PASCOS 2009

Multi-Field Inflation on the Landscape

0806.1953, 0809.3242, 0812.0367

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Why are multi-field models interesting?

"Natural" in string theory: many moduli fields are present.

Assisted inflation effect (Liddle, Mazumdar and Schunck 98):

Recent developments:

- implementations of concrete models in string theory (active field); new effects (i.e. staggered inflation, infl. from random potentials H.Tye et.al. 09)

- largely unexplored theory or (p)re-heating (danger of heating hidden sectors D. Greene 08, potentially no parametric resonance D. Battefeld, S. Kawai 08; D.Battefeld, T.Battefeld, J.Giblin 09.

- possibly larger non-Gaussianities (model dependent, see review Wands 07)

Main Question

What are the consequences if fields drop out of (decay, stabilize, …) multi-field inflation in a staggered fashion?

This is a generic feature in many models of multi-field inflation in string theory.

E.g. in:

- Inflation from multiple tachyons
  Majumdar, Davis 03
- Inflation from multiple M5-branes
  Becker, Becker, Krause 05
- Inflation on the landscape
  Battefeld, Battefeld 08;
- …

Outline

- Analytic formalism to compute effects due to staggered inflation
  - background
  - perturbations
  - observables: scalar spectral index, tensor to scalar ratio, …
- Application
  - inflation on the landscape
  - comparison with WMAP5
  - work in progress …
- Conclusions

Note: $m_p^2 \equiv 1$ throughout

Analytic Formalism to deal with decaying fields

Smooth out N(t) and introduce a continuous decay rate:

$$\Gamma(t) \equiv -\dot{\mathcal{N}}/\mathcal{N}.$$

which is Model dependent. For the smoothing to be a good approximation, we need that several fields decay in any given Hubble time.

Further simplifying assumptions:

- uncoupled fields
- identical potentials (relaxed in D.B., T.B. 08)
- identical initial conditions (relaxed in D.B., T.B. 08)

Effects we recover:

- additional decrease of energy that drives inflation
- additional, leading order contributions to observables (e.g. scalar spectral index)

Effects we do not recover:

- sharp features in observables
- ringing in the power-spectrum
- additional grav.waves, non-Gaussianities caused by decaying fields

Background evolution

Define: $\varphi \equiv \sqrt{\mathcal{N}}\varphi_A$

$W(\varphi) = \mathcal{N}V(\varphi/\sqrt{\mathcal{N}})$ (Relaxed later on)

Energy transfer to additional component:

$$\dot{\rho}_\varphi = -3H(\rho_\varphi + p_\varphi) + \dot{\mathcal{N}}V$$

$$\dot{\rho}_r = -3H(\rho_r + p_r) - \dot{\mathcal{N}}V$$

See Watson, Perry, Kane, Adams 06 for related work on a relaxing CC.

Small parameters:

$$\bar{\varepsilon} \equiv \frac{3}{2}(1+w_r)\frac{\rho_r}{\rho_\varphi + \rho_r}$$

$$\varepsilon_{\mathcal{N}} \equiv -\frac{\dot{\mathcal{N}}}{\mathcal{N}}\frac{1}{2H} = \frac{\Gamma}{2H}$$

$$\hat{\varepsilon} \equiv -\frac{\dot{H}}{H^2}$$

$$\simeq \varepsilon + \bar{\varepsilon}$$

$$\varepsilon_A \equiv \frac{1}{2}\left(\frac{V_A'}{W}\right)^2 \ll 1 \quad , \quad \varepsilon \equiv \frac{1}{2}\left(\frac{W'}{W}\right)^2 \ll 1 \, ,$$

$$\eta_A \equiv \frac{V_A''}{W} \quad , \quad |\eta_A| \ll 1 \, ,$$

$$\eta \equiv \frac{W''}{W} \quad , \quad |\eta| \ll 1 \, ,$$

Can show that within inflationary models of interest to first order in small parameters:

$$\varepsilon_{\mathcal{N}} \simeq \bar{\varepsilon}$$

Background evolution

We get

$$\begin{aligned} \dot{\rho}_\varphi &\simeq -2H(\varepsilon_{\mathcal{N}} + \varepsilon)\rho_\varphi \\ \dot{\rho}_r &\simeq 2H(\varepsilon_{\mathcal{N}} - \bar{\varepsilon})\rho_\varphi \end{aligned}$$

⇦ This leads to a scaling solution during inflation.

