Multifield reheating and the fate of primordial observables

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Why reheating?

- Its a somewhat neglected topic
  - In single field models, zeta is conserved (on super horizon scales), so not so important
  - Its a difficult topic
- But even in single field, affects the value of “N” we should use, biggest uncertainty for predictions of “chaotic inflation”
- Multifield models, zeta continues to evolve on all scales, no excuse to ignore this!
- Inflation alone doesn't specify observables, need to keep calculating
- Exception if adiabatic attractor reached during inflation, Joel Meyers talk and Yuki Watanabe's poster, f_{NL} decays to a small value except in special cases

  Kim, Liddle and Seery 2010
- We will find a different conclusion from reheating cf inflation

Perturbative reheating

- Mainly for simplicity, can model with one additional term in each fields equation of motion

$$\ddot{\chi} + (3H + \Gamma_\chi)\dot{\chi} + W_{,\chi} = 0$$

- Require $m \gg \max\{H, \Gamma\}$ to remain in correct regime of validity
- Gamma switched on first time field crosses its minimum (if ever), a different time for each field
- Evolve until radiation is strongly dominant and fields have decayed

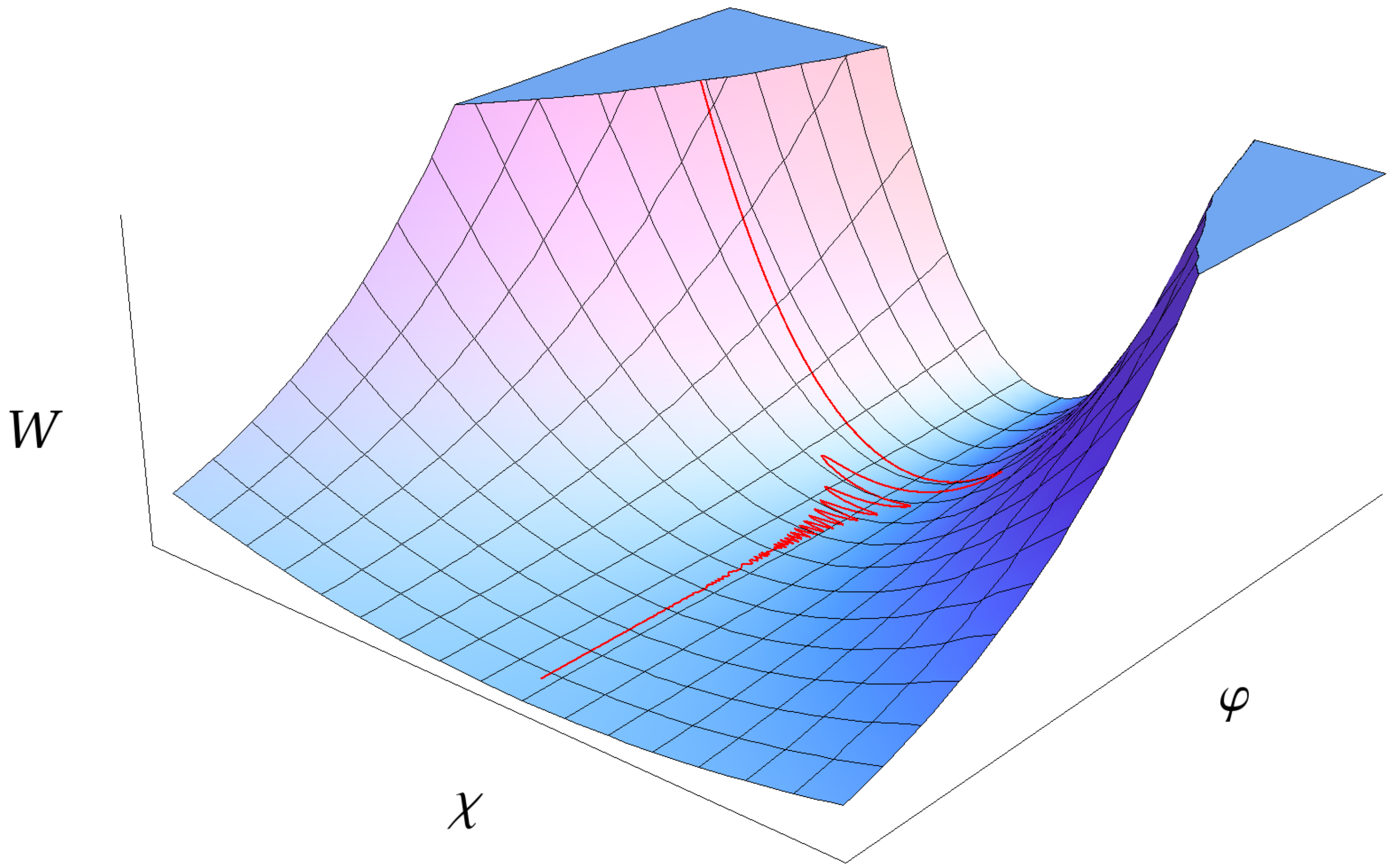
Numerics and delta N

- Need excellent error control, long integration time with oscillating fields
  - Talk to Ewan, he did the hard work
  - Used delta N formalism with 7 point stencil (ie lots of initial conditions, then calculate differences)
  - Tested against only known relevant exact solution – CB & Tasinato '09

