Monte Carlo Markov Chain Analysis of CMB + LSS experimental data within the Effective Field Theory of Inflation

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Outline of the talk

- Monte Carlo Markov Chains and cosmological parameters

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- The COSMOMC program

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- Summary and conclusions

MCMC and cosmological parameters

Experimental data:	$\longleftrightarrow$	Cosmological model:
CMB, LSS, SN, Lensing, Ly$-\alpha$, ...		Ω_b, Ω_c, H_0, τ, A_s, n_s, r, ...

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From probability distribution of data to likelihood over model parameters:

$$\Pr\big(X_{\rm data}\big) \longrightarrow L\big(\theta_1, \theta_2, \dots, \theta_n | X_{\rm data}\big)$$

Gaussian case:

$$L = e^{-\chi^2/2}\,, \quad \chi^2 = \sum_{\rm data} \big[X(\boldsymbol{\theta})_{\rm model} - X_{\rm data}\big]^2\,, \quad \boldsymbol{\theta} = \theta_1, \theta_2, \dots, \theta_n$$

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MCMC are sets of parameters distributed according to L, produced with an acceptance/rejection one-step algorithm (*e.g.* Metropolis)

$$W(\boldsymbol{\theta}_{n+1}, \boldsymbol{\theta}_n) = g(\boldsymbol{\theta}_{n+1}, \boldsymbol{\theta}_n) \min \left\{1, \frac{L(\theta_{n+1})\, g(\boldsymbol{\theta}_{n+1}, \boldsymbol{\theta}_n)}{L(\theta_n)\, g(\boldsymbol{\theta}_n, \boldsymbol{\theta}_{n+1})}\right\}$$

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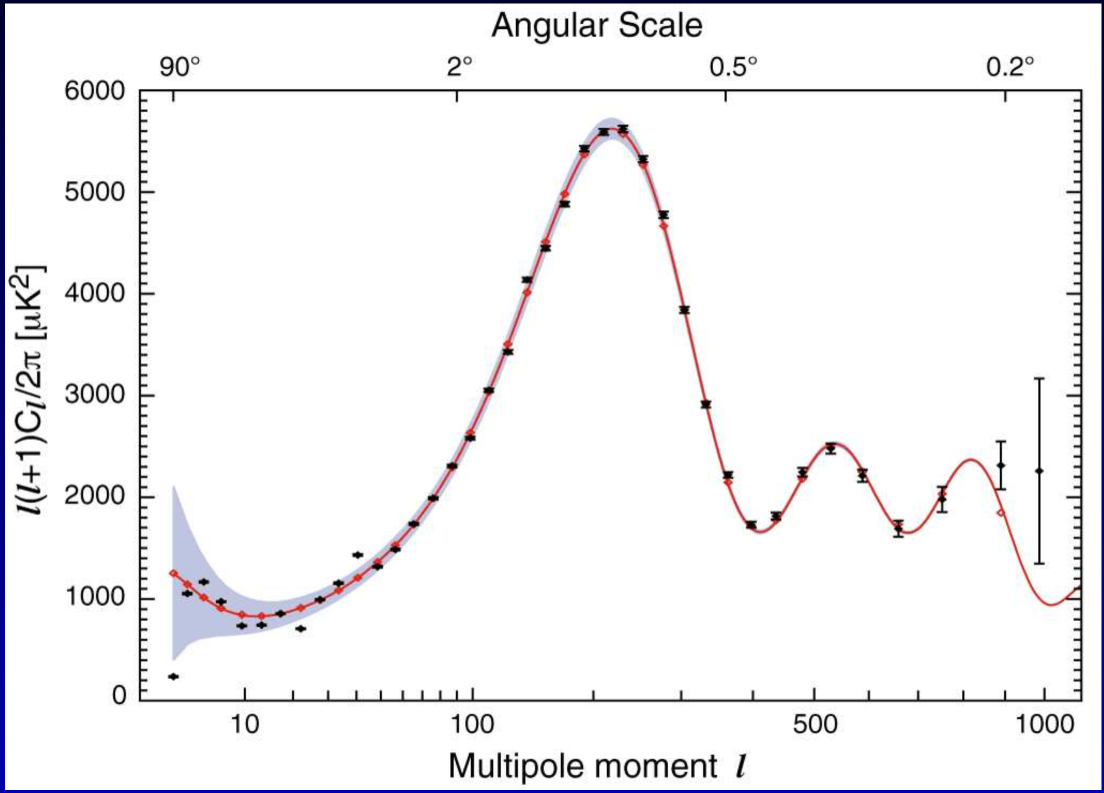
$\boxed{\text{L includes COSMIC VARIANCE}}$ (in primordial fluctuations, $\ell \lesssim 300$)

WMAP 3-years (http://lambda.gsfc.nasa.gov)



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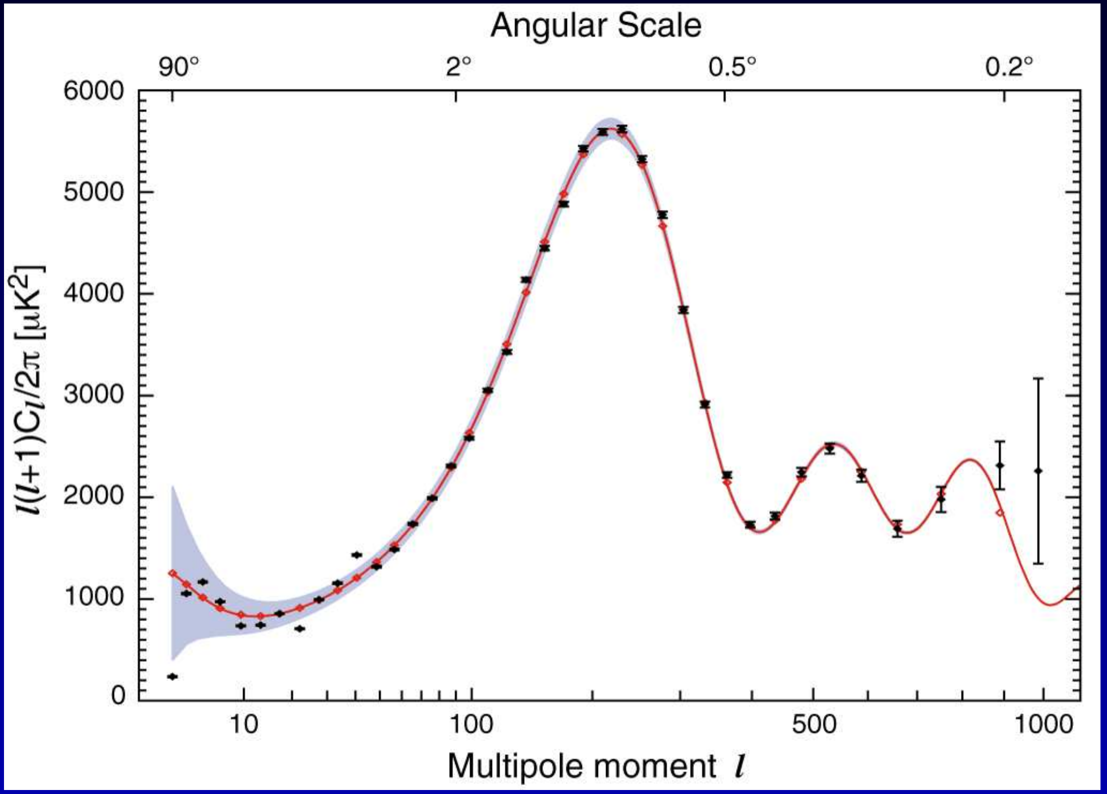

Spergel et al. 2006

param	$100\Omega_b h^2$	$\Omega_m h^2$	H_0	τ	n_s	σ_8
best fit	2.22	0.127	73.2	0.091	0.954	0.756
Δ	0.073	0.008	3.2	0.03	0.016	0.049

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- Quite accurate, easy to use, fairly well documented
- Comes with tool for analyzing results and useful MATLAB scripts
- Not very fast, but runs well on clusters

CMB, LSS and the FlatΛCDM+r model

Datasets: WMAP3, ACBAR, CBI2, BOOMERANG03, SDSS

MCMC parameters: ω_b, ω_c, τ, Θ (slow), A_s, n_s, r (fast)

Context: $\Omega_\nu = 0, \ldots$; standard priors, no SZ, no lensing, linear mpk, . . .