The effective single field evolves according to

$$\begin{aligned} 3H\dot{\varphi} &\simeq -W'\gamma \\ \gamma &\equiv 1 + \varepsilon_{\mathcal{N}}\varphi\frac{W}{W'} \end{aligned}$$

Resembles warm Inflation (Barera 95),
but

- the radiation-bath originates from transferring potential energy, not kinetic
- model can arise in string theory
- avoids many problems of regular warm inflation

Next, perturbations; new effects due to

- presence of ρ_r and perturbations therein
- additional decrease of W due to the decay rate $\Gamma \neq 0$

Perturbations (straightforward)

We can show that isocurvature/entropy perturbations are suppressed (follow Malik, Wands, Ungarelli 03, …), so we can focus on adiabatic perturbations.

Use the Mukhanov variable, satisfying $$v_k'' + \left(k^2 c_s^2 - \frac{z''}{z}\right) v_k = 0$$

Where $$z \equiv \frac{1}{\theta c_s}, \quad \theta^2 \equiv \frac{1}{3a^2(1+w)} \qquad w = p/\rho$$

$$p = p_\varphi + p_r \qquad \rho = \rho_\varphi + \rho_r$$

Focus on large scales, so

$$c_s^2 \approx \dot{p}/\dot{\rho}$$

Imposing QM initial conditions and using the background solution, we can compute the curvature perturbation

$$v_k = z\zeta_k$$

and the power-spectrum: $$\mathcal{P}_\zeta = \frac{k^3}{2\pi^2}|\zeta_k|^2$$

Perturbations

The scalar spectral index $n_s - 1 = \frac{d\ln \mathcal{P}_\zeta}{d\ln k}$

becomes

$$n_s - 1 \simeq -2(\varepsilon + \varepsilon_{\mathcal{N}}) - \frac{2}{\varepsilon\gamma^2 + \varepsilon_{\mathcal{N}}}\left[\varepsilon\gamma^2(2\varepsilon - \varepsilon_{\mathcal{N}} - \eta) + (\varepsilon + \varepsilon_{\mathcal{N}})(1-\delta)(\varepsilon\gamma(\gamma - 1) + \frac{\varepsilon_{\mathcal{N}}}{2})\right]$$

Recover known limits:

$$\delta \equiv \frac{\dot{\Gamma} H}{\Gamma \dot{H}}$$

- Usual slow roll: $\left.\begin{array}{l}\Gamma = 0\\ \varepsilon_{\mathcal{N}} = 0\end{array}\right\}$ $n_s^{SR} - 1 \simeq -6\varepsilon + 2\eta$

- Dynamically relaxing CC (Inflation without Inflatons):

$$\left.\begin{array}{l}\varepsilon_{\mathcal{N}} = const\\ \delta = 1\\ \varepsilon = \eta = 0\end{array}\right\} \quad n_s^{relax.CC} - 1 = -2\varepsilon_{\mathcal{N}}$$

Watson, Perry, Kane, Adams 06 .

Perturbations

- If slow roll contributions are negligible (interesting case) we get

$$\mathcal{P}_\zeta \simeq \frac{1}{8\pi^2\bar{\varepsilon}}\frac{H^2}{m_{pl}^2}$$

$$n_s - 1 \simeq (\delta - 3)\bar{\varepsilon}$$

$$\frac{\Gamma}{2H} \equiv \varepsilon_{\mathcal{N}} \simeq \bar{\varepsilon} \equiv \frac{3}{2}(1+w_r)\frac{\rho_r}{\rho_r+\rho_I}$$

$$\delta \equiv \frac{\dot{\Gamma}H}{\Gamma\dot{H}}$$

A similar computation for gravity waves leads to

$$\mathcal{P}_T \simeq \frac{2}{\pi^2}\frac{H^2}{m_{pl}^2}$$

$$n_T \equiv \frac{d\,\ln\mathcal{P}_T}{d\,\ln k} \simeq -2\bar{\varepsilon}\,.$$

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_\zeta} \simeq 16\bar{\varepsilon}\,.$$

