Title: Cosmology 5

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Abstract:

Nongaussianity* from tachyonic preheating in hybrid inflation

∗ and spectral distortion

Jim Cline (with Neil Barnaby), McGill University

Theory Canada 2, 9 June 2006, Perimeter Institute

Outline

Based on the paper

JC and N. Barnaby, astro-ph/0601481,
Phys. Rev. D73 (2006) 106012

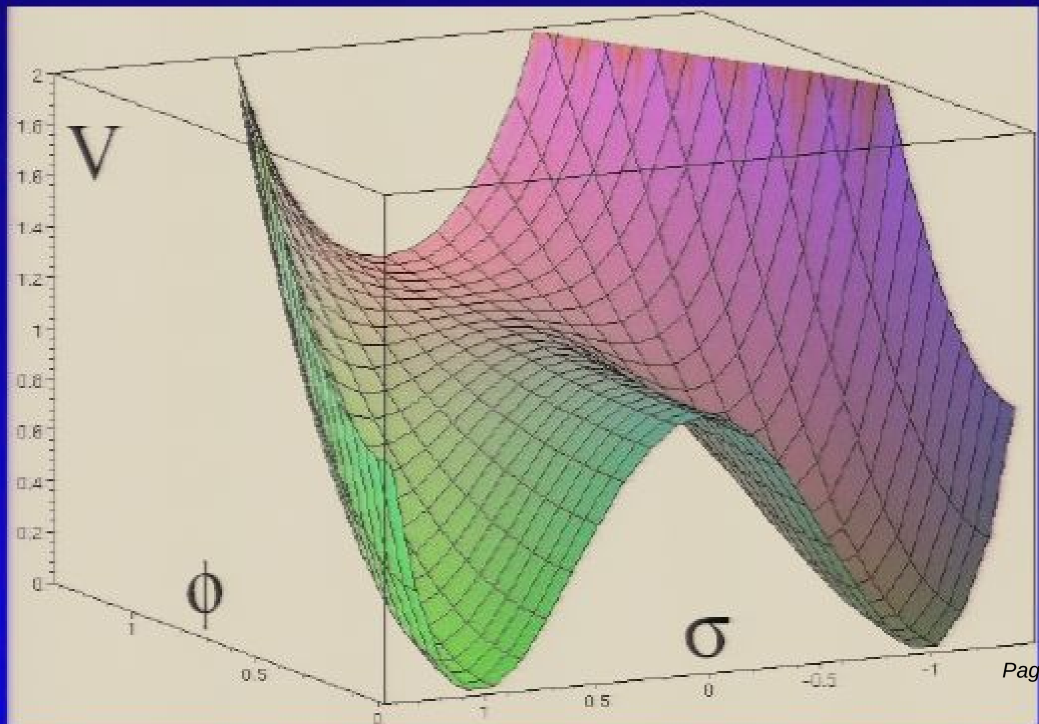
- Brief introduction:
  hybrid inflation and tachyonic preheating
- What we found:
  new constraints on hybrid inflation parameters
- How we computed it:
  tachyonic contribution to curvature fluctuation at second order in cosmological perturbation theory
- Conclusions / future directions:
  inverted hybrid and brane-antibrane inflation

Hybrid Inflation

- motivated by supergravity and string theory
- requires sub-Planckian field values, unlike chaotic inflation.

$$V(\varphi,\sigma) = \frac{\lambda}{4}(\sigma^2 - v^2)^2 + \frac{m_\varphi^2}{2}\varphi^2 + \frac{g^2}{2}\varphi^2\sigma^2$$

"Waterfall" field σ becomes tachyonic at critical value of φ, triggering end of inflation



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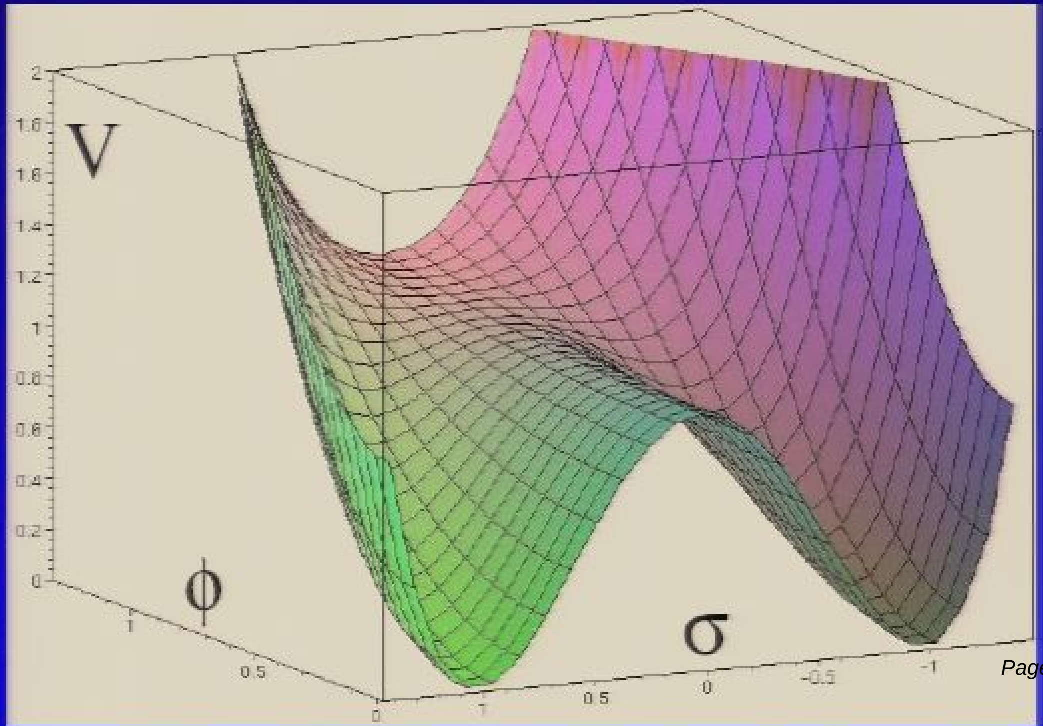
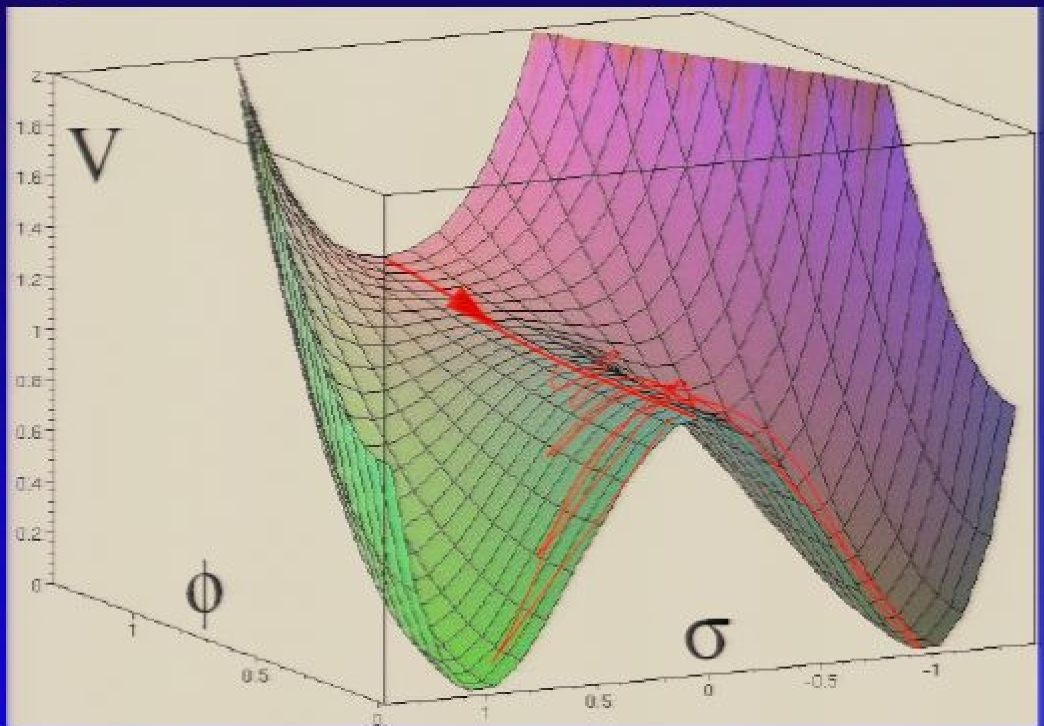


A more accurate picture (during inflation)

- Universe fragments into regions with $\sigma = \pm v$, separated by domain walls (which must decay).
- Initially regions are microscopically small, $\sim \frac{1}{\sqrt{\lambda} v}$.
- $\langle\sigma\rangle = 0$ on large scales, but quantum fluctations $\delta\sigma$ become large, $\sim v$.



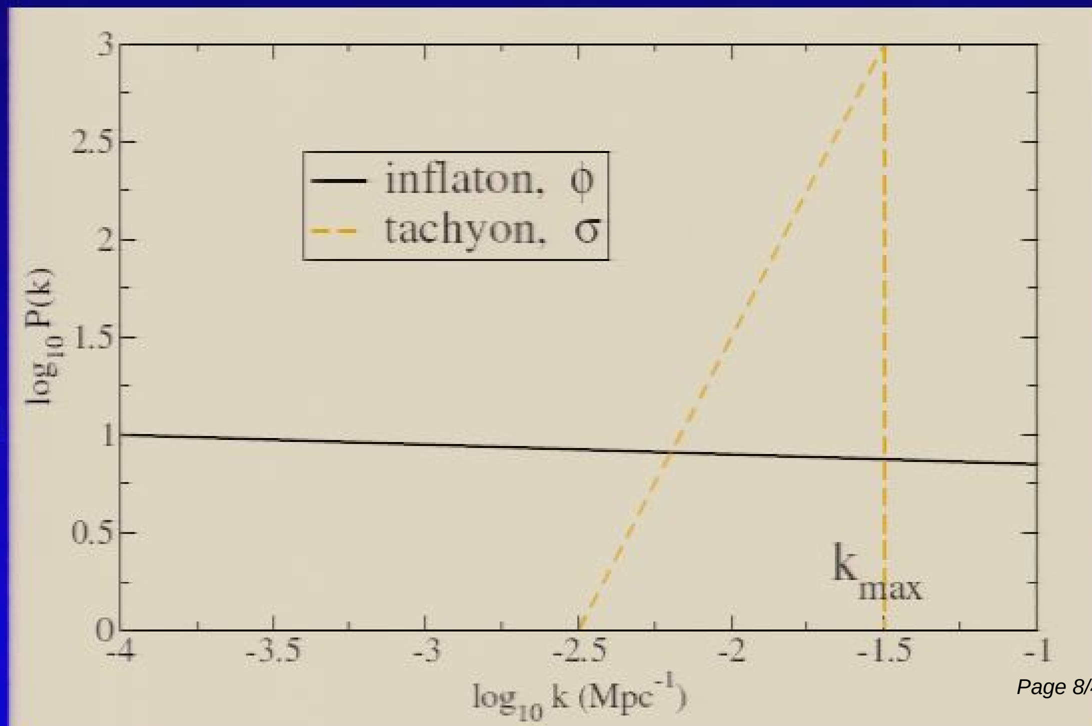
- The tachyonic fluctuations can affect CMB spectrum