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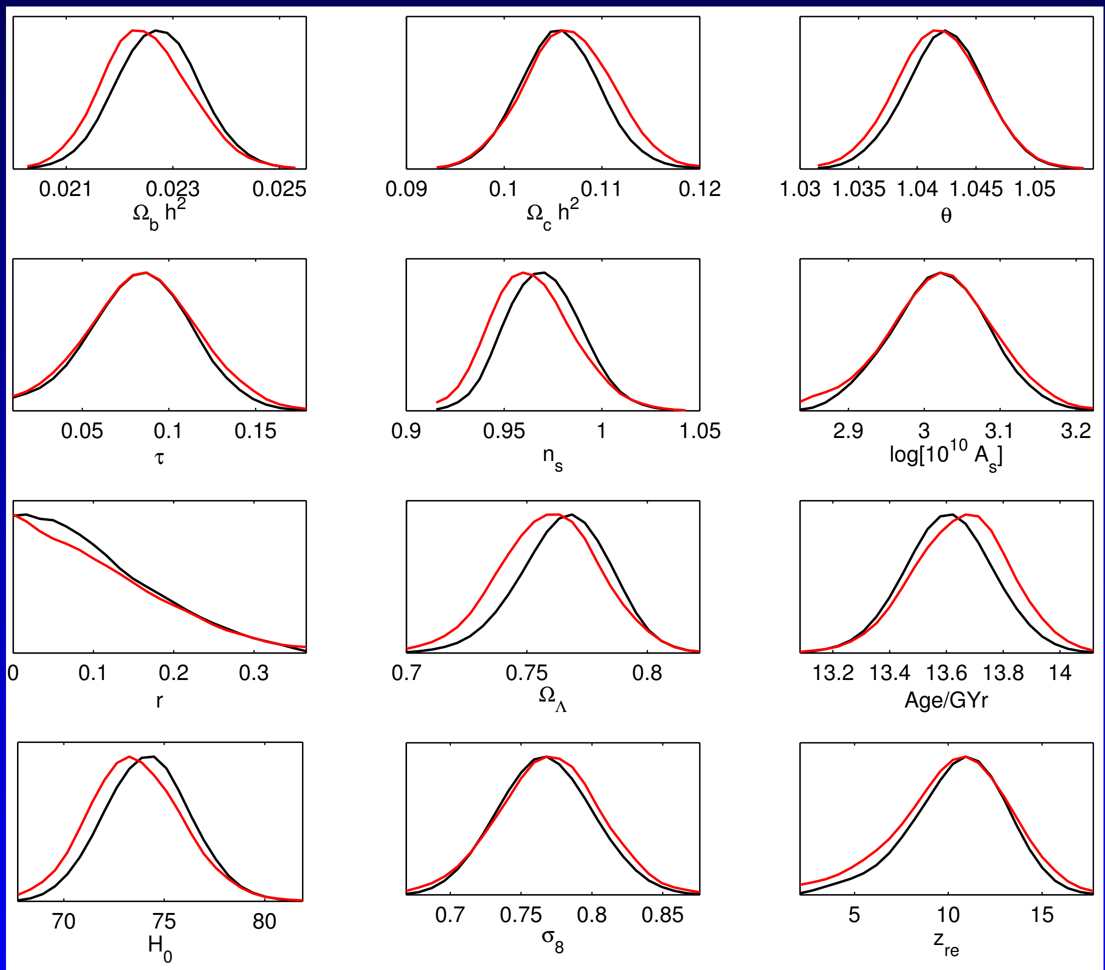
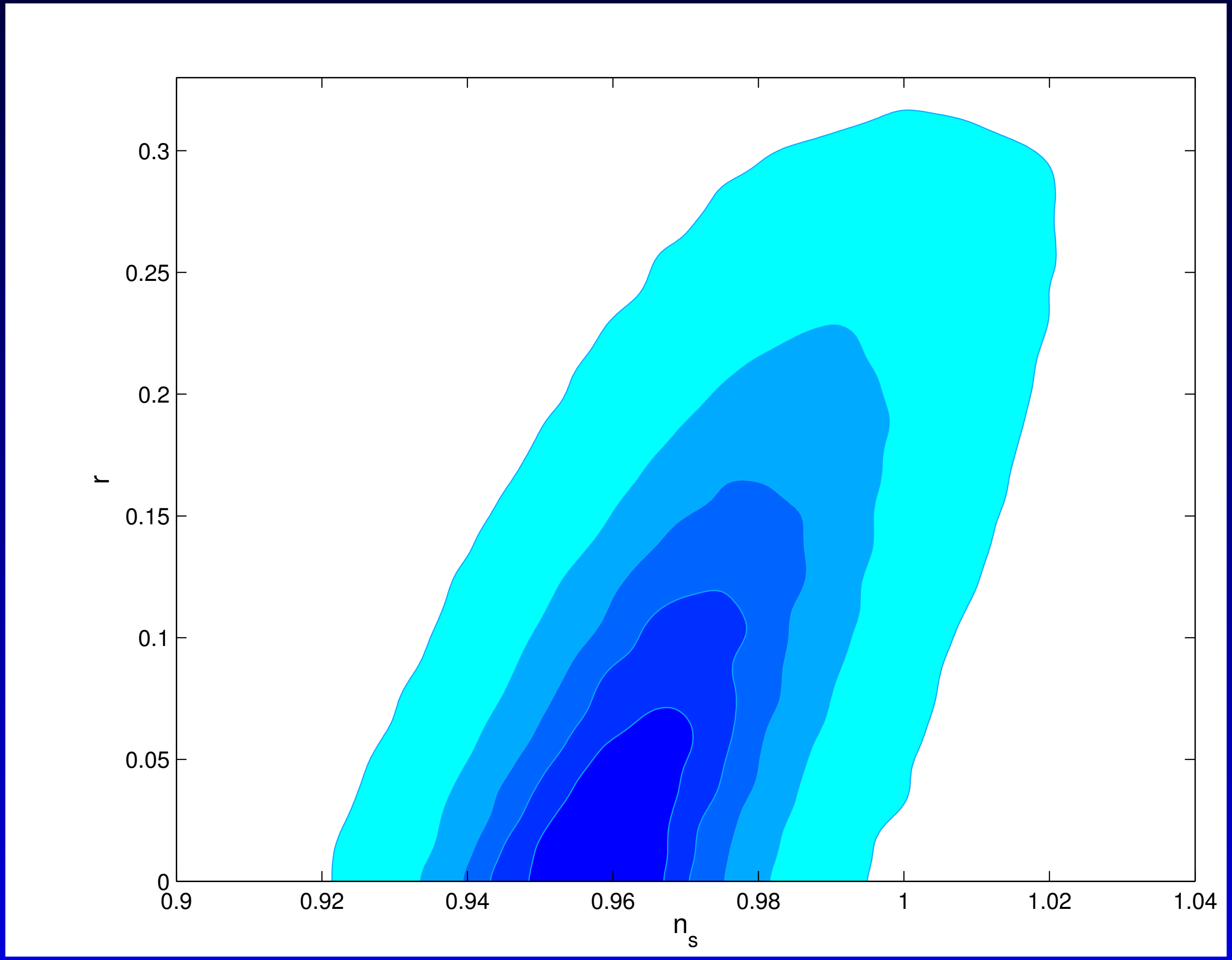


param	best fit
$100\Omega_b h^2$	2.232
$\Omega_m h^2$	0.128
τ	0.956
H_0	73.03
σ_8	0.771
$\log[10^{10} A_s]$	0.303
n_s	0.956
r	0.016
$-\log(L)$	2714.038