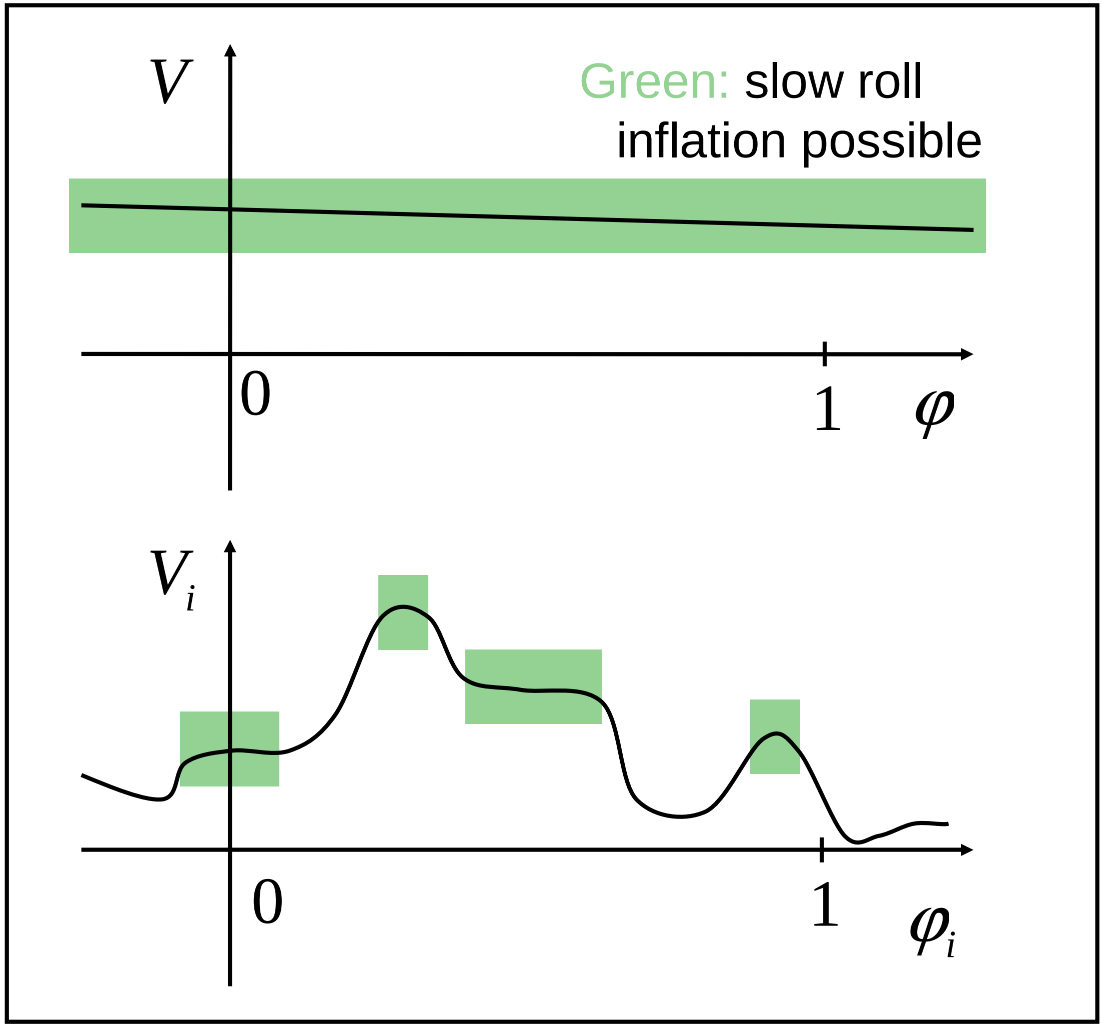
Application: Inflation on the Landscape

D.Battefeld, T.Battefeld 08

What potential(s) do we expect?

A: Long flat stretches?
(needed for single field inflation).

B: Short flat stretches, hills and valleys, sharp drops, …?