Effects on spectrum of CMB (1)

Two observable effects on cosmic microwave background: (1) Spectrum of density perturbations gets nonscale-invariant distortion,

$$P(k) \sim \left(\frac{\delta\rho}{\rho}\right)_k^2 \sim A_\phi \left(\frac{k}{k_0}\right)^{n_s - 1} + A_\sigma \left(\frac{k}{k_0}\right)^3$$

Distortion has spectral index $n_s = 4$ up to some maximum k value, $k_{\max}$



Effects on spectrum of CMB (2)

Two observable effects on cosmic microwave background: (2) Nongaussian perturbations are generated in the curvature perturbation ζ:

$$\underbrace{\langle \zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle}_{\text{bispectrum}} = (2\pi)^{-3/2}\, B(k_i)\, \delta(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$$

B is conventionally parametrized as

$$B(k_i) = -\frac{6}{5} f_{NL} \left(P(k_1)P(k_2) + \text{perms.}\right)$$

in terms of (nearly) scale-invariant spectrum

$$P(k) \cong (4\pi)^2 \times 10^{-10}\, k^{n_s - 4}$$

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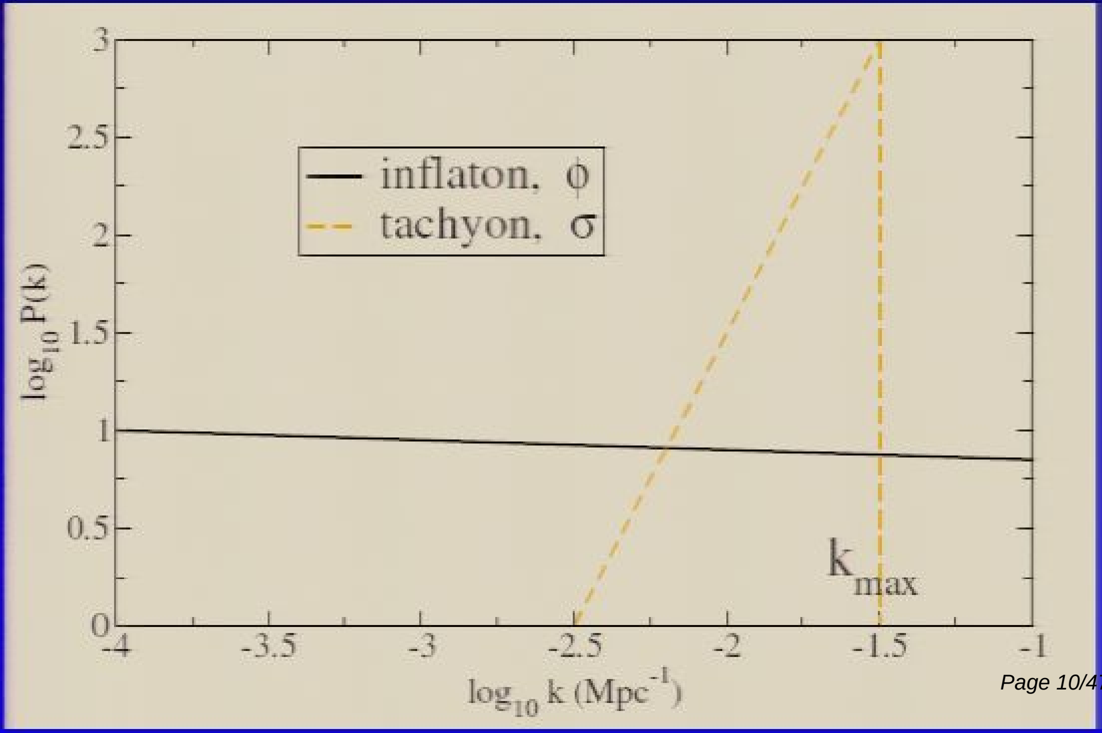

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Note

In single-field inflation, f_{NL} does not depend on magnitude of k, and B is scale invariant,

$$B(k) \sim \frac{10^{-20}}{k^6}$$

In our case, B is not scale invariant,

$$B \sim \text{ constant}$$

at small k. Strongest limit comes from largest k.

Experimental Constraints

WMAP experiment constrains nonlinearity parameter

$$|f_{NL}| \lesssim 100$$

since nongaussian δT fluctuations are not observed.

We also define *linear* parameter

$$f_L = \frac{A_\sigma}{A_\phi} = \frac{P_\sigma(k_{\max})}{P_\phi(k_{\max})}$$

at $k_{\max}$ = maximum k probed by CMB data. We conservatively take

$$f_L < 1$$

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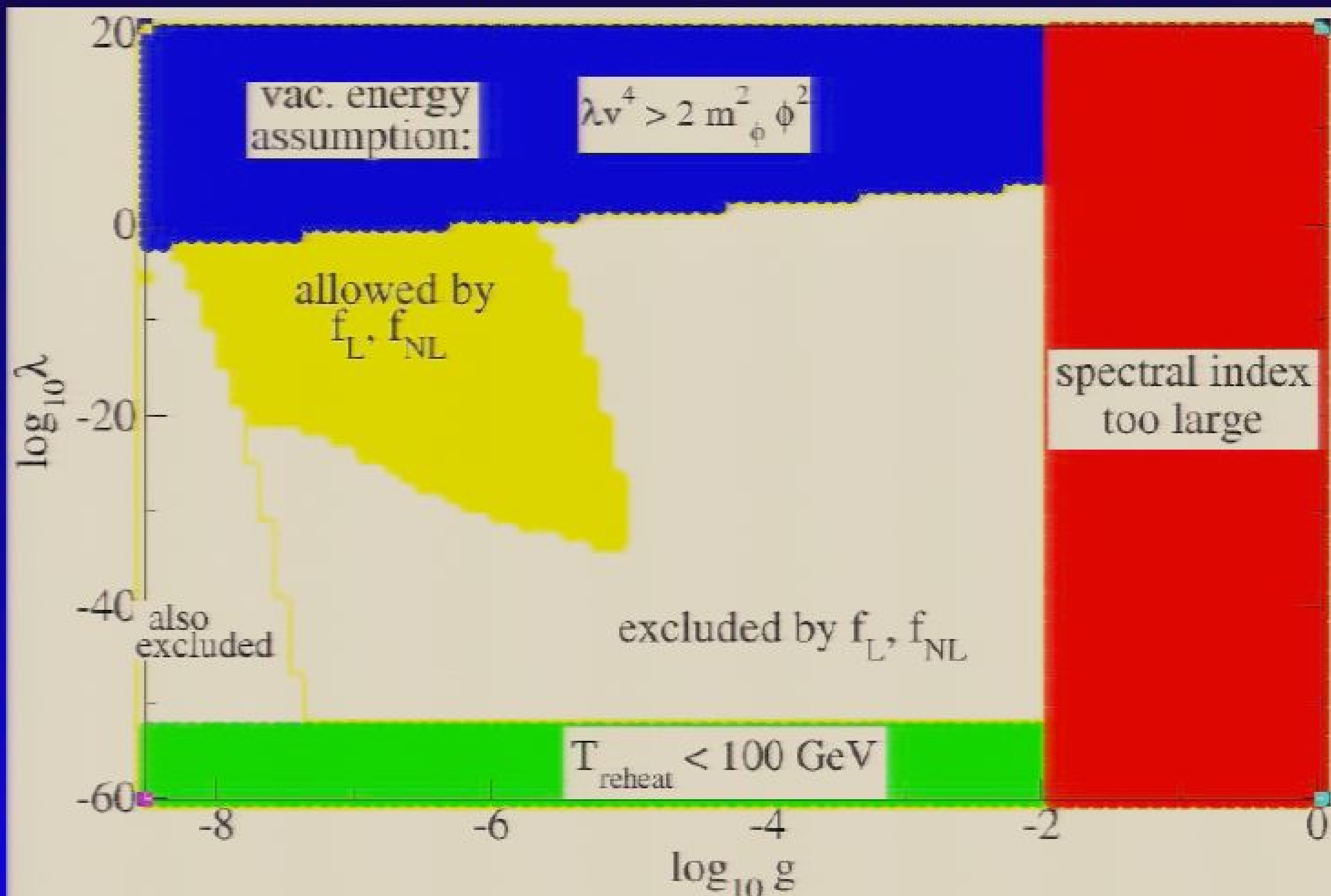
Constraints on parameter space

- Parameter space of model: $\{\lambda, g, v, m_\phi^2\}$
- Fix m_ϕ^2 using normalization of CMB spectrum
- Choose v, obtain constraints in g-λ plane, *e.g.*, $v/M_p = 10^{-3}$:



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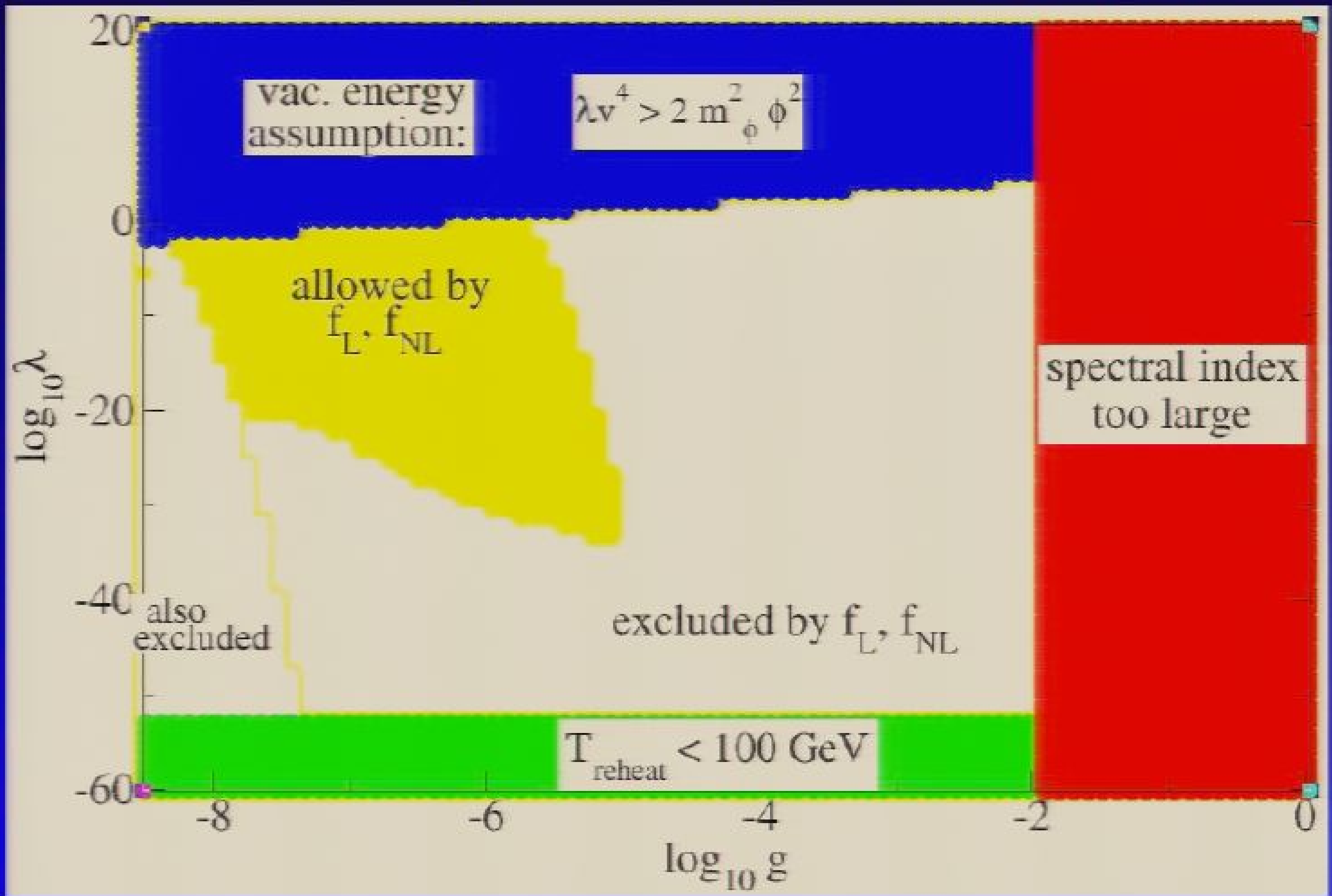