The marginalized $ns - r$ probability

CL: 12%, 27%, 45%, 68% and 95%



EFT of inflation (à la Boyanowski–De Vega–Sanchez)

Single scalar field $\phi + quantum\ fluctuations$

$$H^2 = \frac{\rho}{3\,M_{\rm Pl}^2} = \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right] \qquad \text{(Friedmann)}$$

$$\ddot{\phi} + 3\,H\dot{\phi} + V'(\phi) = 0 \qquad \text{(condensate dynamics)}$$

units: $\hbar = 1$, $c = 1$, $M_{\rm Pl} = 2.4 \times 10^{18}$ GeV

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Slow roll: M = energy scale of inflation $\sim M_{\rm GUT} \sim 10^{16}$ **GeV** is fixed by the amplitude (measured in CMB!) of adiabatic scalar perturbations at some cosmologically-relevant reference scale $k_{\rm pivot}$

$$V(\phi) = N\,M^4\,w(\chi)\;, \quad \chi = \frac{\phi}{\sqrt{N}\,M_{\rm Pl}}\;, \quad w(\chi) \sim \mathcal{O}(1)\;, \quad N \gtrsim 50$$

where
$$N = -\frac{1}{M_{\rm Pl}^2}\int_{\phi_{\rm exit}}^{\phi_{\rm end}} d\phi\,\frac{V(\phi)}{V'(\phi)} = -N\int_{\chi_{\rm exit}}^{\chi_{\rm end}} d\chi\,\frac{w(\chi)}{w'(\chi)}$$

is the number of efolds from $k_{\rm pivot}$ horizon exit to the end of inflation

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$\boxed{\text{Wide separation of scales} \longleftrightarrow \text{EFT + slow-roll}}$

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$\boxed{\text{Understanding start and end of inflation} \longrightarrow \text{N}}$

$\boxed{H \ll M \ll M_{\mathrm{Pl}}} \longrightarrow$

quantum loops = double expansion in $\frac{H^2}{M_{\mathrm{Pl}}^2}$ and $\frac{1}{N}$

slow roll = expansion in $\frac{1}{N}$

graviton corrections suppressed by $\frac{H^2}{M_{\mathrm{Pl}}^2}$

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See–saw–like inflaton mass and slow-roll Hubble parameter

$$m = \frac{M^2}{M_{\rm Pl}} \sim 2.45 \times 10^{13}\,{\rm GeV}\;, \qquad H = \sqrt{N}\, m\, \mathcal{H} \sim 10^{14}\,{\rm GeV}$$

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$$n_s = 1 - \frac{1}{N}\left\{3\left[\frac{w'(\chi)}{w(\chi)}\right]^2 - 2\frac{w''(\chi)}{w(\chi)}\right\}\;, \qquad \frac{dn_s}{d\ln k} = \mathcal{O}\left(\frac{1}{N^2}\right)$$

$$r = \frac{8}{N}\left[\frac{w'(\chi)}{w(\chi)}\right]^2\;, \qquad |\Delta_{\rm ad}^{(S)}|^2 = \frac{N^2}{12\pi^2}\left(\frac{M}{M_{\rm Pl}}\right)^4 \frac{w^3(\chi)}{w'^2(\chi)}$$

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Trinomial realization: $\boxed{V(\phi) = V_0 \pm \frac{1}{2}m^2\phi^2 - \frac{1}{3}mg\phi^3 + \frac{1}{4}\lambda\phi^4}$

Trinomial new (= small field) inflation

$$w(\chi) = -\frac{1}{2}\chi^2 - \frac{1}{3}h\sqrt{\frac{y}{2}}\chi^3 + \frac{1}{32}y\chi^4 + \frac{2}{y}F(h)$$

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$$\Delta = \sqrt{h^2+1}\,, \quad h \geq 0 \longrightarrow \text{absolute minimum} = \chi_{\rm end} = \sqrt{\frac{8}{y}}(\Delta+h) > 0$$

$$F(h) = \frac{8}{3}h^4 + 4h^2 + 1 + \frac{8}{3}h\Delta^3 \longrightarrow w(\chi_{\rm end}) = w'(\chi_{\rm end}) = 0$$

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fixing N $\longrightarrow$

$$\boxed{\begin{aligned} y = {} & z - 2h^2 - 1 - 2h\Delta + \frac{4}{3}h(h+\Delta-\sqrt{z}) \\ & + \frac{16}{3}h(\Delta+h)\Delta^2\log\left[\frac{1}{2}\left(1+\frac{\sqrt{z}-h}{\Delta}\right)\right] \\ & - 2F(h)\log\left[\sqrt{z}(\Delta-h)\right] \end{aligned}}$$

where $z \equiv \frac{y}{8}\chi^2_{\rm exit}$ and $z_1 = 1 - \frac{z}{(\Delta+h)^2}$ acts as normalized *effective coupling*.

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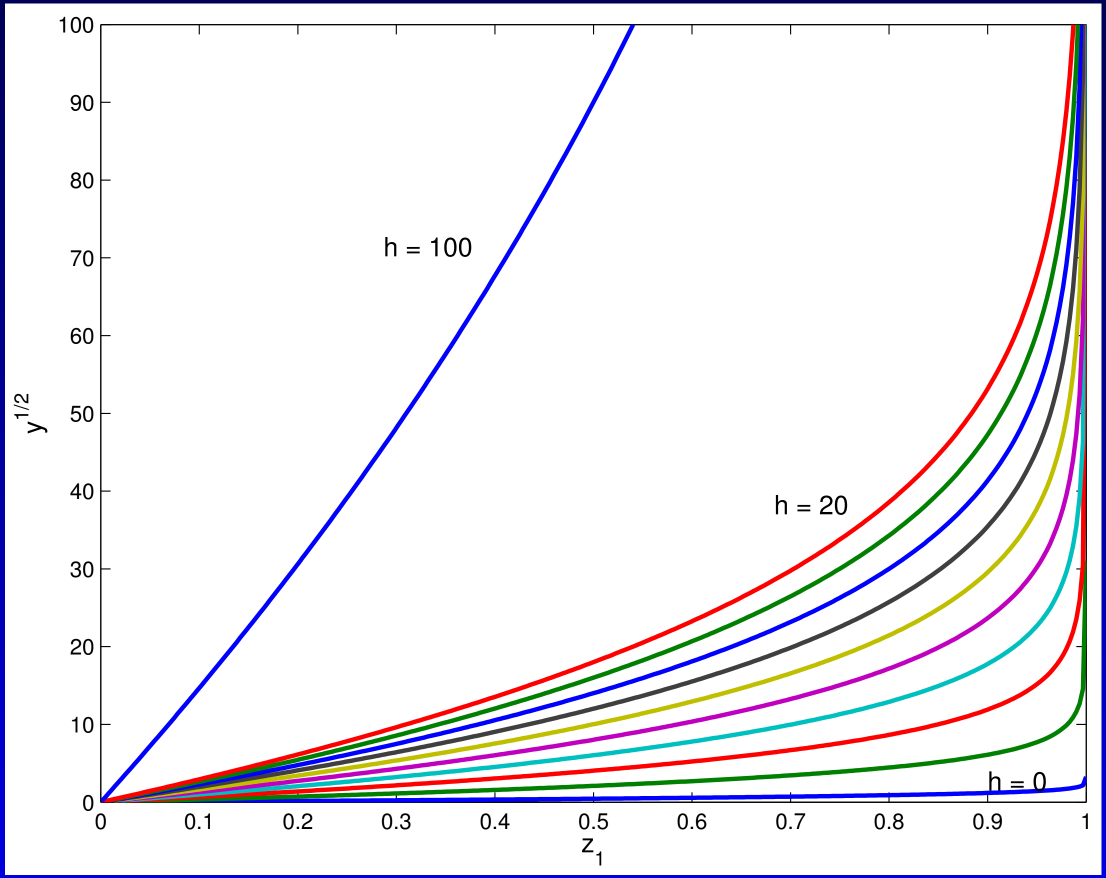