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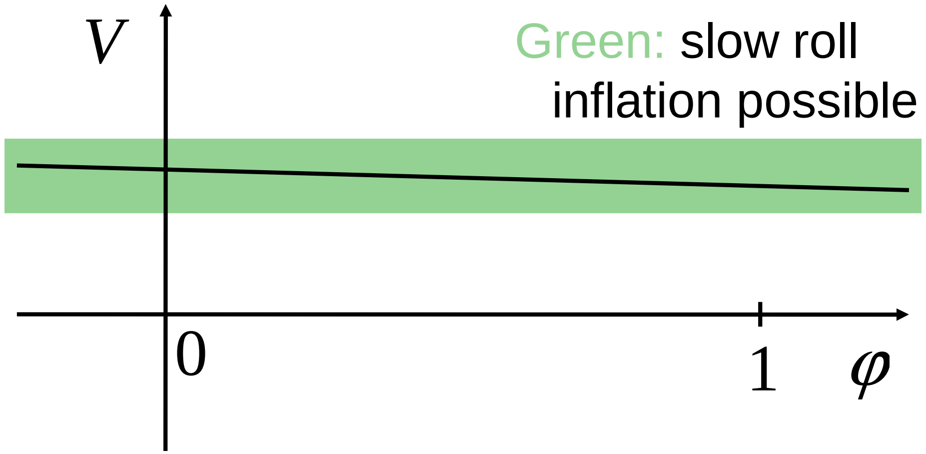
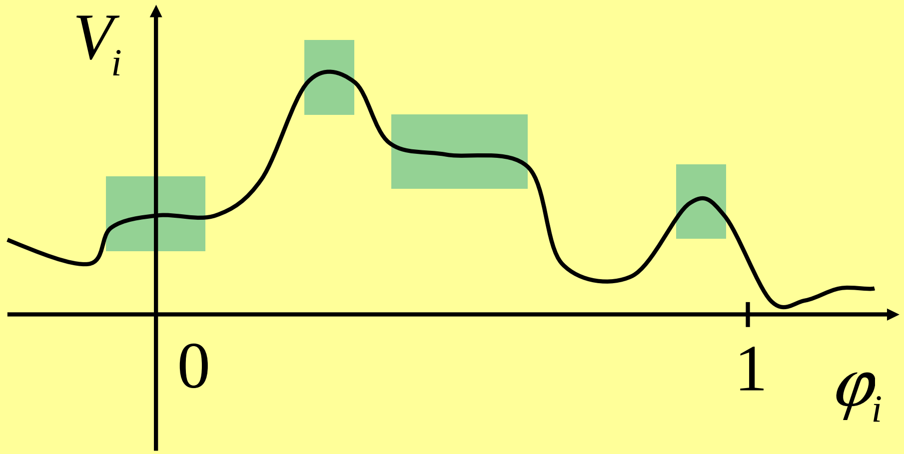
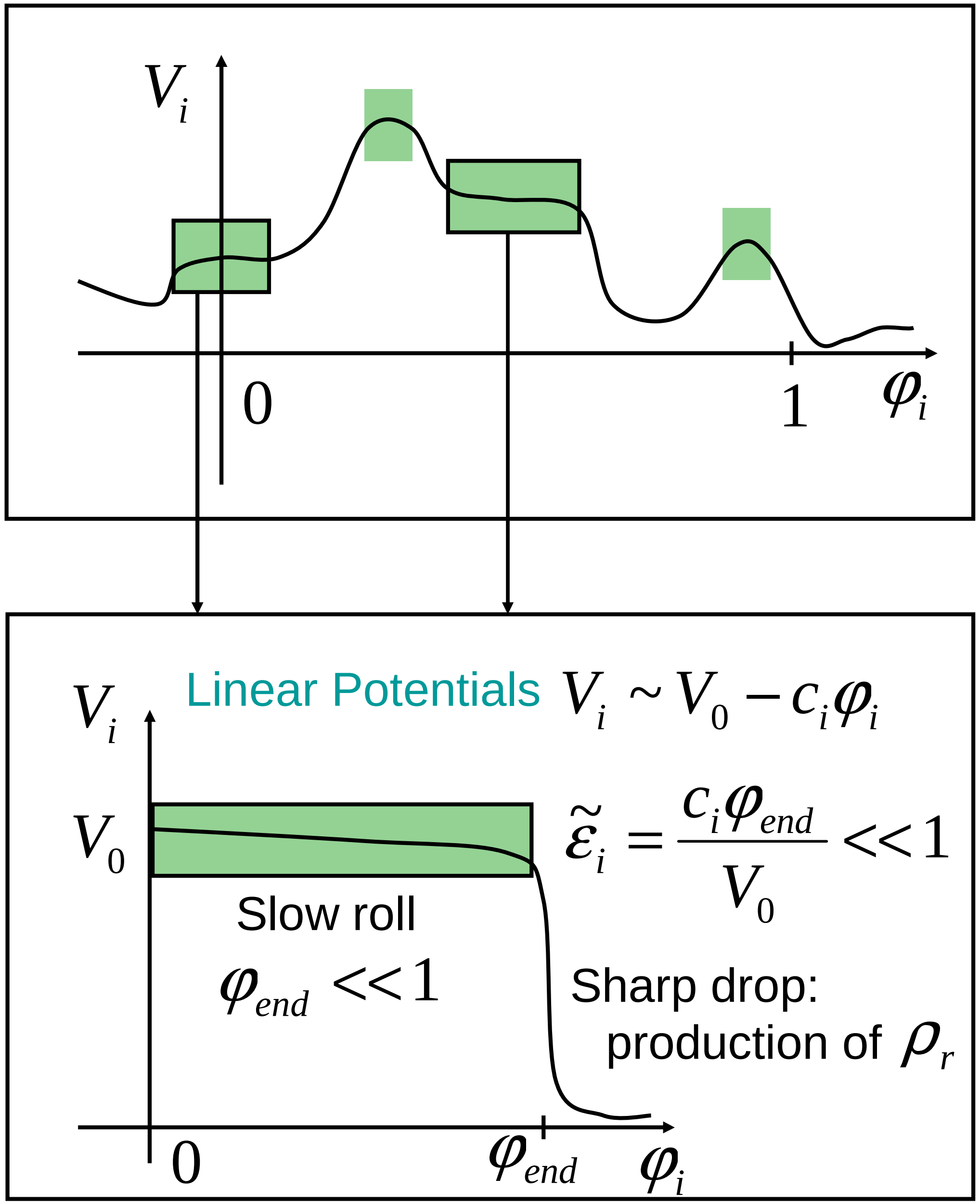