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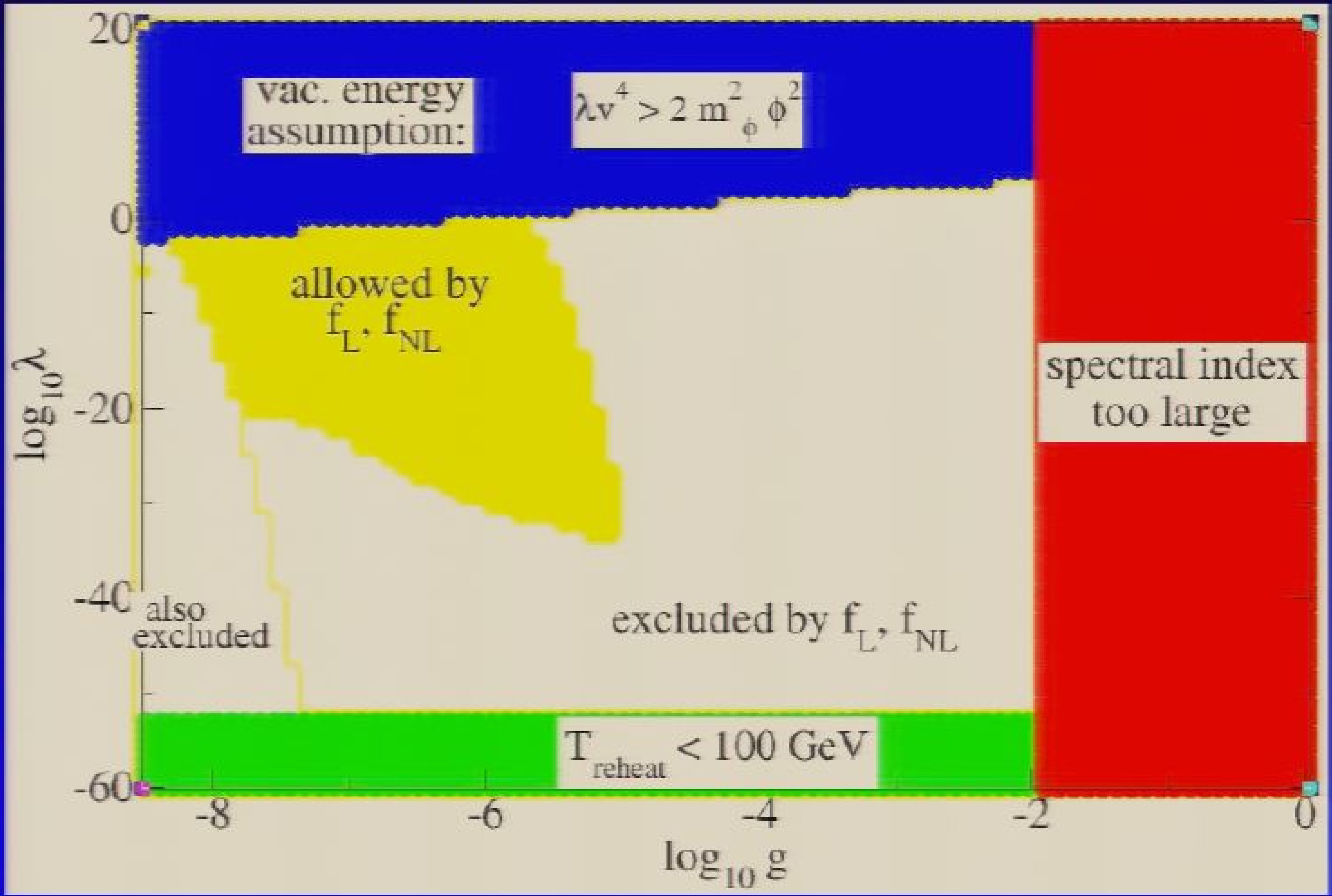
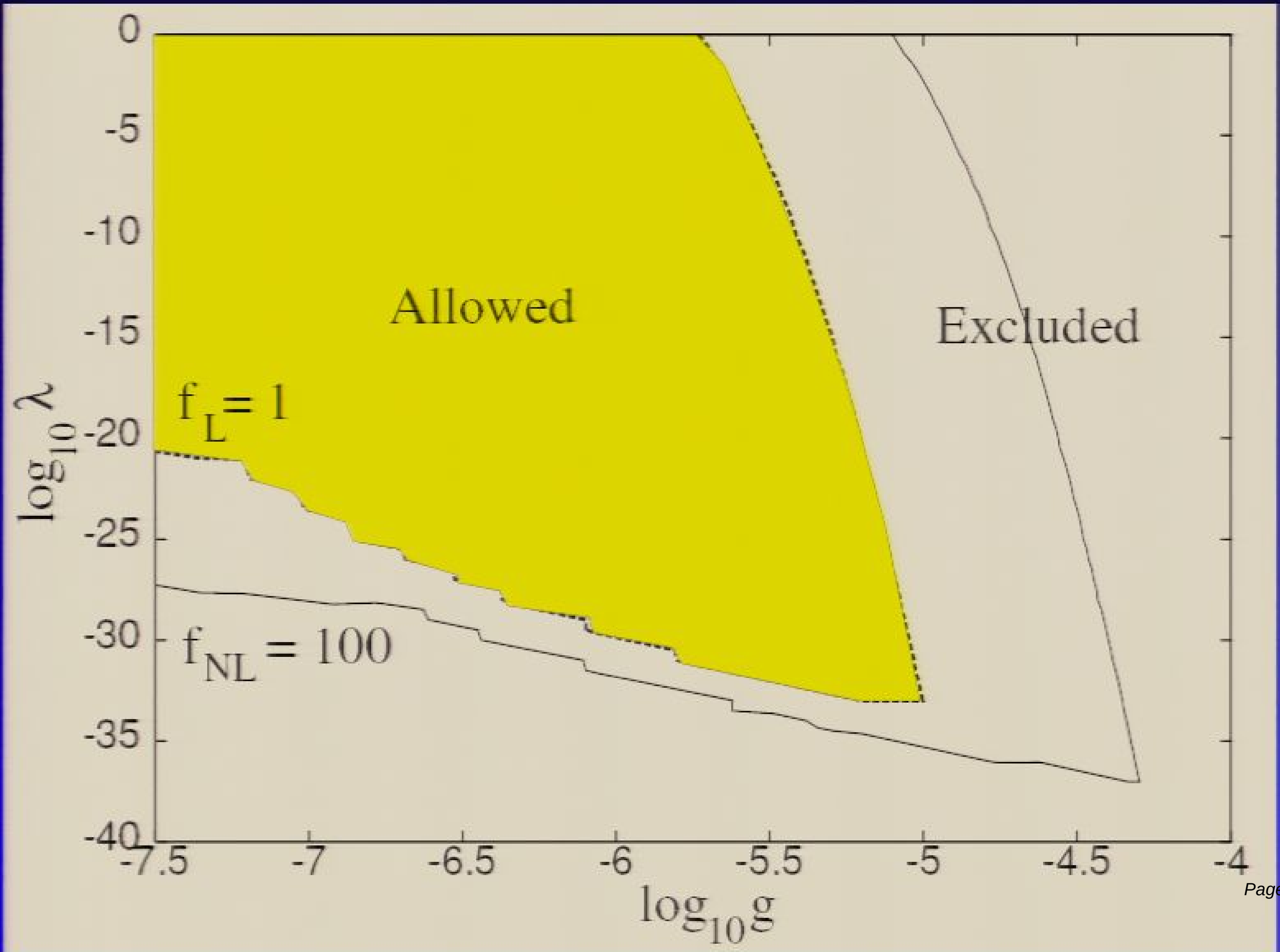


A closer look

Spectral distortion gives more stringent limits than nongaussianity.



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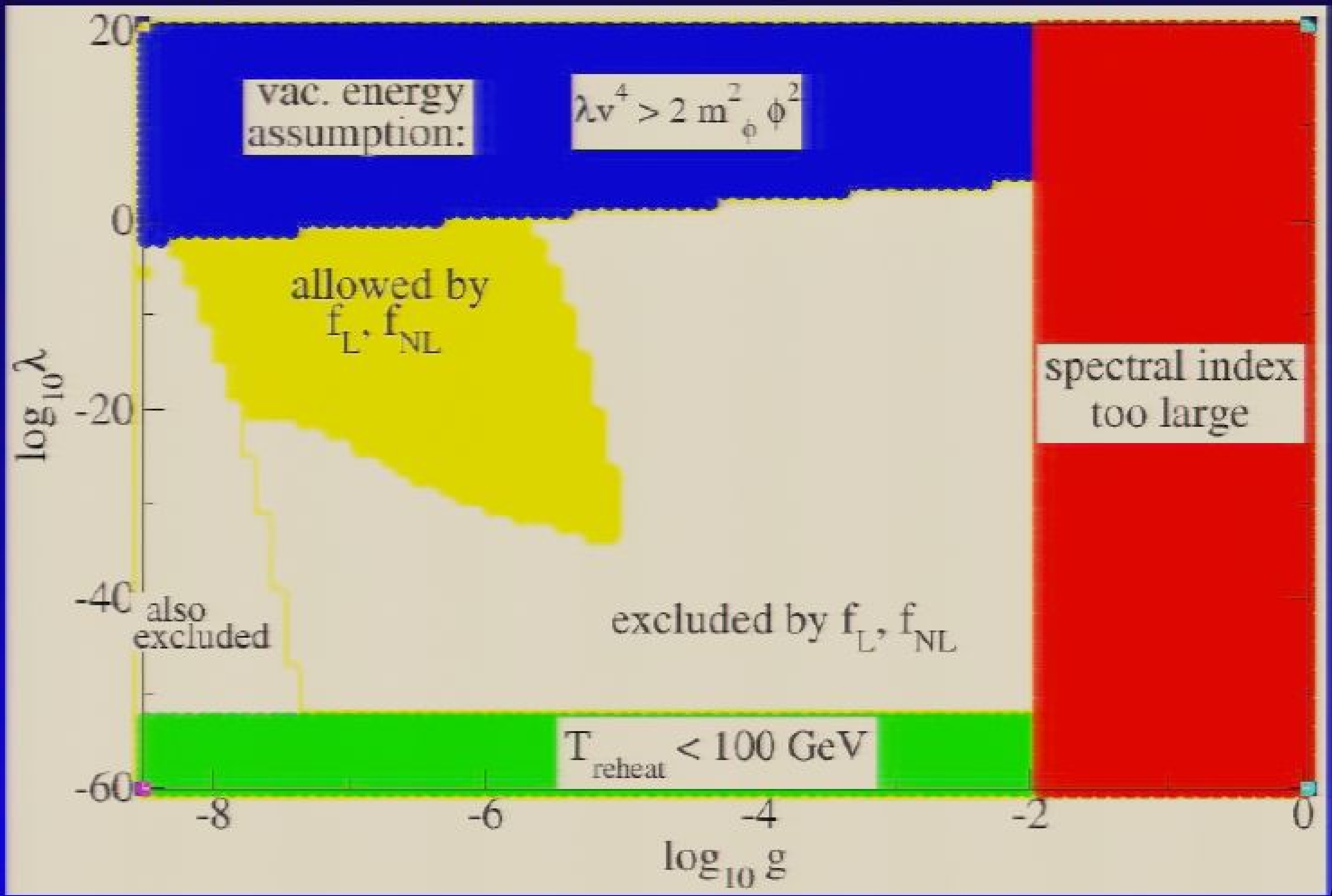