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$$r = \frac{16y}{N} \frac{z(z + 2h\sqrt{z} - 1)^2}{\left[F(h) - 2z + \frac{8}{3}hz^{3/2} + z^2\right]^2}$$

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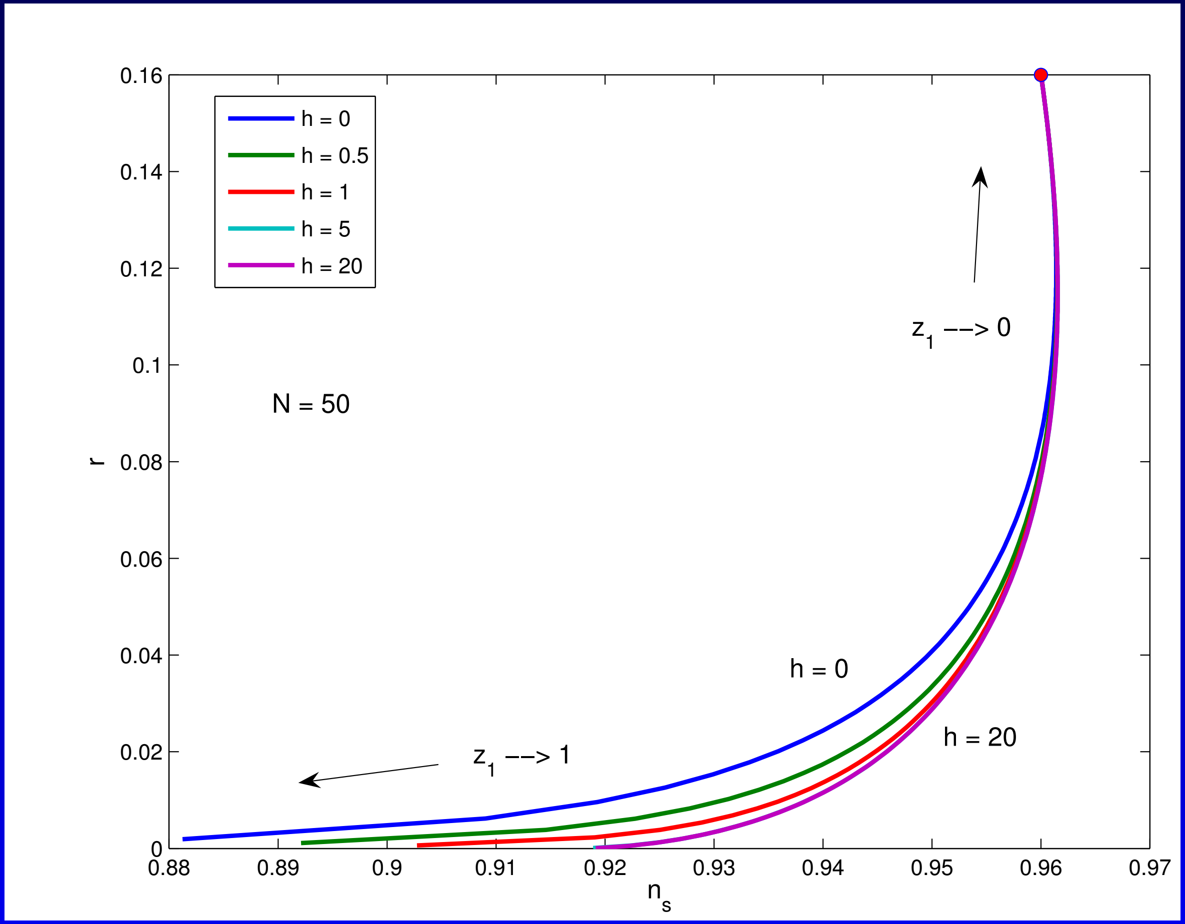

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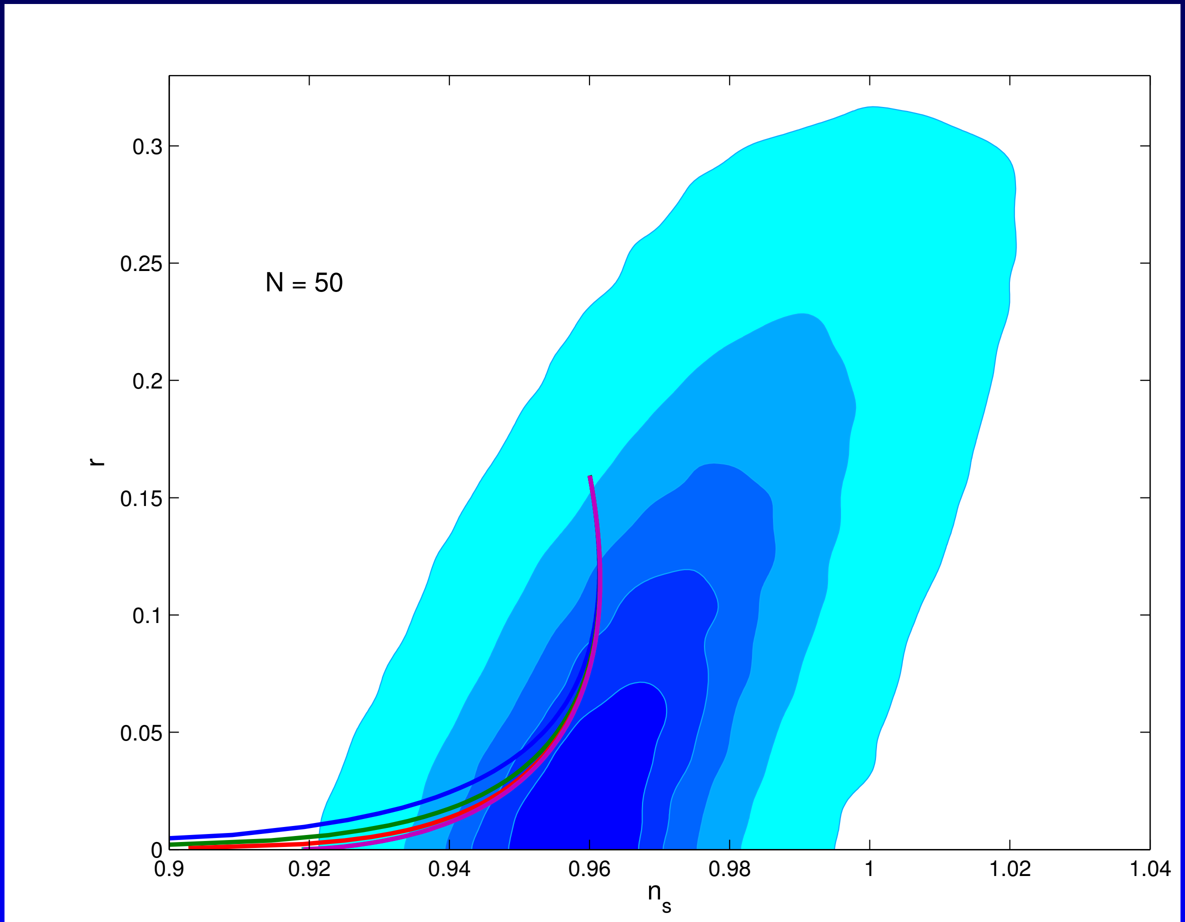