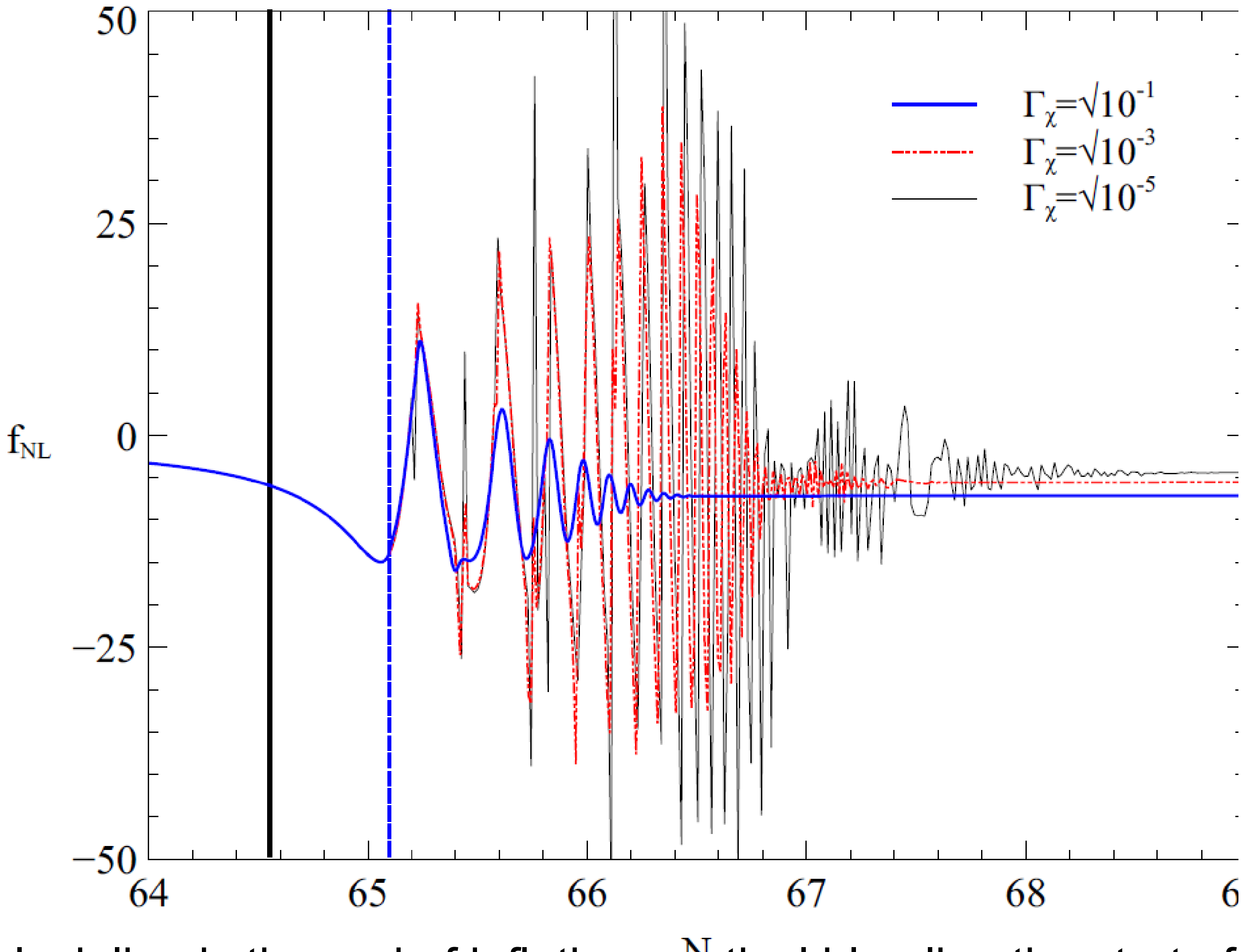
$$r = \frac{8}{\sum_I N_{,I}^2}, \; n_\zeta - 1 = -2\epsilon_* + \frac{2}{H_*}\frac{\sum_{IJ}\dot{\varphi}_{*J} N_{,JI} N_{,I}}{\sum_K N_{,K}^2}, \; f_{NL} = \frac{5}{6}\frac{\sum_{IJ} N_{,IJ} N_{,I} N_{,J}}{\left(\sum_I N_{,I}^2\right)^2}$$