B: Short flat stretches, hills and valleys, sharp drops, …?

Focus on this case



Expand around flat stretches (assume separable V)



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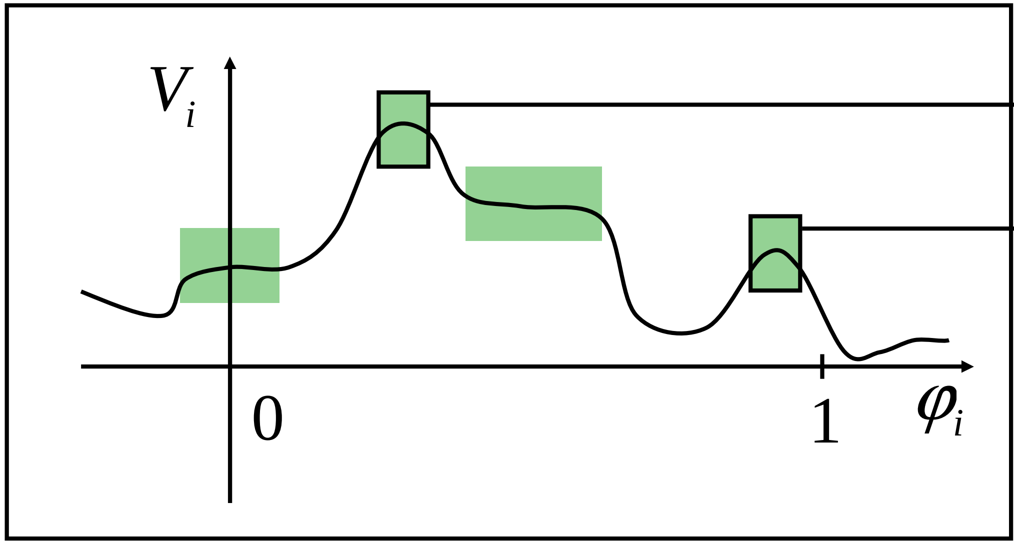
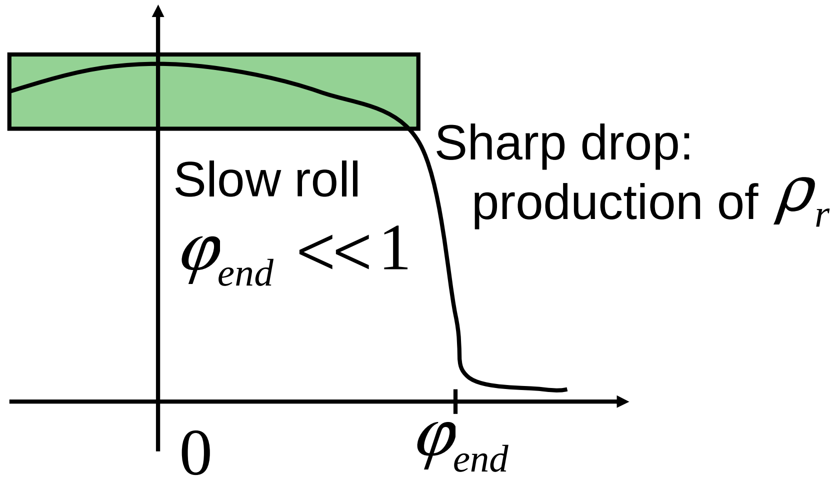