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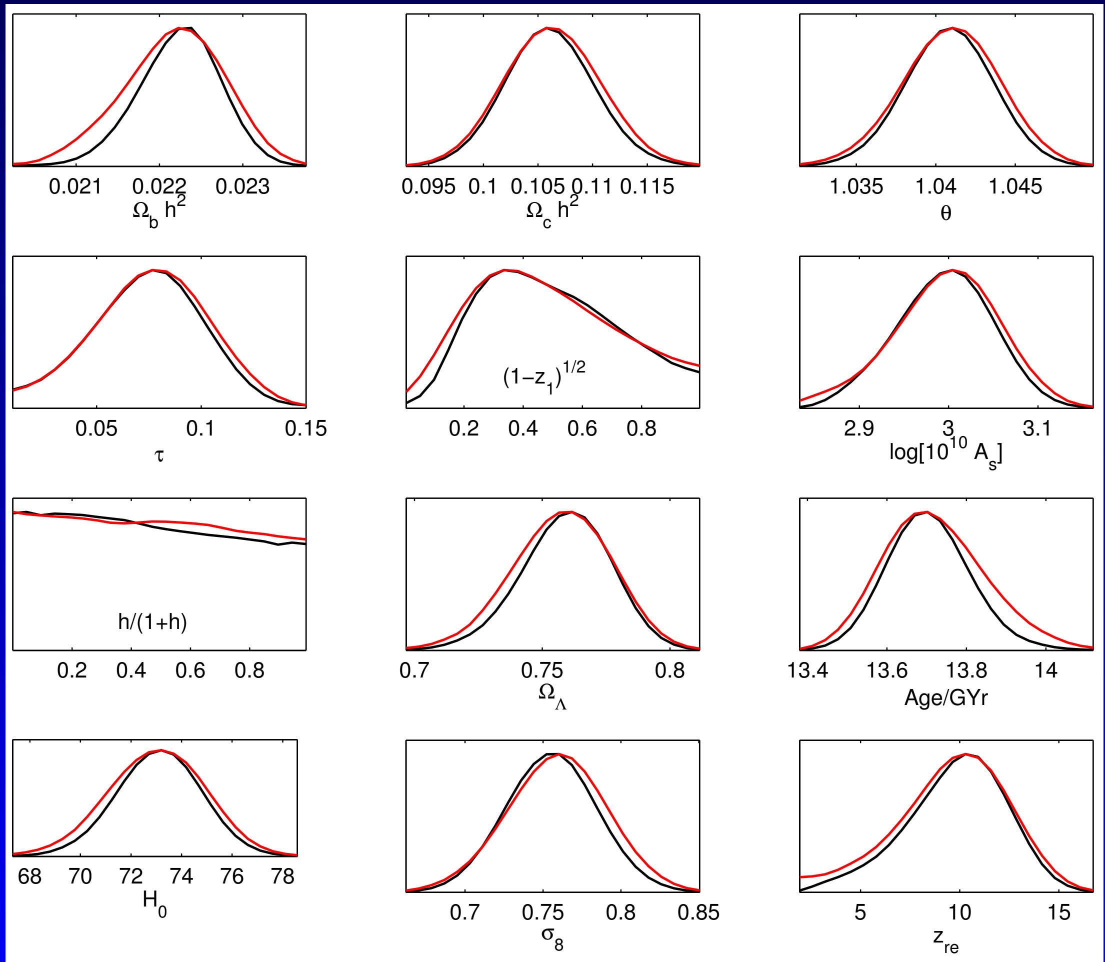

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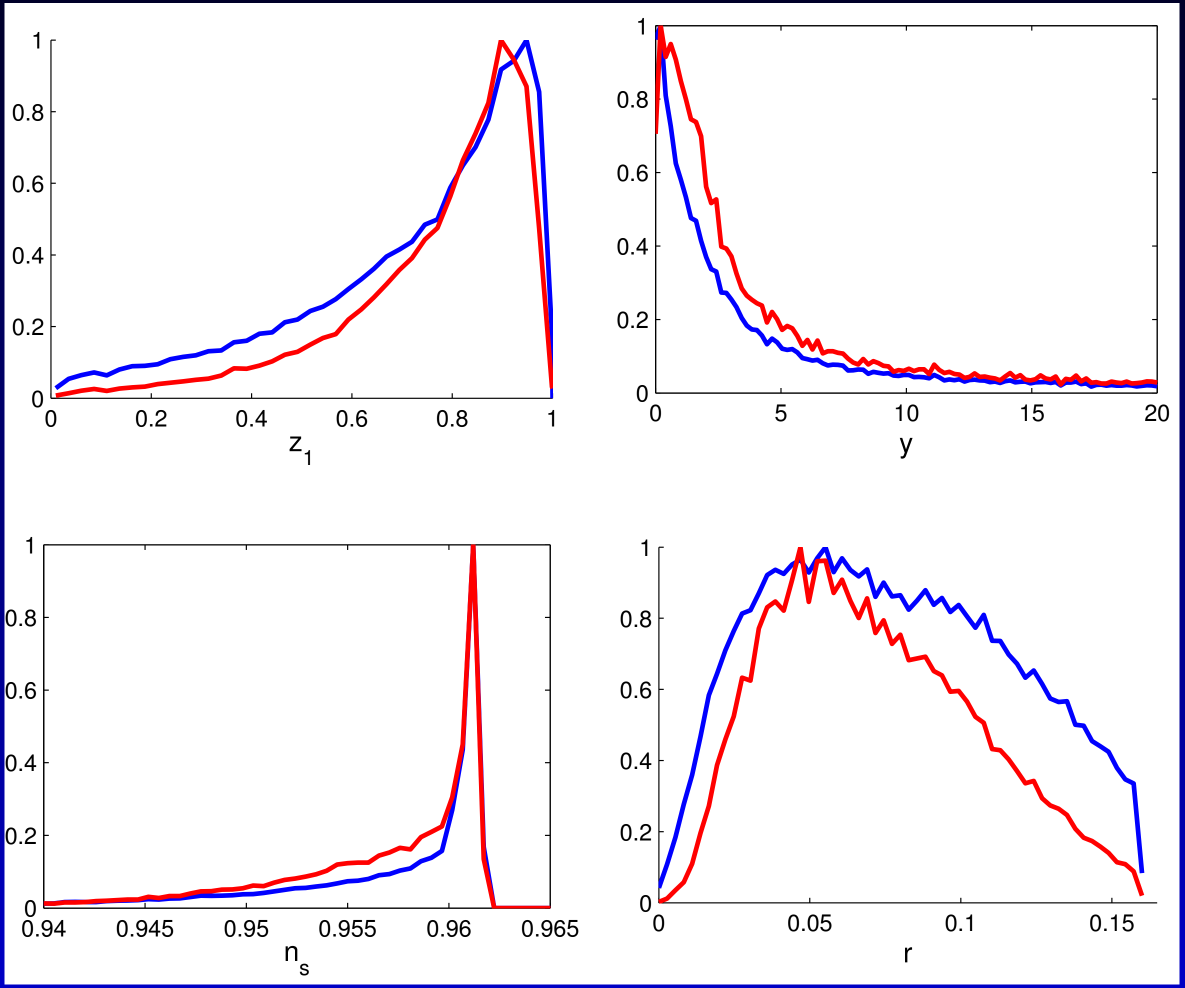
H_0	72.9
σ_8	0.767
$\log[10^{10} A_s]$	0.302
z_1	0.885
h	0.266
$-\log(L)$	2714.153

FlatΛCDM+r vs. trinomial new inflation

param	best fit 1	best fit 2
$100\Omega_b h^2$	2.232	2.22
$\Omega_m h^2$	0.128	0.128
τ	0.956	0.847
H_0	73.03	72.9
σ_8	0.771	0.767
$\log[10^{10} A_s]$	0.303	0.302
n_s	0.956	0.9557
r	0.016	0.054
$-\log(L)$	2714.038	2714.153