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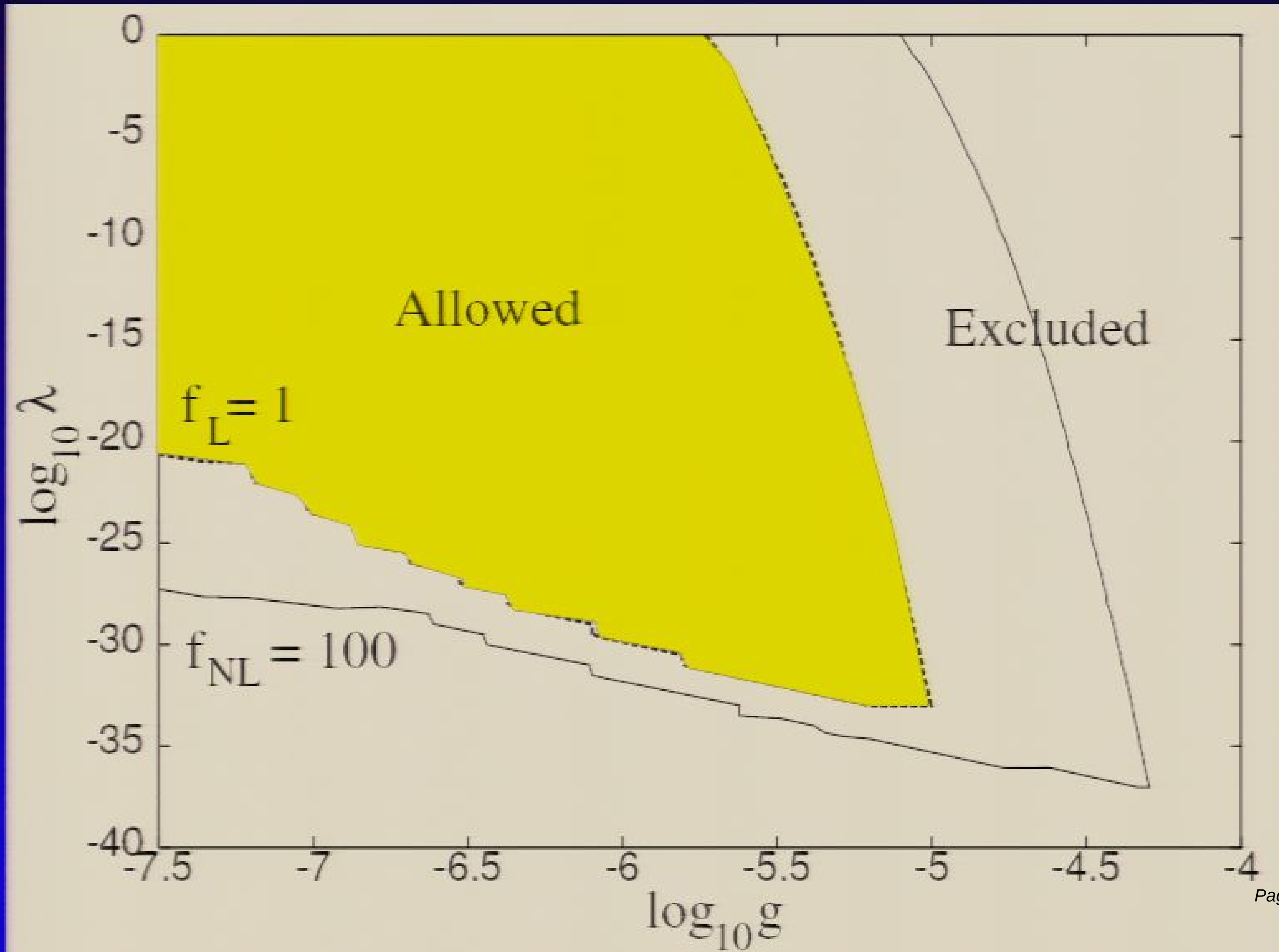
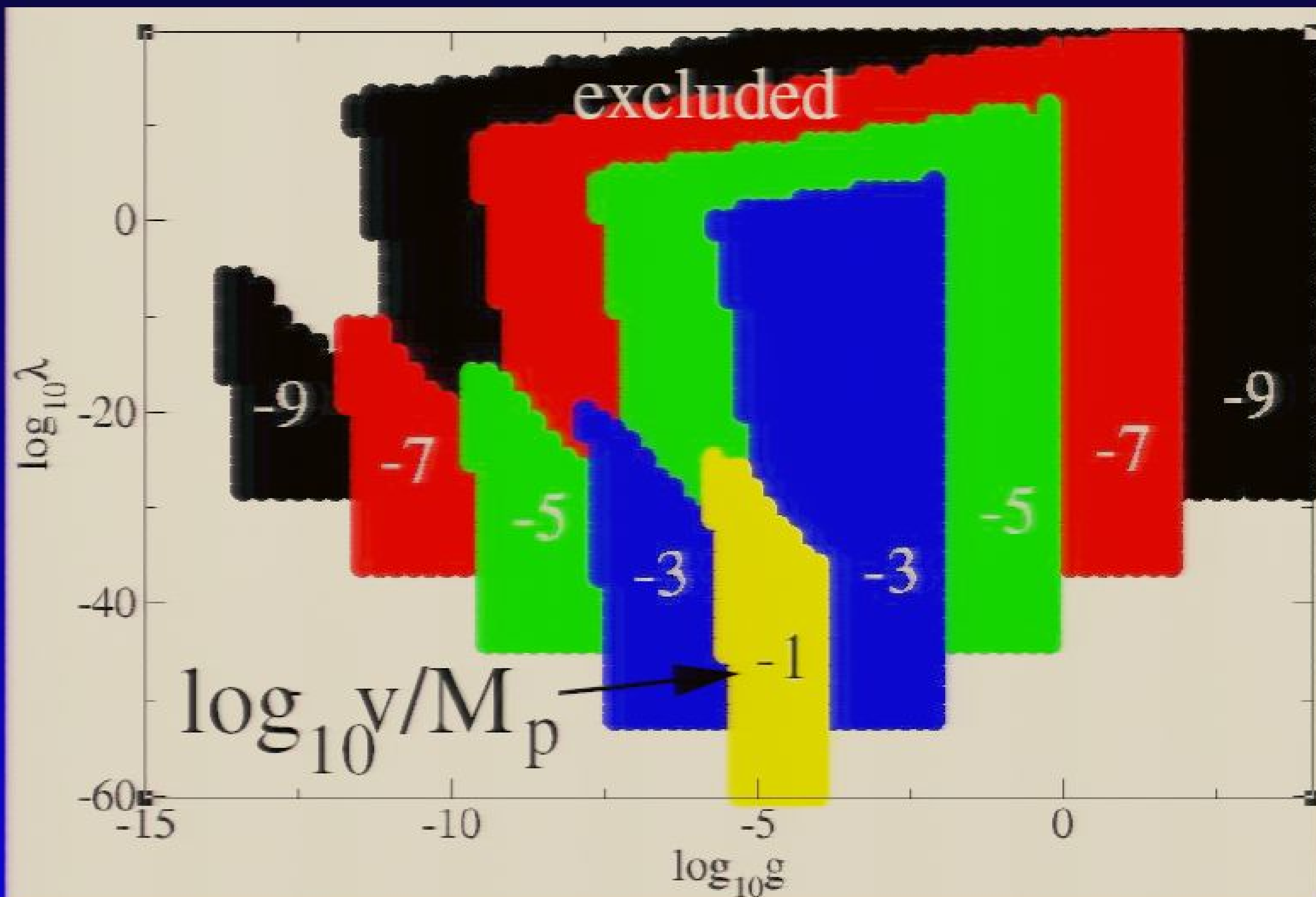


Other values of v

Excluded regions get larger as v/M_p gets smaller:



Cosmological perturbation theory

Must choose a gauge for metric; we take longitudinal —similar to Coulomb gauge in electrodynamics,

$$
\begin{aligned}
g_{00} &= -a(\tau)^2\left[1+2\phi^{(1)}+\phi^{(2)}\right] \\
g_{0i} &= 0 \\
g_{ij} &= a(\tau)^2\Big[\left(1-2\psi^{(1)}-\psi^{(2)}\right)\delta_{ij} \\
&+ \frac{1}{2}\left(\partial_i\chi_j^{(2)}+\partial_j\chi_i^{(2)}+\chi_{ij}^{(2)}\right)\Big]
\end{aligned}
$$

Matter fields, sources for metric fluctuations:

$$
\begin{aligned}
\varphi(\tau,\vec{x}) &= \varphi_0(\tau)+\delta^{(1)}\varphi(\tau,\vec{x})+\frac{1}{2}\delta^{(2)}\varphi(\tau,\vec{x}) \\
\sigma(\tau,\vec{x}) &= \sigma_0(\tau)+\delta^{(1)}\sigma(\tau,\vec{x})+\frac{1}{2}\delta^{(2)}\sigma(\tau,\vec{x})
\end{aligned}
$$