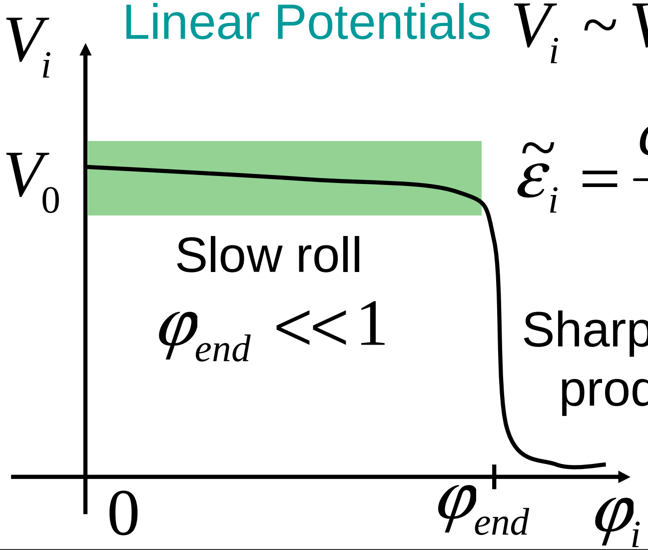
Hilltop Potentials



$$V_i \sim V_0 - \frac{m_i^2}{2}\varphi_i^2$$

$$\tilde{\varepsilon}_i = \frac{m_i^2 \varphi_{end}^2}{V_0} << 1$$

Linear Potentials $V_i \sim V_0 - c_i \varphi_i$



$$\tilde{\varepsilon}_i = \frac{c_i \varphi_{end}}{V_0} << 1$$

In either case we arrive at staggered inflation, Note: the decay rate is not a free parameter.

Initial conditions and potentials:

Spread fields evenly

$$\varphi_i(t=0) = \varphi_{ini} + \frac{\varphi_{end} - \varphi_{ini}}{\mathcal{N}(t=0)}(i-1)$$