The lower bound on r



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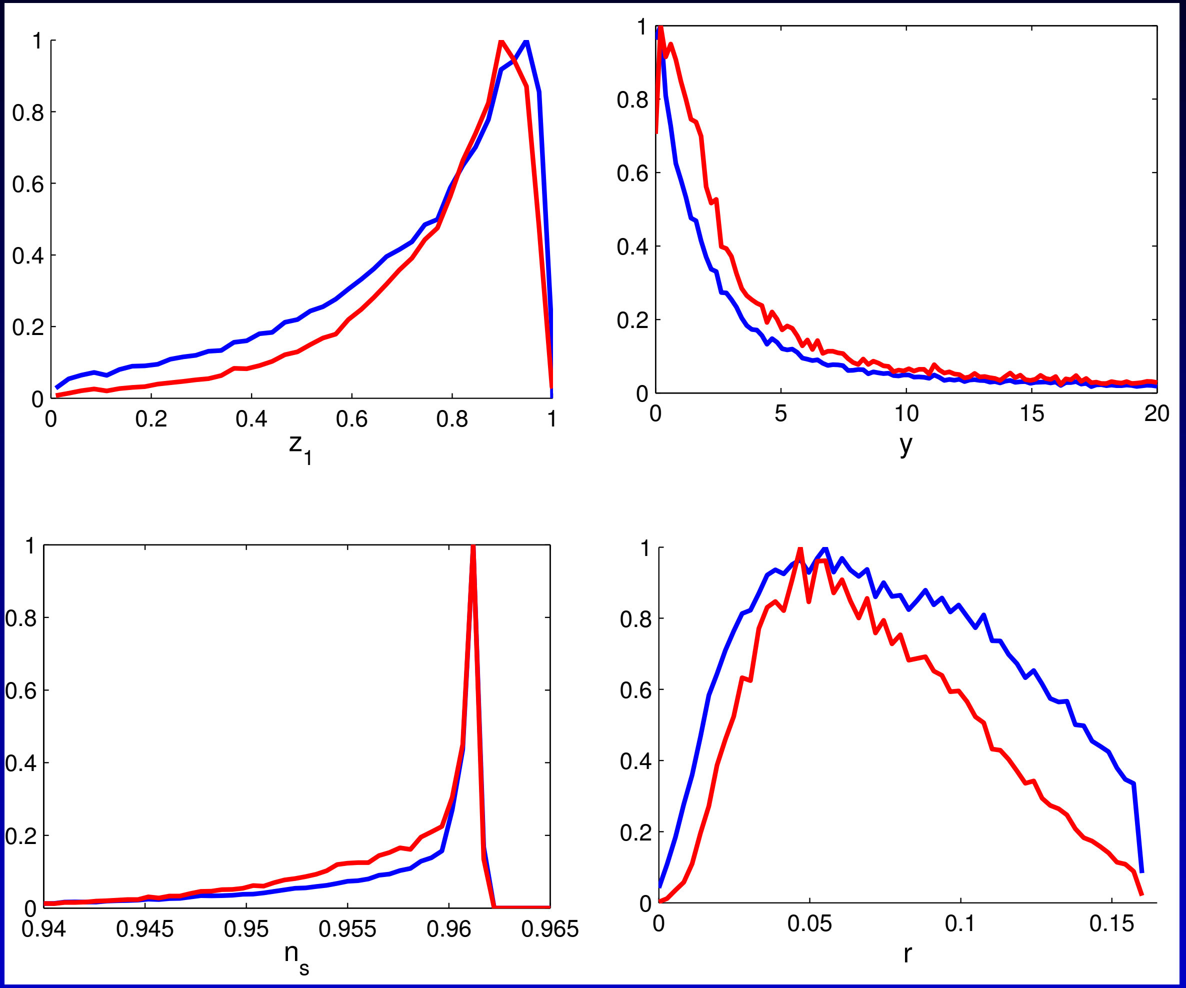

CL: $r > 0.016$ (95%) , $r > 0.049$ (68%)

ML: $r = 0.054$, ML: $y = 1.2$, MV: $r = 0.077$, MV: $y = 2.03$

Trinomial chaotic (= large field) inflation

$$w(\chi) = \frac{1}{2}\chi^2 + \frac{1}{3}h\sqrt{\frac{y}{2}}\chi^3 + \frac{1}{32}y\chi^4 \, , \quad -1 < h \leq 0$$

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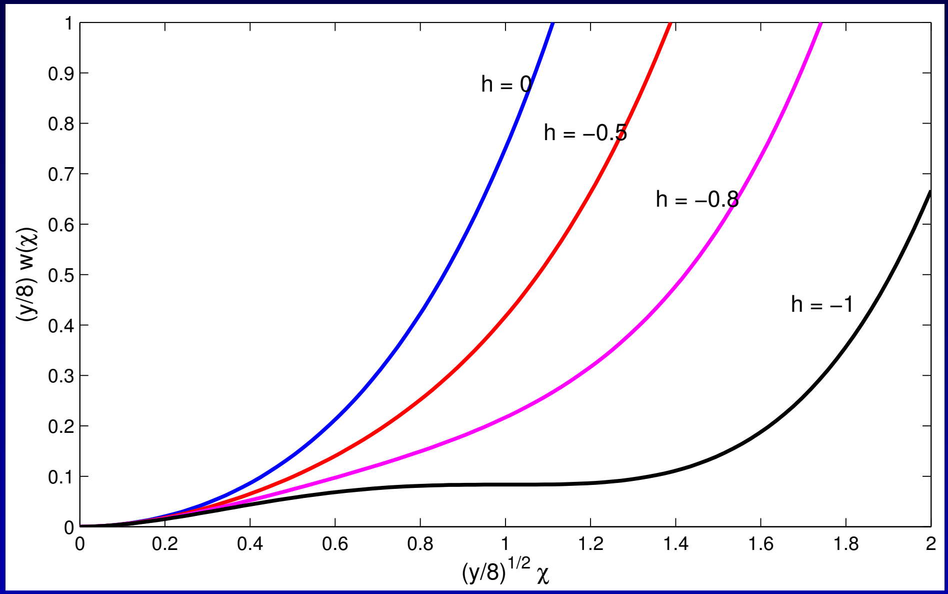

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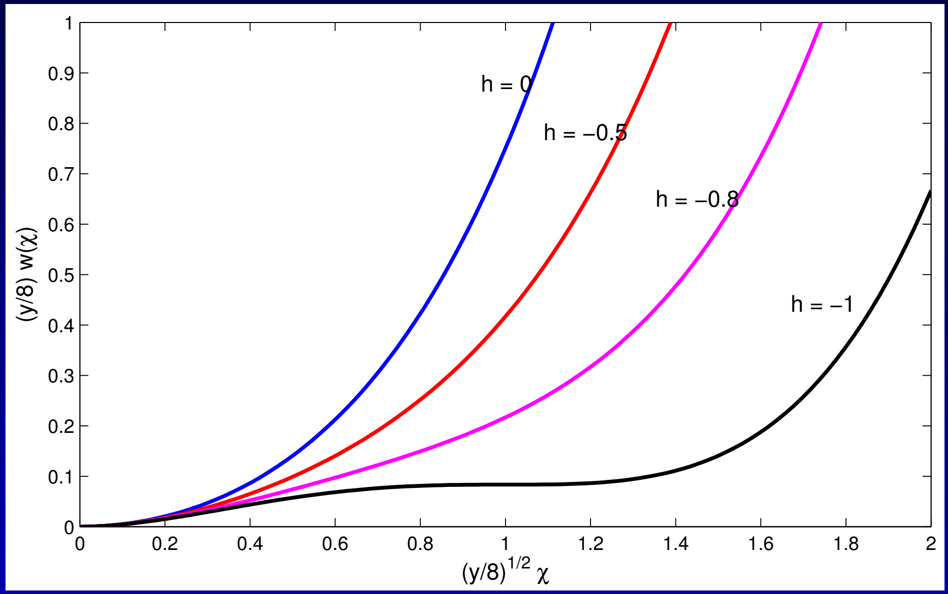

fixing $N \longrightarrow$

$$\boxed{\begin{aligned} y &= z + \frac{4}{3}h\sqrt{z} + \left(1 - \frac{4}{3}h^2\right)\log\left(1 + 2h\sqrt{z} + z\right) \\ &\quad - \frac{4h}{3\Delta}\left(\frac{5}{2} - 2h^2\right)\left[\arctan\left(\frac{h+\sqrt{z}}{\Delta}\right) - \arctan\left(\frac{h}{\Delta}\right)\right] \end{aligned}}$$

where $z \equiv \frac{y}{8}\chi^2_{\text{exit}}$ acts as *effective coupling*, $0 \leq y < \infty$, $0 \leq z < \infty$

$$n_s = 1 - \frac{y}{2Nz}\left[3\frac{\left(1+2h\sqrt{z}+z\right)^2}{\left(1+\frac{4}{3}h\sqrt{z}+\frac{1}{2}z\right)^2} - \frac{1+4h\sqrt{z}+3z}{1+\frac{4}{3}h\sqrt{z}+\frac{1}{2}\,z}\right]$$