Procedure

(1) Solve Einstein equations for 2nd order curvature perturbation (Malik, astro-ph/0506532)

$$
\begin{aligned}
\zeta^{(2)} \; &= \; \frac{1}{3-\epsilon}\frac{1}{(\varphi_0')^2}\left[\varphi_0' Q_\varphi'^{(2)} + a^2 \frac{\partial V}{\partial \varphi} Q_\varphi^{(2)}\right] \\
&+ \; \frac{1}{3-\epsilon}\frac{1}{(\varphi_0')^2}\left[\left(Q_\sigma'^{(1)}\right)^2 + a^2 m_\sigma^2 \left(Q_\sigma^{(1)}\right)^2\right] \\
&+ \; \frac{1}{3-\epsilon}\frac{1}{(\varphi_0')^2}\left[\left(Q_\varphi'^{(1)}\right)^2 + a^2 m_\varphi^2 \left(Q_\varphi^{(1)}\right)^2\right] \\
&+ \; 4(3+\epsilon-\eta)\left(\frac{3-2\epsilon}{3-\epsilon}\right)\left(\frac{\mathcal{H}}{\varphi_0'} Q_\varphi^{(1)}\right)^2 \\
&+ \; (-10+2\epsilon+2\eta)\left(\frac{\mathcal{H}}{\varphi_0'} Q_\varphi^{(1)}\right)^2
\end{aligned}
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Procedure

(1) Solve Einstein equations for 2nd order curvature perturbation (Malik, astro-ph/0506532) where

$$\epsilon,\ \eta = \text{slow-roll parameters},$$

$$' = \frac{d}{d\tau},\ (\tau = \text{conformal time}), \quad \mathcal{H} = \frac{1}{a}\frac{da}{d\tau}$$

1st order Sasaki-Mukhanov variables:

$$Q_\varphi^{(1)} = \frac{\varphi_0'}{\mathcal{H}}\mathcal{R}^{(1)} \qquad Q_\sigma^{(1)} = \delta^{(1)}\sigma$$

2nd order Sasaki-Mukhanov variables:

$$\begin{aligned} Q_\varphi^{(2)} &= \delta^{(2)}\varphi + \frac{\varphi_0'}{\mathcal{H}}\psi^{(2)} + (2 + 2\epsilon - \eta)\frac{\varphi_0'}{\mathcal{H}}\left(\phi^{(1)}\right)^2 \\ &+ 2\frac{\varphi_0'}{\mathcal{H}^2}\phi^{(1)}\phi'^{(1)} + \frac{2}{\mathcal{H}}\phi^{(1)}\delta^{(1)}\varphi'. \end{aligned}$$

Procedure

(2) Numerically solve for quantum fluctuations of σ in time-dependent background,

$$\frac{d^2}{dN^2}\delta^{(1)}\sigma_k + 3\frac{d}{dN}\delta^{(1)}\sigma_k + \left[\hat{k}^2 e^{-2N} - cN\right]\delta^{(1)}\sigma_k = 0$$

where

$$N = Ht = \text{number of e-foldings}$$

and tachyon (mass)^2 is time-dependent,

$$m_\sigma^2 = cN + O(N^2); \quad c = 96\frac{M_p^4 m_\phi^2}{\lambda v^6} = 22000g\frac{M_p}{v}$$

Technical assumption: m_σ^2 varies linearly with time during inflation. Consistent with constraint on spectral index,

$$n_s > 0.95$$

Procedure

(3) Find spectrum and bispectrum of $\zeta^{(2)} = F[(\delta^{(1)}\sigma)^2]$,

$$\left\langle \zeta^{(2)}_{k_1}\,\zeta^{(2)}_{k_2} \right\rangle_{\rm con} = \delta(\vec{k}_1 + \vec{k}_2) S(\vec{k}_i)$$

$$\left\langle \zeta^{(2)}_{k_1}\,\zeta^{(2)}_{k_2}\,\zeta^{(2)}_{k_3} \right\rangle_{\rm con} \equiv (2\pi)^{-3/2}\,\delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\,B(\vec{k}_i)$$

using tachyon two-point function,

$$\left\langle \delta^{(1)}\sigma_{p_i}\delta^{(1)}\sigma_{q_i} \right\rangle = \xi_{p_i}\xi_{q_i}\,\delta^{(3)}(p_i + q_i)$$

where mode function ξ satisfies tachyon e.o.m.,

$$\delta^{(1)}\sigma(x) = \int \frac{d^3k}{(2\pi)^{3/2}}\,a_k\,\xi_k(N)\,e^{ikx} + \text{h.c.}$$

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Important Details: $\zeta^{(2)}$

Previous authors have had difficulty solving for $\zeta^{(2)}$,

$$
\begin{aligned}
\zeta^{(2)} &\ni -\frac{\phi'^{(2)}}{\epsilon\mathcal{H}} - \left(\frac{1}{\epsilon}+1\right)\phi^{(2)} + \frac{1}{3-\epsilon}\frac{\partial^k\partial_k\phi^{(2)}}{\epsilon\mathcal{H}^2} \\
&+ \frac{1}{\epsilon\mathcal{H}}\triangle^{-1}\gamma' + \triangle^{-1}\gamma - \frac{1}{3-\epsilon}\frac{1}{\epsilon\mathcal{H}^2}\gamma \\
&+ \frac{1}{3-\epsilon}\frac{1}{(\varphi_0')^2}\left[\left(\delta^{(1)}\sigma'\right)^2 + a^2 m_\sigma^2\left(\delta^{(1)}\sigma\right)^2\right] \\
&+ \cdots \\
\phi_k^{(2)}(\tau) &= \int d\tau' G_k(\tau,\tau')(-\tau')^{2(\epsilon-\eta)} J_k(\tau') \\
G_k(\tau,\tau') &= \frac{\pi}{2}\Theta(\tau-\tau')(\tau\tau')^{1/2+\eta-\epsilon} \\
&\times \left[J_\nu(-k\tau)Y_\nu(-k\tau') - J_\nu(-k\tau')Y_\nu(-k\tau)\right] \\
\nu &\cong 1/2 + 3\epsilon - \eta
\end{aligned}
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J(\tau,\vec{x}) &= a^2\kappa^2 m_\sigma^2\left(\delta^{(1)}\sigma\right)^2 - 2\kappa^2\left(\delta^{(1)}\sigma'\right)^2 \\
&+ 2\kappa^2\mathcal{H}(1+\eta-\epsilon)\triangle^{-1}\partial_i\left(\delta^{(1)}\sigma'\partial^i\delta^{(1)}\sigma\right) \\
&+ 4\kappa^2\triangle^{-1}\partial_\tau\partial_i\left(\delta^{(1)}\sigma'\partial^i\delta^{(1)}\sigma\right) \\
&- \mathcal{H}(1+2\epsilon-2\eta)\triangle^{-1}\gamma' + \triangle^{-1}\gamma'' \\
&+ \text{inflaton contributions} \\
\gamma &= -3\kappa^2\triangle^{-1}\partial_i\left(\partial^k\partial_k\delta^{(1)}\sigma\partial^i\delta^{(1)}\sigma\right) \\
&- \frac{\kappa^2}{2}\left(\partial_i\delta^{(1)}\sigma\partial^i\delta^{(1)}\sigma\right) + \cdots .
\end{aligned}
$$

Looks highly nonlocal due to inverse Laplacians!

Important Details: $\zeta^{(2)}$

But with sufficient care, final expression simplifies greatly, and is local, as demanded by causality:

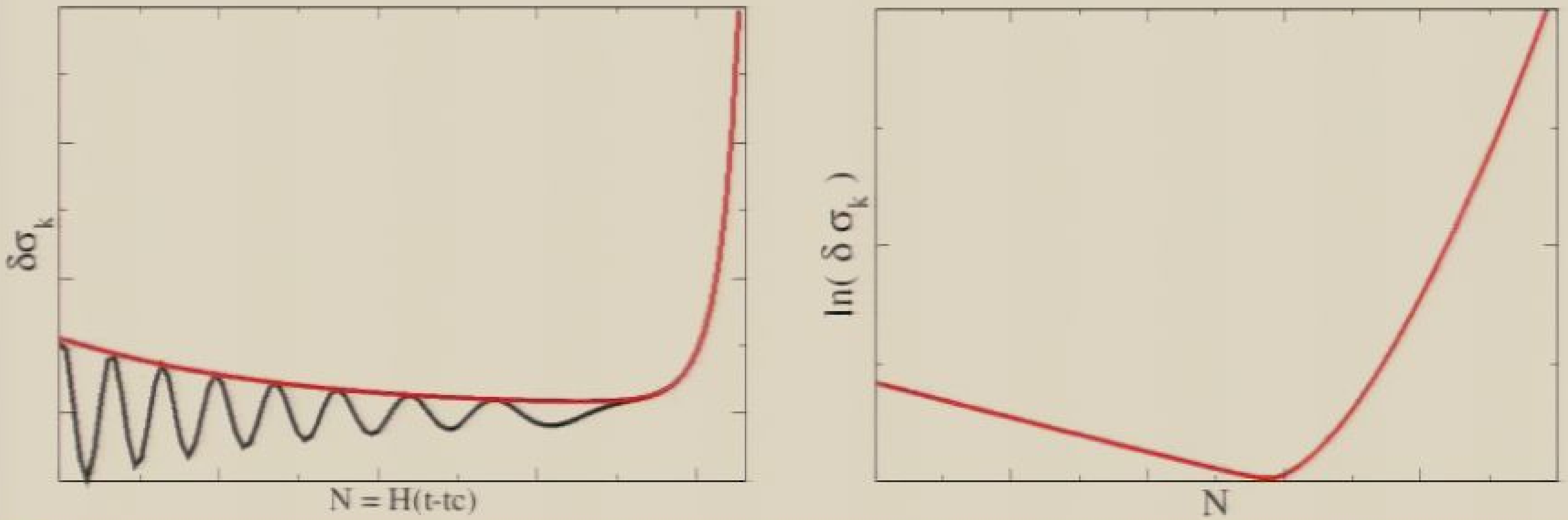
$$\zeta_\sigma^{(2)} \cong \frac{\kappa^2}{\epsilon}\int_{-1/a_iH}^{\tau} d\tau' \left[\frac{\left(\delta^{(1)}\sigma'\right)^2}{\mathcal{H}(\tau')} - \frac{\mathcal{H}(\tau')^2}{\mathcal{H}(\tau)^3}\left(\left(\delta^{(1)}\sigma'\right)^2 - a^2 m_\sigma^2 \left(\delta^{(1)}\sigma\right)^2\right)\right]$$

plus small slow-roll expansion (ϵ, η) corrections

More Details: $\xi(k)$

The tachyon modes $\xi(k)$ are Airy functions,

$$\delta^{(1)}\sigma_k(N) \sim b_k\, e^{-3N/2}\, \mathrm{Bi}\left[c^{-2/3}\,(9/4 + cN)\right]$$



We can get analytic insight with WKB approximation,

$$\xi_k \cong \begin{cases} (2k^3)^{-1/2}\left(H + ike^{-N}\right), & N < N_k \\ b_k\, e^{-\frac{3}{2}N + \frac{9}{4c}(1+\frac{4}{9}cN)^{3/2}} (1 + |1 + \frac{4}{9}cN|)^{-1/4}, & N > N_k \end{cases}$$