Potentials: allow for slightly different slopes or masses: $l \ll 1$

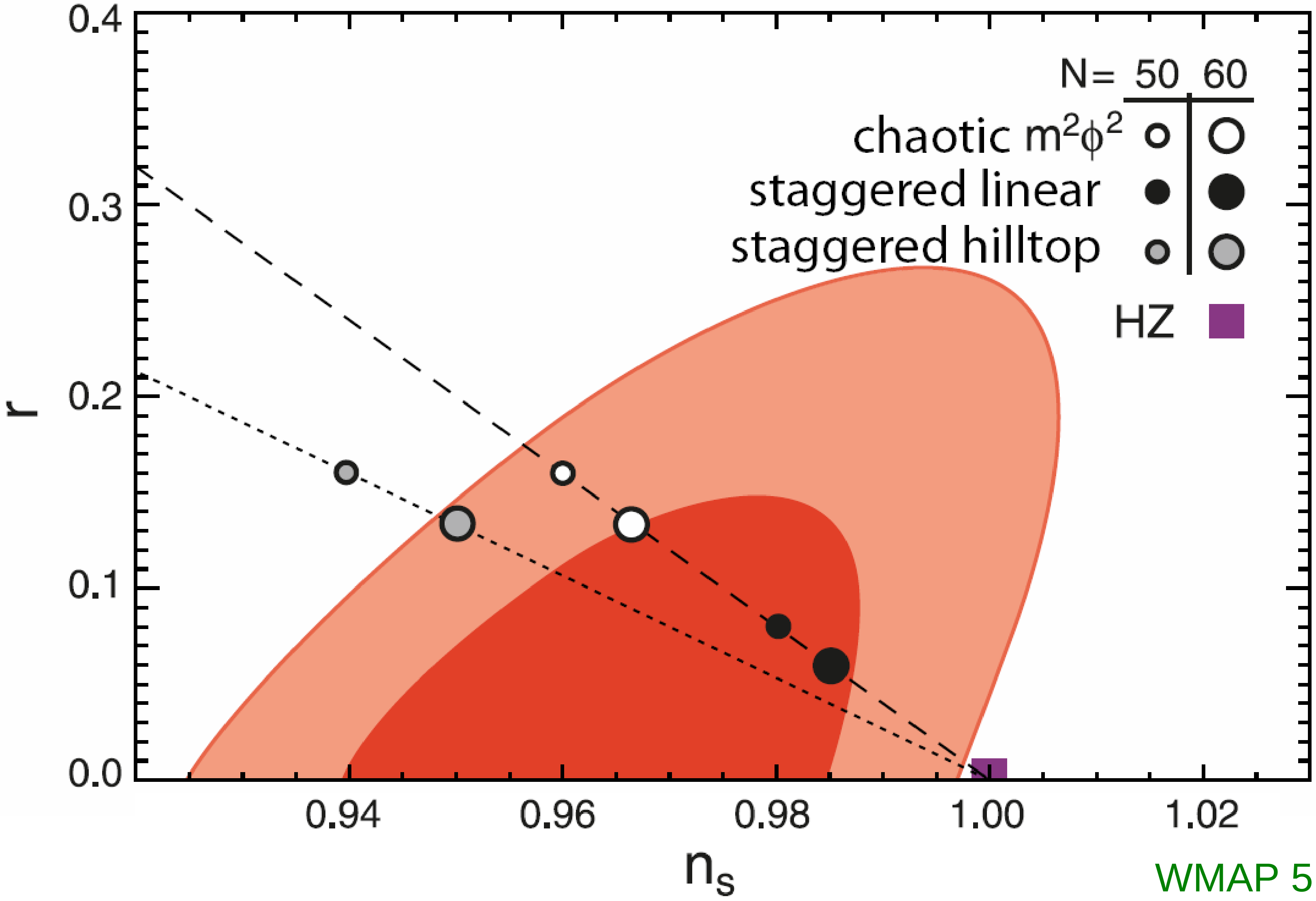
Linear: $c_i = c\left(1 + l\frac{i}{\mathcal{N}}\right)$ Hilltop: $m_i^2 = m^2(1 + li/\mathcal{N})$

