rm eff} = 3.86 \pm 0.25$


Planck+WMAP+BICEP2+ACT+SPT+BAO+Cepheids+SNeIa
Planck
WMAP9
Cepheids+SNeIa
Carnegie HP
HST Key Project
MCP
RXJ1131−1231
SZ clusters
0.60
0.65
0.70
0.75
0.80
0.85
Hubble Constant (h)


arXiv#
BBN and CMB observations
0803.3465 D/H+^{4}He
1001.4440 ^{4}He
1103.1261 D/H+^{4}He
1205.3785 D/H
1208.0032 D/H+^{4}He
1001.4538 WMAP7+H_0+BAO
1006.3795 WMAP7+CBI+VSA+BOOMERANG+ACBAR+H_0+SN+BAO
1006.3795 WMAP7+CBI+VSA+BOOMERANG+ACBAR+H_0+SN+SDSS
1009.0866 WMAP7+ACT
1009.0866 WMAP7+ACT+H_0+BAO
1104.2333 SPT+WMAP7+BAO
1104.2333 SPT+WMAP7+H_0
1104.2333 SPT+WMAP7+H_0+BAO
1105.3182 SPT+WMAP7
1105.3182 SPT+WMAP7+H_0+BAO
1201.6658 SPT+WMAP7+H(z)
1201.6658 WMAP7+ACT+H(z)
1212.5226 SPT+WMAP9+ACT
1212.5226 SPT+WMAP9+ACT+H_0+BAO
1212.6267 SPT+WMAP7
1212.6267 SPT+WMAP7+H_0+BAO
1301.7343 SPT+WMAP9
1301.7343 WMAP9+ACT
1301.7343 SPT+WMAP9+H_0+BAO
1301.7343 WMAP9+ACT+H_0+BAO
1302.1841 WMAP9+ACT
1302.1841 SPT+WMAP9
1302.1841 SPT+WMAP9+ACT
1303.4317 SPT+WMAP9+H_0+BAO
1303.4317 WMAP9+ACT+H_0+BAO
1303.5076 PLANCK+SPT+WMAP+ACT+BAO
1303.5076 PLANCK+SPT+WMAP+ACT+H_0
1403.8049 BICEP2+PLANCK+SPT+WMAP+ACT+H_0+BAO
1404.1825 BICEP2+PLANCK+SPT+WMAP+ACT+H_0+BAO
0
2
4
6
$N_{\rm eff}$

- Combining observations of CMB with data from BAO
  Planck Collaboration reported

$$h = 0.674 \pm 0.012 \quad \text{and} \quad N_{\rm eff} = 3.30 \pm 0.27$$

- However ☞ if the value of h is not allowed to float in the fit
  but instead is frozen to HST value $h = 0.738 \pm 0.024$
  Planck CMB data then gives $N_{\rm eff} = 3.62 \pm 0.25$
  suggesting new neutrino-like physics (at around 2.3σ level)

- BICEP2 + Planck data favor

$$h = 0.72 \pm 0.01 \quad \text{and} \quad N_{\rm eff} = 3.86 \pm 0.25$$

- More CMB data is needed to resolve this issue

- Alteratively ☞ we may be lucky
  and data from LHC14 could provide definite answer

- Consider right-handed partners of 3 (left-handed) SM neutrinos
- For decoupling in quark-hadron crossover transition

  $3\,\nu_R$ generate $\Delta N_{\nu_R} = 3 \left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 < 3$ extra r.d.o.f. @ BBN & CMB
- Consistency with present constraints on $N_{\rm eff}$ permits us to identify allowed parameter space of Z' masses and couplings