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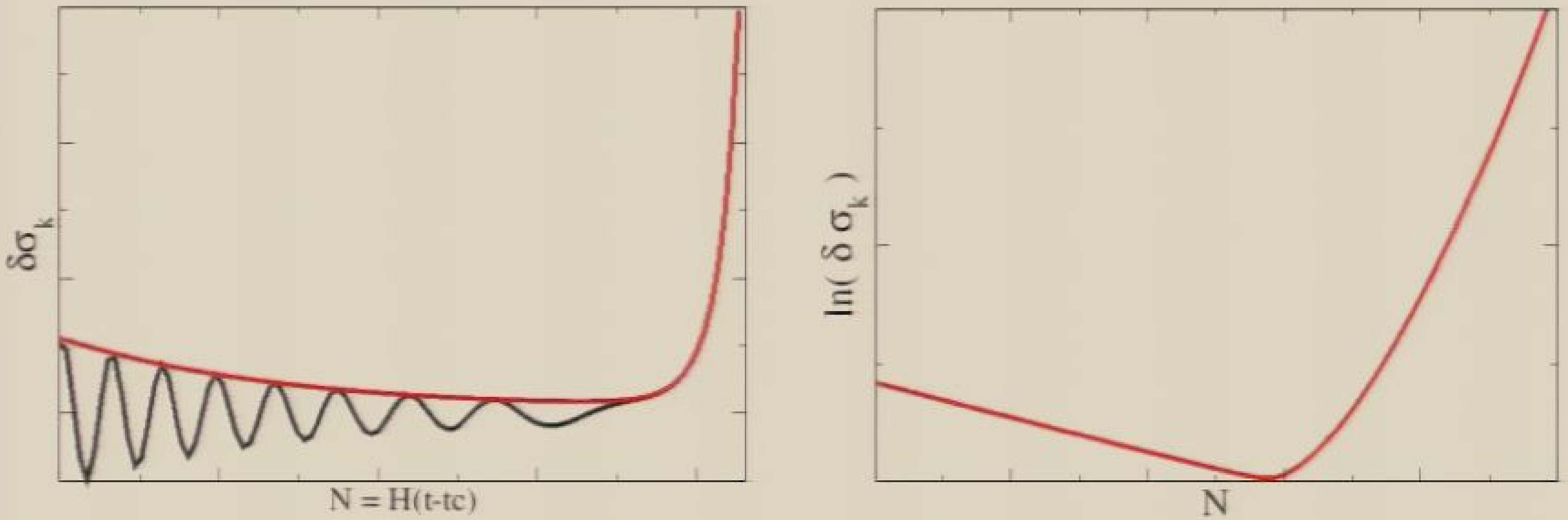


$\xi(k)$ damps like $e^{-3N/2}$ before instability ($N = 0$);
grows like $\exp(\frac{9}{4c}(1 + \frac{4}{9}cN)^{3/2})$ after instability starts.

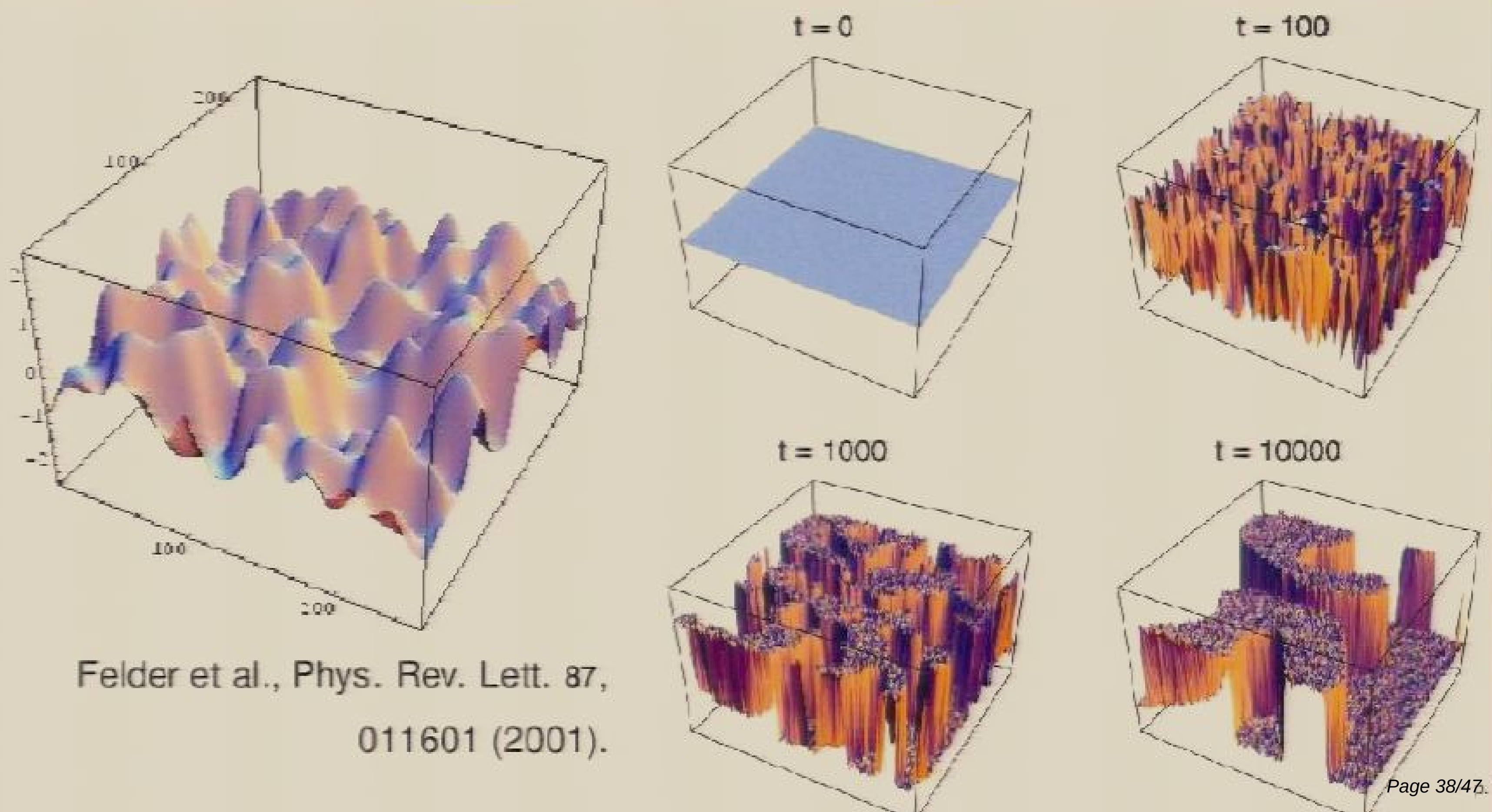
But when do we evaluate $\xi(k)$?

End of inflation

Numerical studies find that inflation ends when

$$\langle(\delta^{(1)}\sigma)^2\rangle = \int \frac{d^3k}{(2\pi)^3}|\xi_k|^2 = \frac{v^2}{4};$$

Back-reaction of tachyon fluctuations stops inflation



Felder et al., Phys. Rev. Lett. 87, 011601 (2001).

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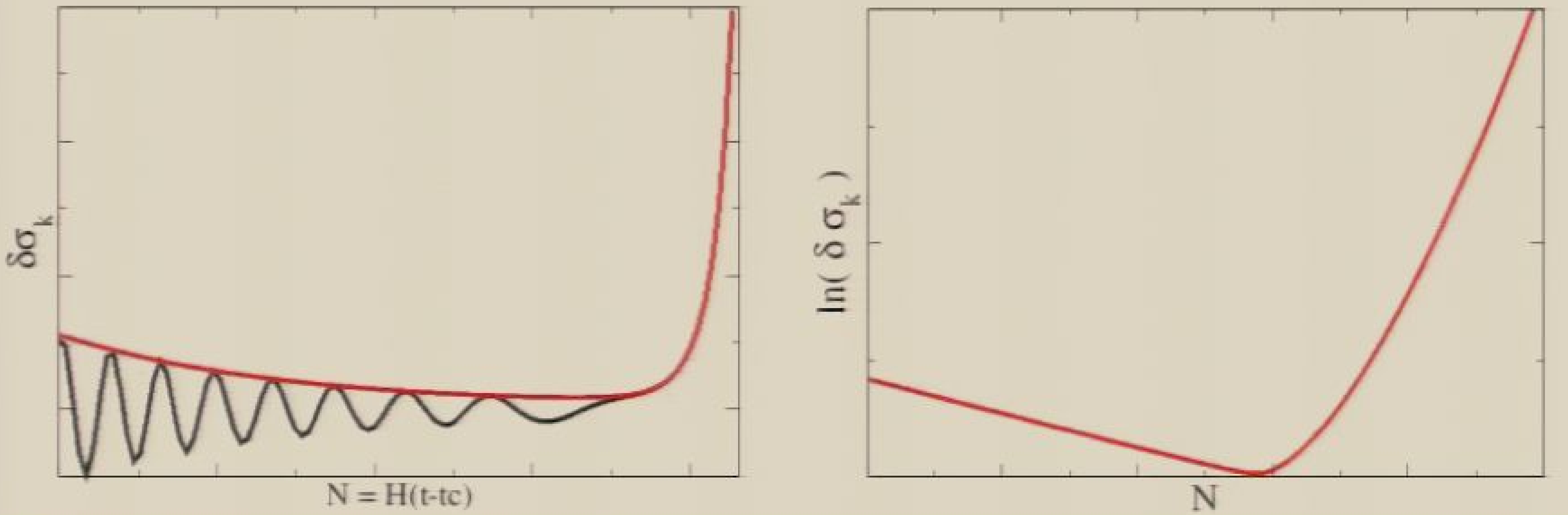