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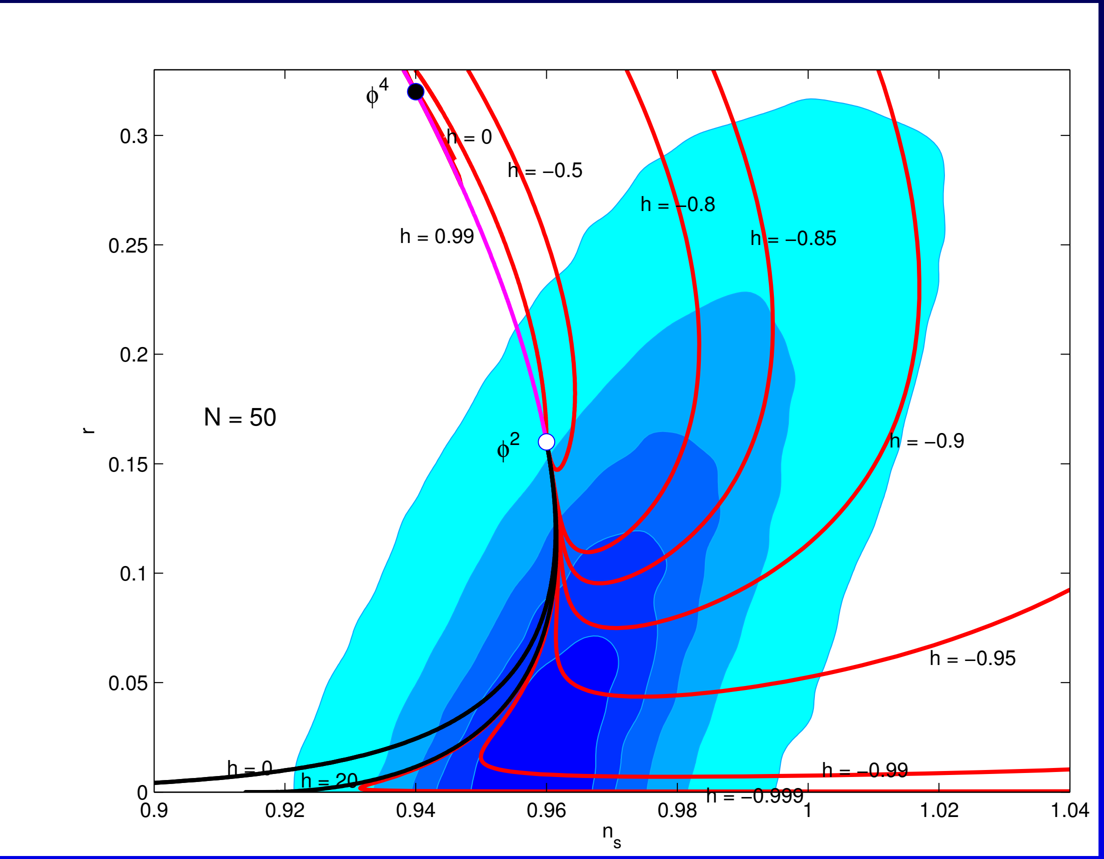

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$$n_s \to 1 - \frac{4}{N} \; , \quad r \to 0 \; , \quad y \sim \frac{1}{1-\sqrt{z}} \to \infty \; , \quad |\Delta_{ad}^{(S)}|^2 \sim \left(\frac{N \, {M^2}^2}{M_{\rm Pl}} \, y \right)^2$$

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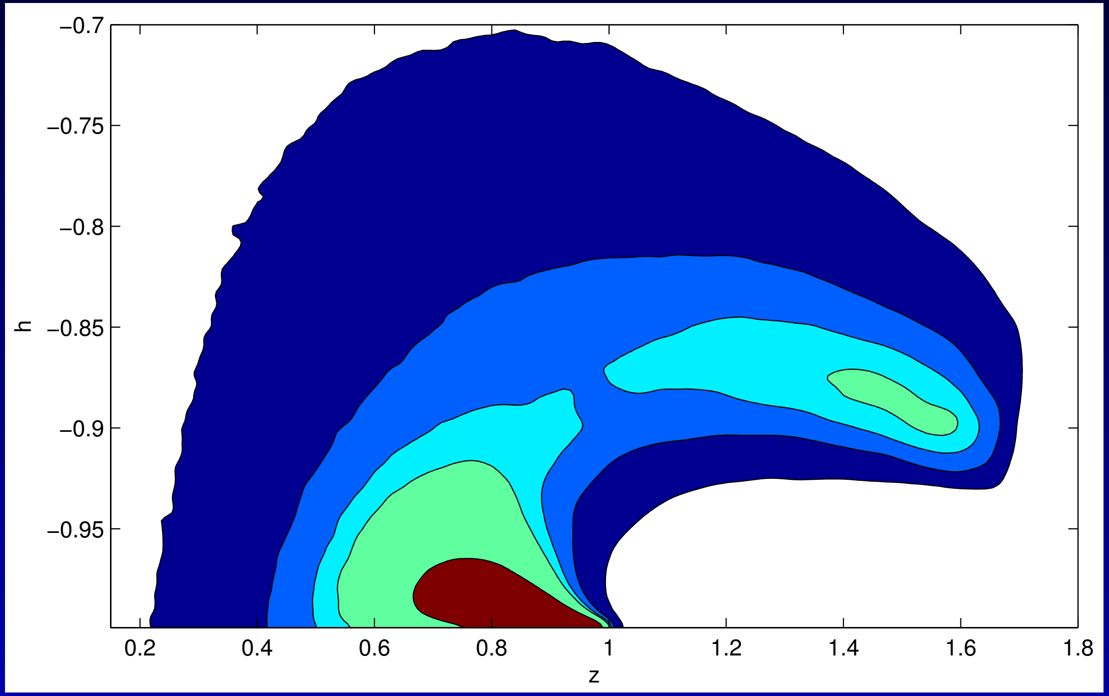
But, even if $\overline{M} \equiv M\,(h+1)^{-1/4}$ is kept fixed:

$$m \sim \frac{\overline{M}^2}{M_{\rm Pl}} (h+1)^{1/2} \;, \quad g \sim \frac{\overline{M}^2}{M_{\rm Pl}^2} (h+1)^{1/4} \;, \quad \lambda \sim \frac{\overline{M}^4}{M_{\rm Pl}^4} (h+1)^{1/2} \;,$$

all vanish yielding a scale–invariant massless free–field.