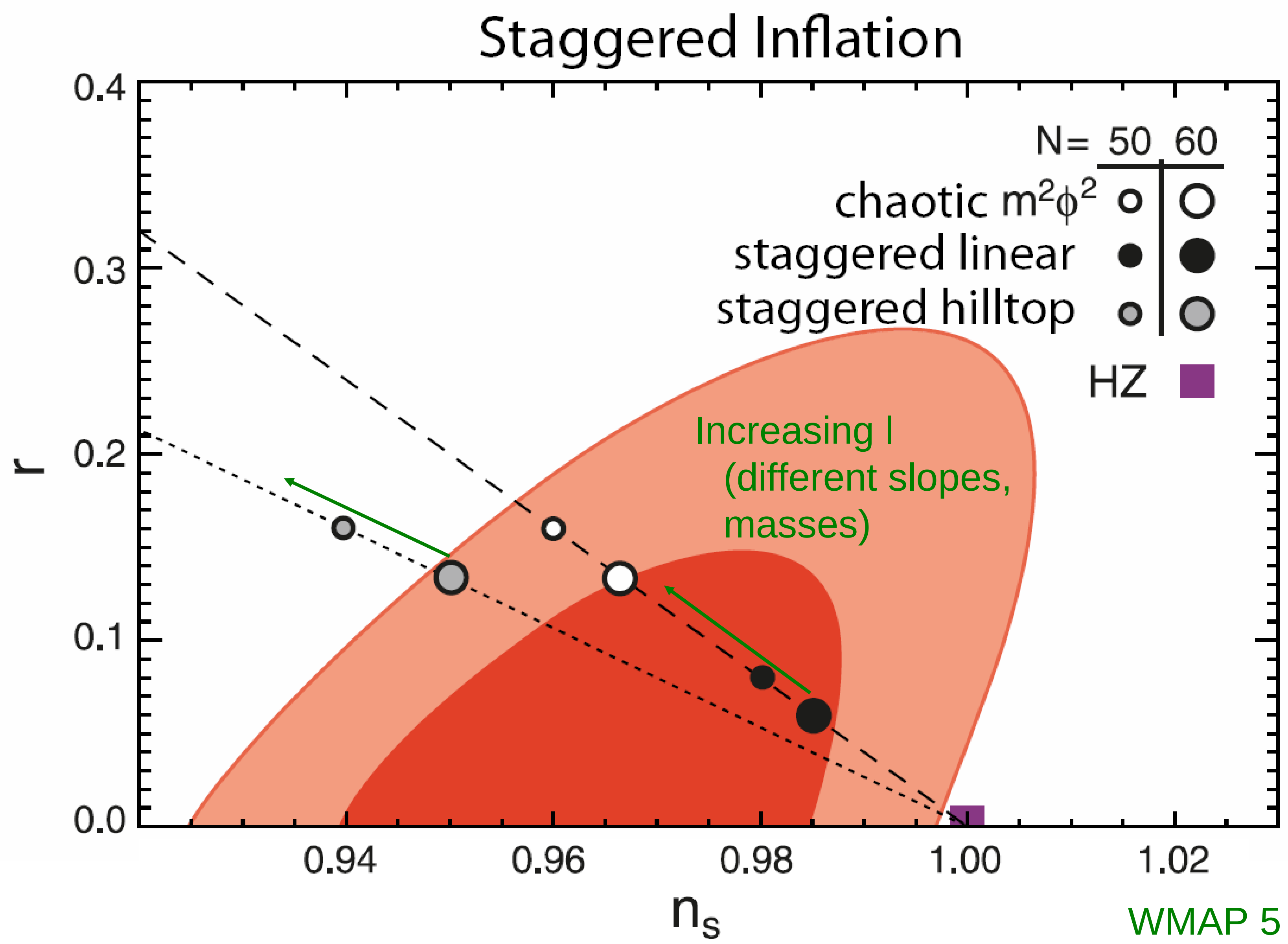
- solve equations of motion
- compute decay rate, delta and number of e-folds
- compute observables (note: SR contributions are negligible in the case at hand)

$$\begin{aligned}
n_s - 1 &\simeq -\frac{1}{N}\left(1 + \frac{2l}{3}\right), \\
n_T &\simeq -\frac{1}{2N}\left(1 + \frac{2l}{3}\right), \\
r &\simeq \frac{4}{N}\left(1 + \frac{2l}{3}\right).
\end{aligned}$$

$$\begin{aligned}
n_s - 1 &\approx -\frac{3}{N}\left(1 + l\frac{3}{4}\right), \\
n_T &\approx -\frac{1}{N}\left(1 + l\frac{3}{4}\right), \\
r &\approx \frac{8}{N}\left(1 + l\frac{3}{4}\right).
\end{aligned}$$

Staggered Inflation





Staggered Inflation
0.4
0.3
0.2
0.1
0.0
r
0.94
0.96
0.98
1.00
1.02
n_s
N= 50 60
chaotic $m^2\phi^2$
staggered linear
staggered hilltop
HZ
Increasing l
(different slopes,
masses)
WMAP 5

Other unique signatures?

Whenever fields decay, slow roll is violated and we could get:

- additional gravitational waves (similar to GW from reheating, see e.g. Easther, Giblin, Lim, 06, 07, 08);

- Non-Gaussianities (similar to NG from steps in a potential, see Easther, Chen, Lim 06, 08)

To compute either one, the decay of fields needs to be understood better.

Need: a concrete implementation within string theory to make progress.

Work in progress:

- Numerical studies to check validity of the analytic framework (~1000 fields with J.Giblin and D.Battefeld)

- Concrete implementation (KKLMMT with multiple brane/anti-brane pairs, with H.Firouzjahi, N.Khosravi and D.Battefeld)

Conclusions

Staggered inflation occurs naturally in several multi-field models within string theory.

We developed an analytic formalism to compute effects on some observables (scalar spectral index, running, gravity waves, …).

Comparison with observations is promising - staggered inflation should be investigated further:

- check framework numerically,
- construct implementations in string theory,
- compute non-Gaussianities,
- compute additional grav. waves from decaying fields, …

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