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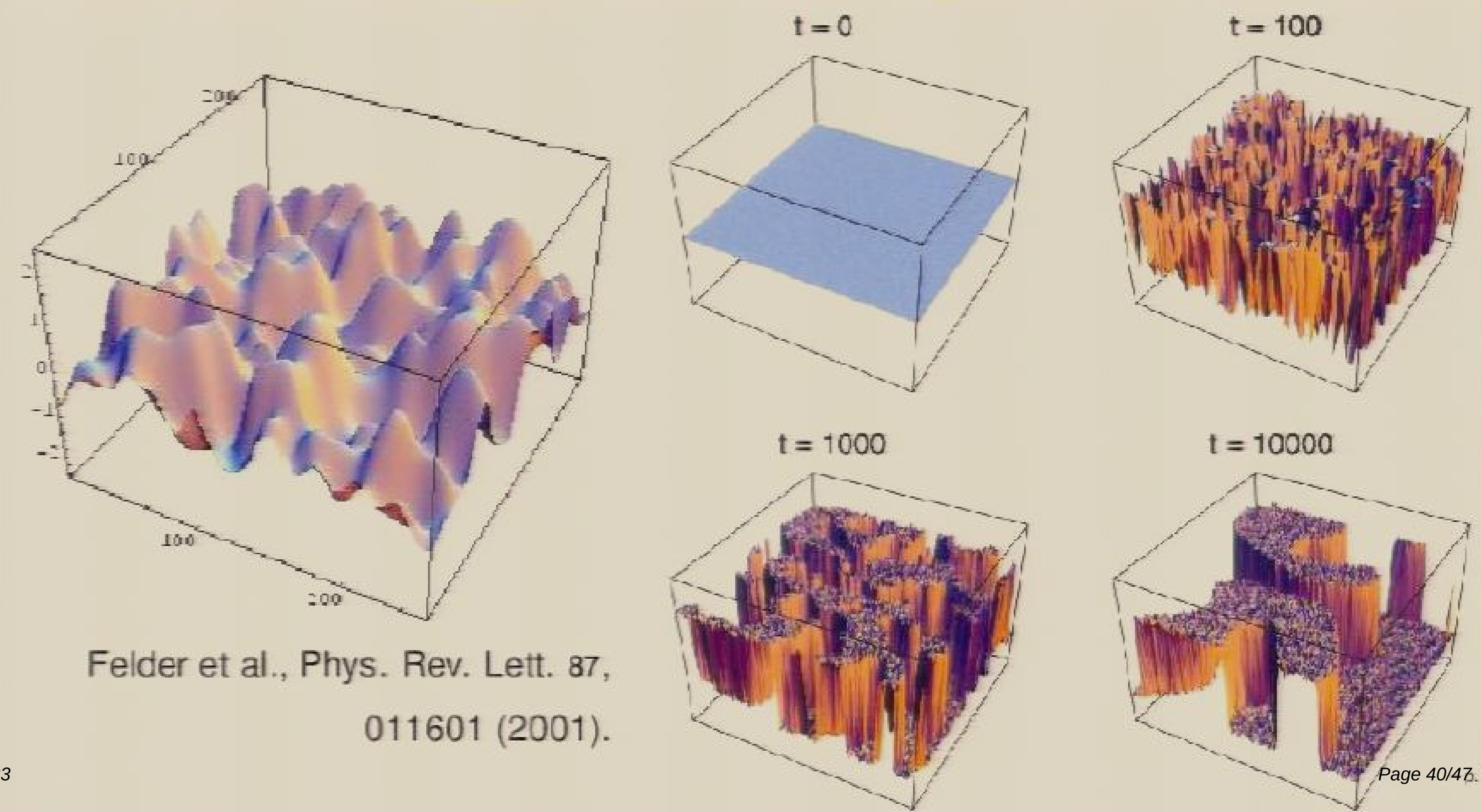

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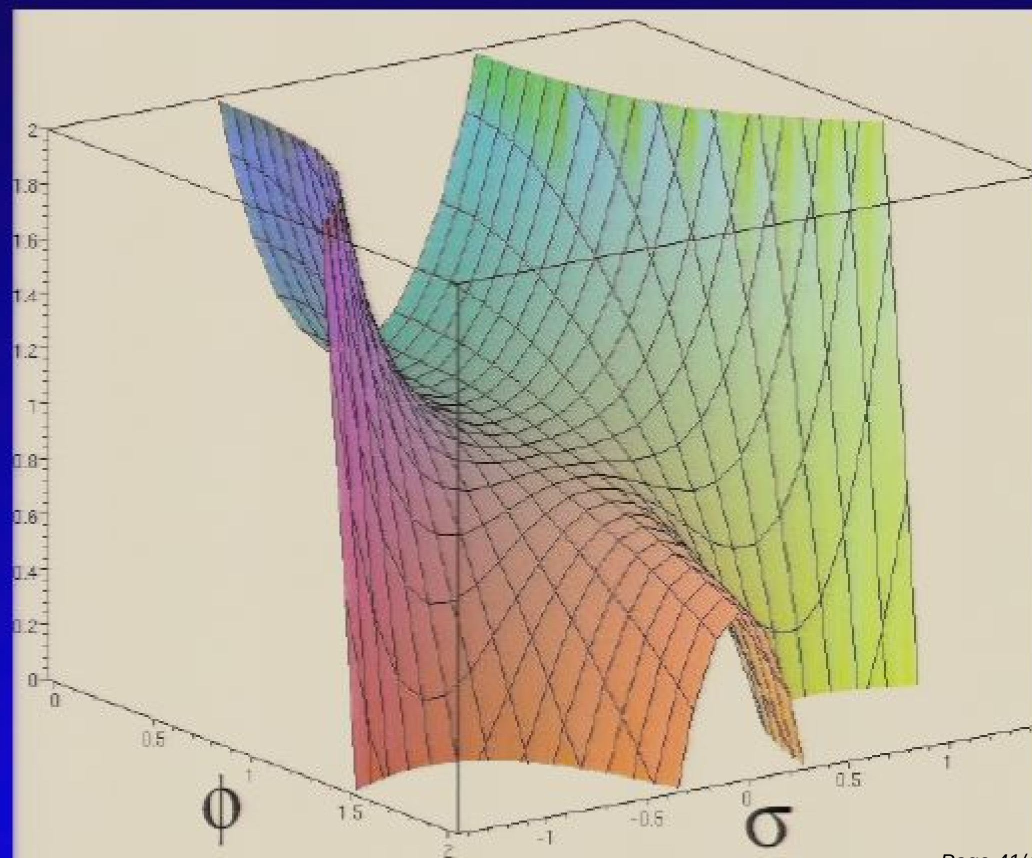
Generalizations: inverted hybrid inflation

WMAP 3rd year data gives spectral index

$$n_s = 0.948^{+0.015}_{-0.018}$$

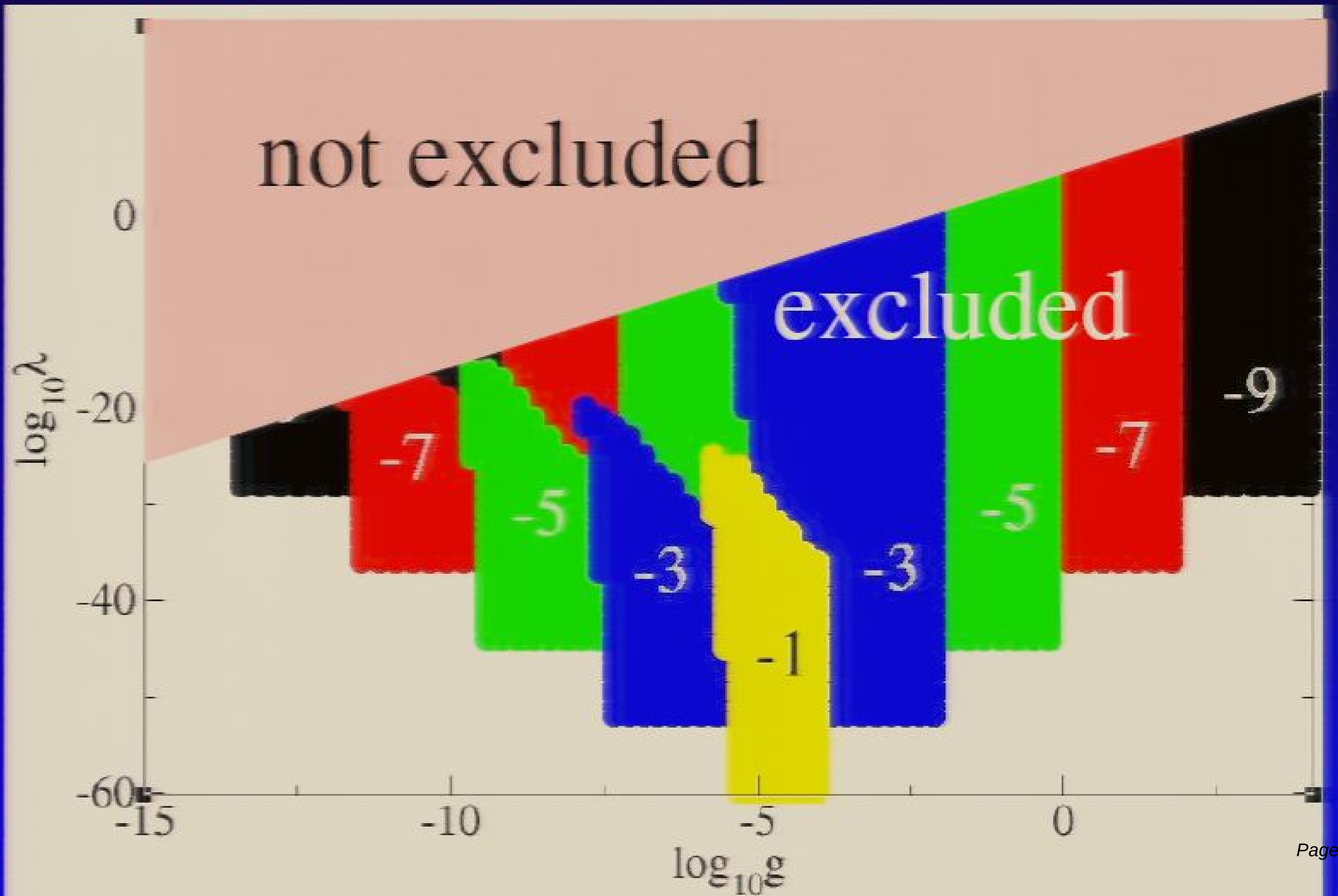
Hybrid inflation $\rightarrow n_s > 1$; *inverted* h.i. $\rightarrow n_s < 1$

$V(\varphi, \sigma) =$
$\frac{\lambda}{4}\left(\sigma^2 + v^2\right)^2$
$-\frac{m_\varphi^2}{2}\varphi^2 - \frac{g^2}{2}\varphi^2\sigma^2$
$+ \ldots$
(so $V \geq 0$)