The marginalized $z - h$ probability

CL: 12%, 27%, 45%, 68% and 95%



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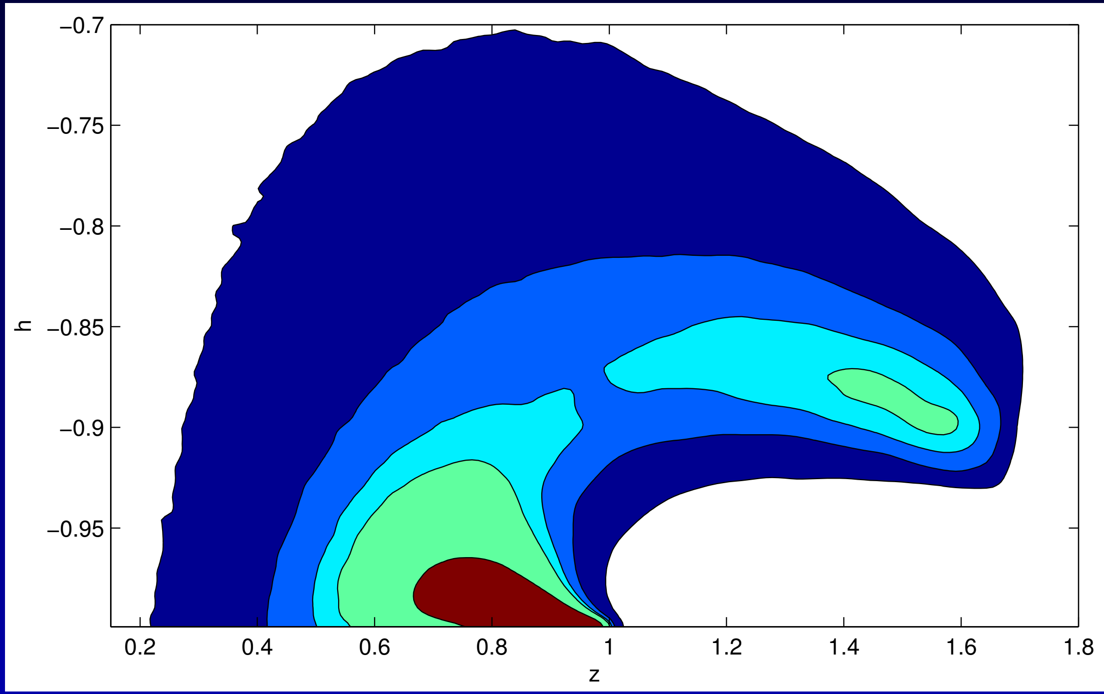

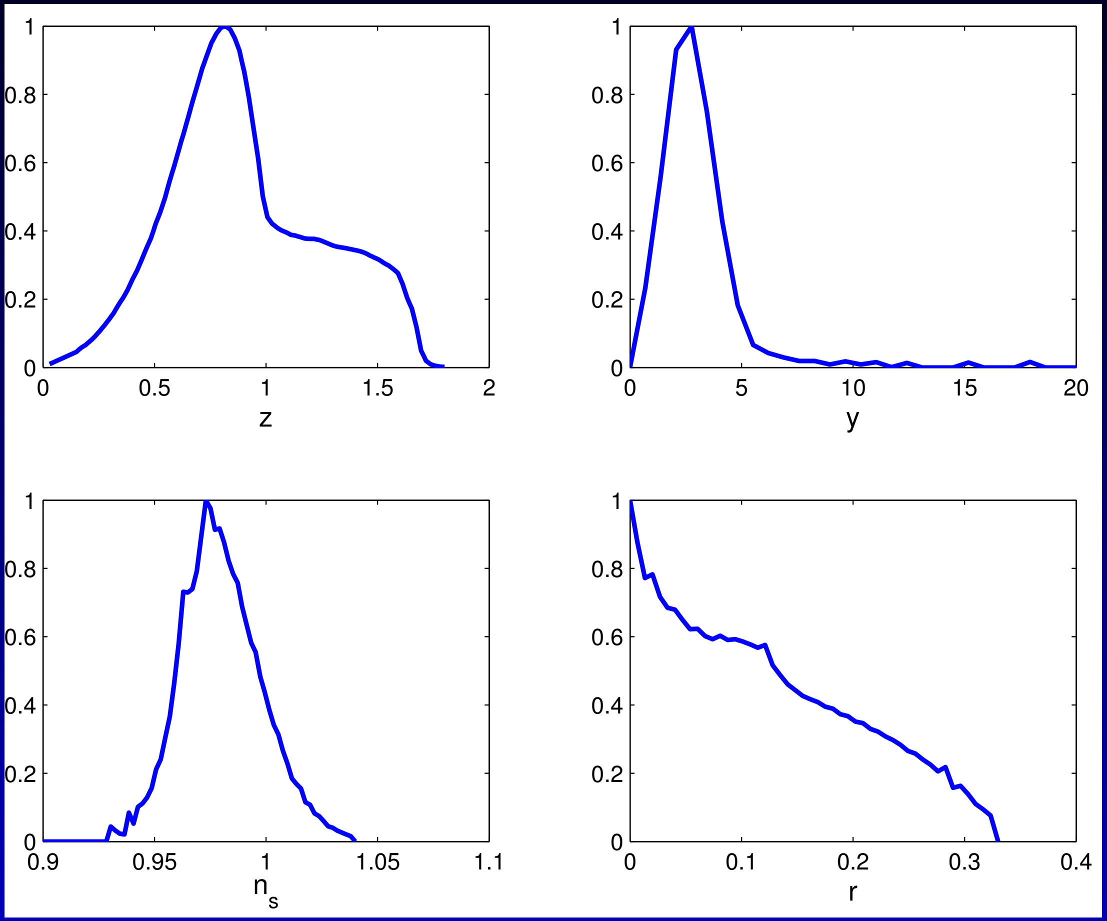

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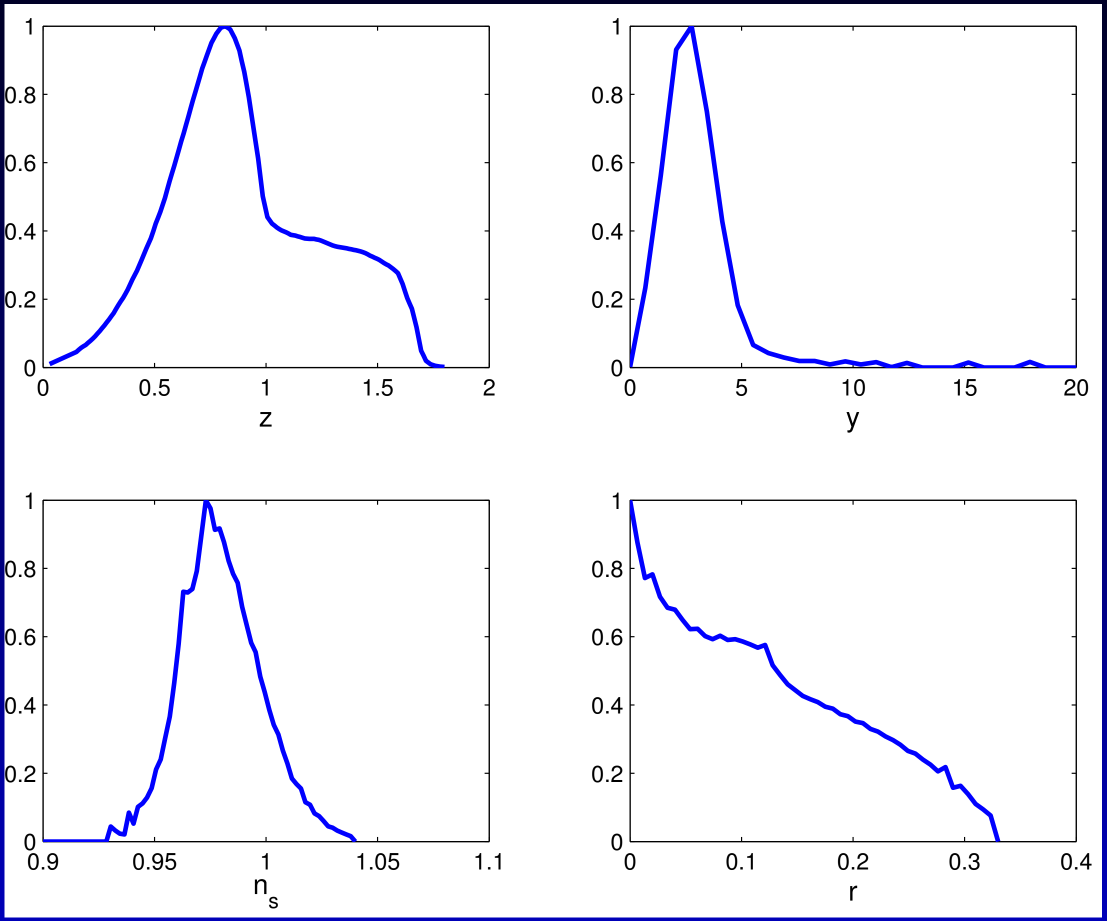

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