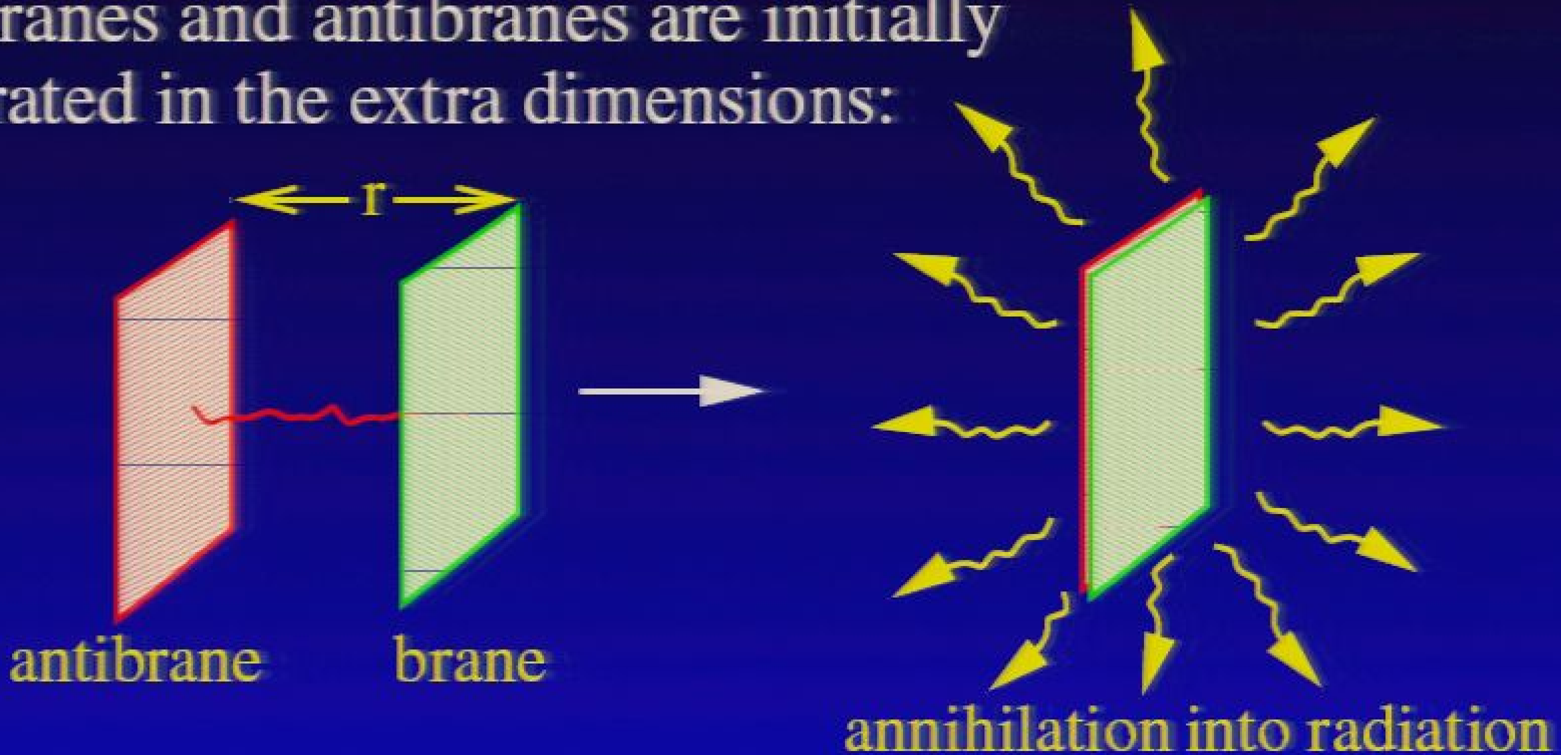
Essential differences

- Potential gets steeper during inverted hybrid inflation
- Slow roll can end *before* tachyonic instability starts
- Need $\lambda < 3.3 \times 10^5 g^2$ to get strong instability



Brane-antibrane inflation

String theory provides new inflation mechanism; 3D branes and antibranes are initially separated in the extra dimensions:

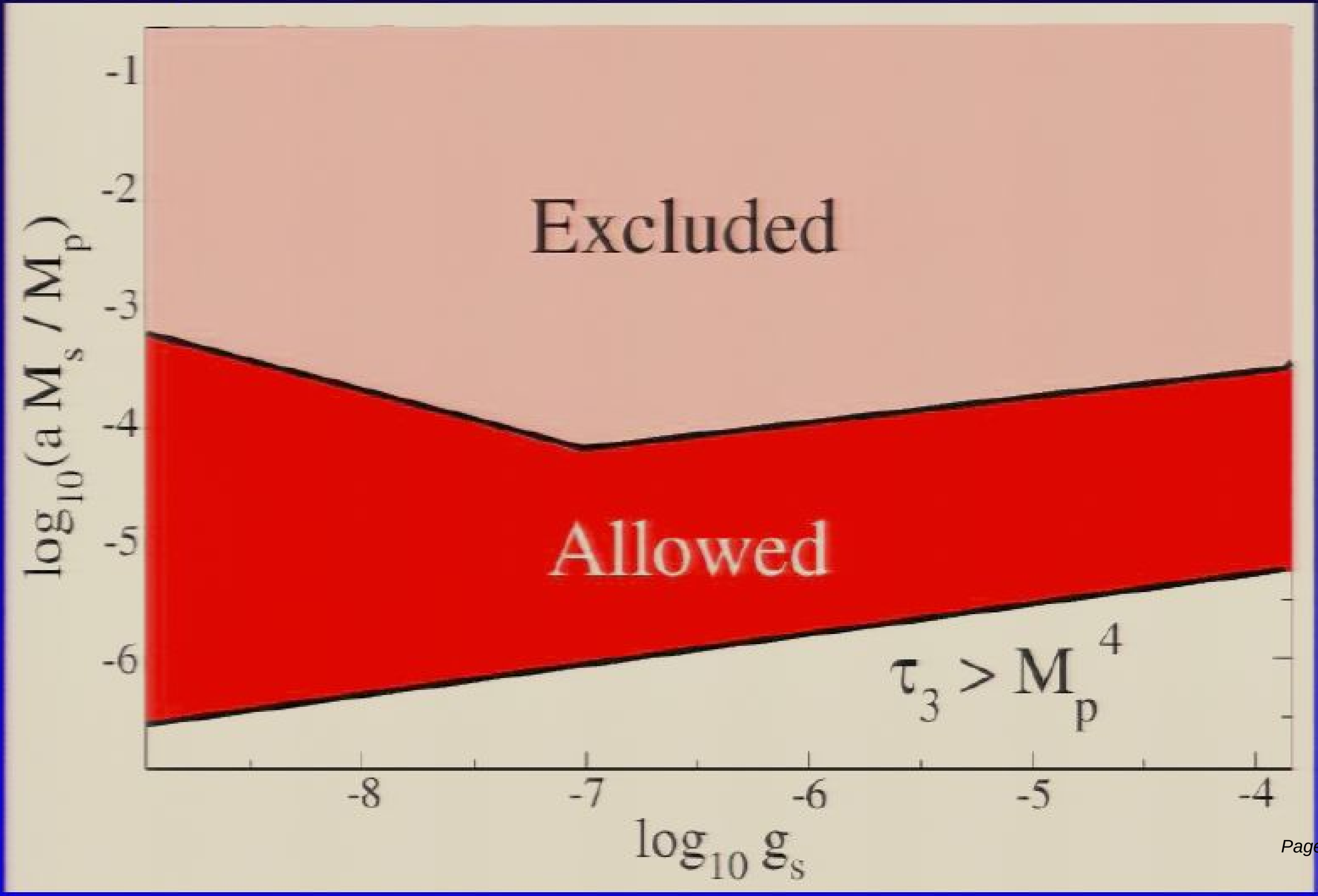


Resembles inverted hybrid inflation, with

$$v = \frac{a}{\pi^{3/2}} \frac{M_s}{\sqrt{g_s}}, \quad \lambda = \frac{\pi^3}{2} g_s, \quad g = a\sqrt{2\pi g_s}$$

Constraints on brane inflation

In KKLMMT scenario (brane in warped throat), constrain warped string scale versus string coupling (a = warp factor)



Conclusion

- Rigorous computation of $\zeta^{(2)}$ due to tachyonic instability; passes consistency test of locality (unlike previous attempts)
- We applied it in hybrid, inverted hybrid, and brane-antibrane inflation, to get significant constraints; more detailed analysis in progress
- Spectral distortion gives somewhat stronger constraint than nongaussianity
- Interesting hint of spectral distortion in CBI and ACBAR CMB data; a positive signal for tachyonic preheating? $\Longrightarrow$

CBI – ACBAR anomaly

from ACBAR collaboration (Chao-lin Kuo et al.), Astrophys.J.600:32-51,2004

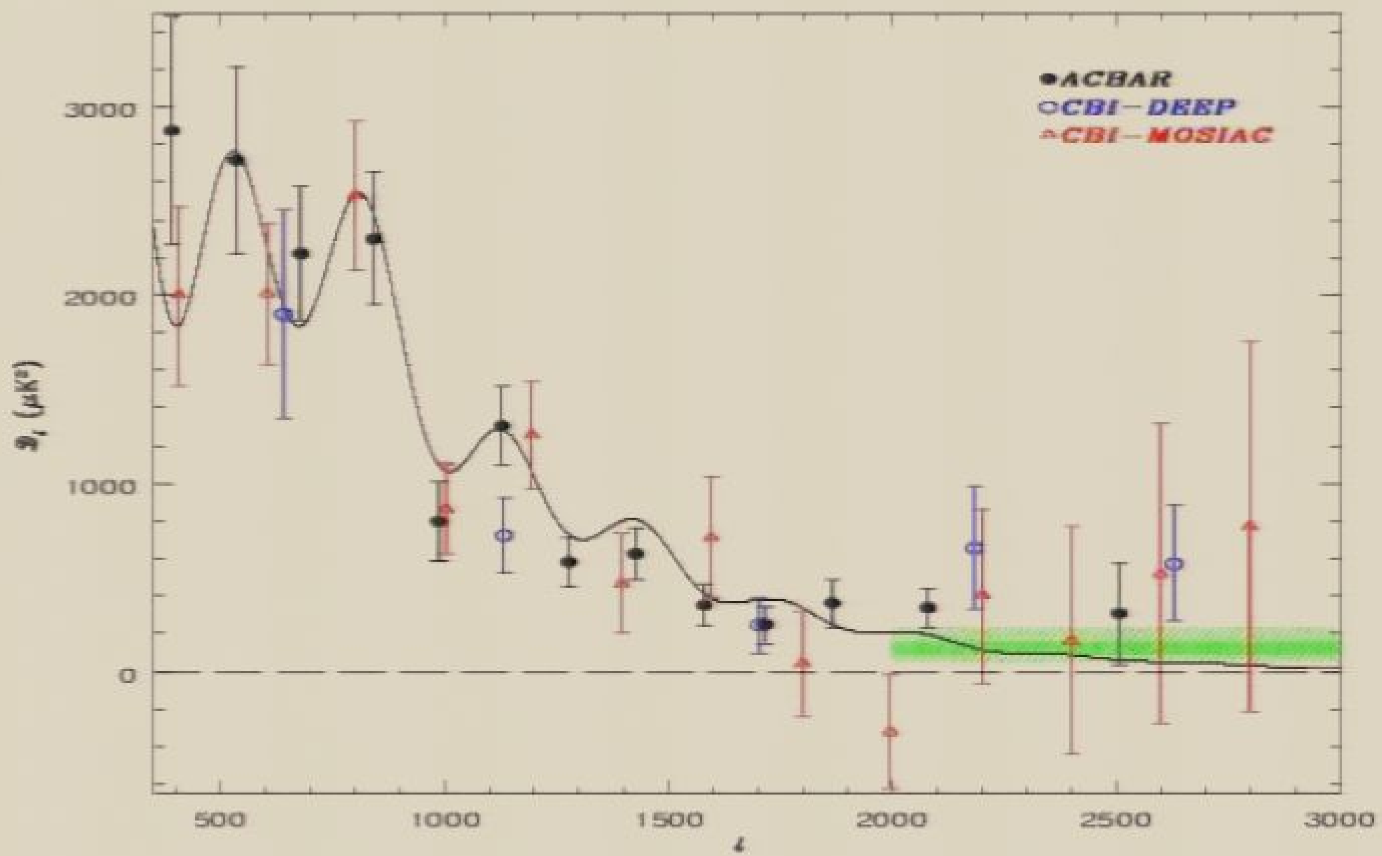


FIG. 10.— The CMB angular power spectrum for the CBI-Deep, CBI-Mosaic, and ACBAR experiments. The data are plotted on top of a fiducial ΛCDM model. The shaded green bar shows the expected contribution to the ACBAR power spectrum if the excess power found in the CBI-Deep data is due to the SZE. The ACBAR data are consistent with the CBI excess being due to SZE, but provide no significant new constraints on the source of the signal.

Conclusion

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