Case study: One minimum model

$$W = W_0 \chi^2 e^{-\lambda \varphi^2}$$



Evolution of f_{NL}



Vertical black line is the end of inflation, vertical blue line the start of reheating
Initial conditions chosen such that non-G is large at end of inflation (small phi value)
Byrnes, Choi and Hall 2008

Other observables

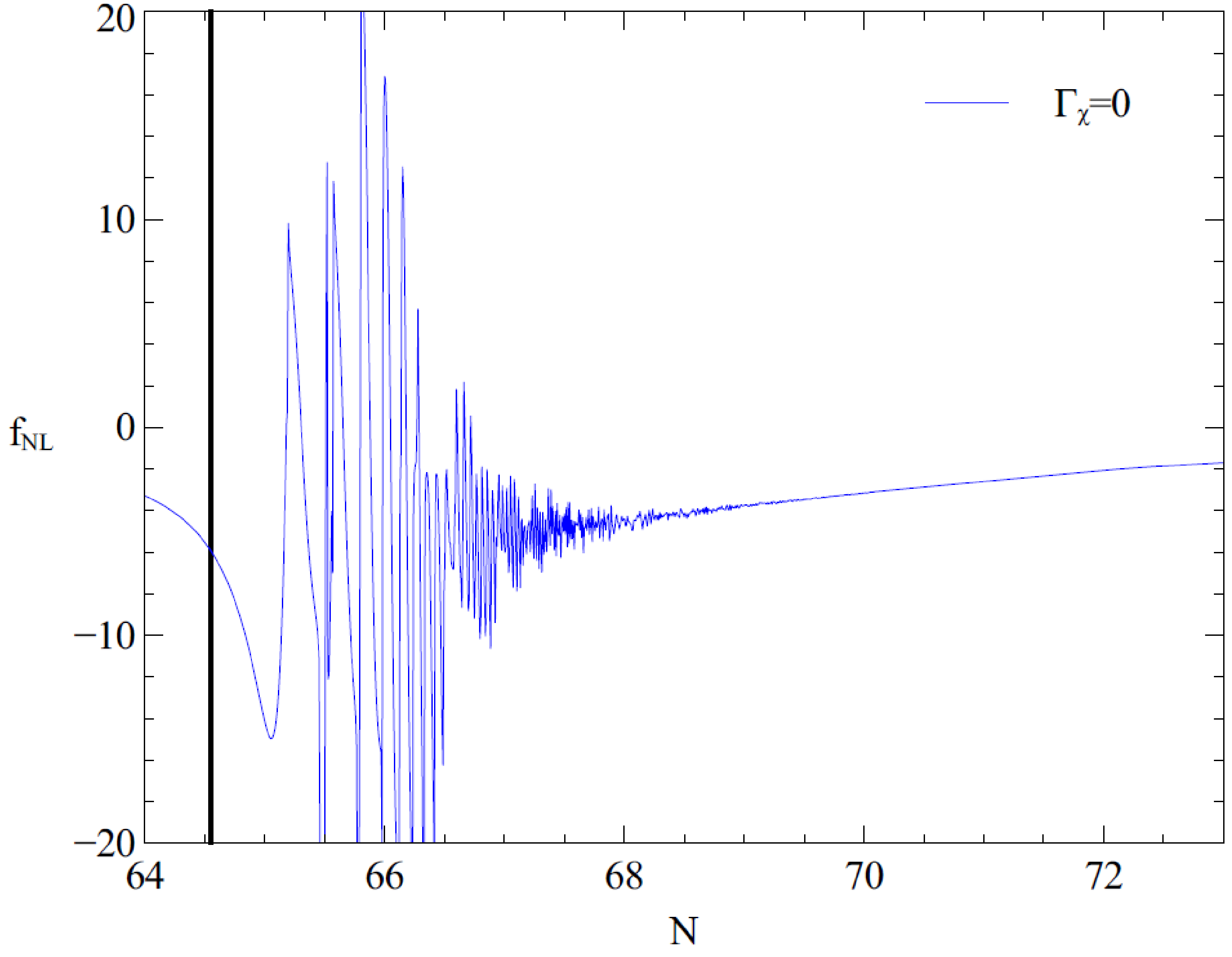
χ^2 minimum: $f_{\rm NL}(t_e) = -5.93$, $n_\zeta(t_e) = 0.763$, $r(t_e) = 2.8 \times 10^{-4}$			
Γ_χ	$f_{\rm NL}^{\rm final}$	$n_s^{\rm final}$	$r^{\rm final}$
$\sqrt{10^{-5}}$	-4.35	0.761	2.4×10^{-4}
$\sqrt{10^{-3}}$	-5.54	0.762	3.9×10^{-4}
$\sqrt{10^{-1}}$	-7.14	0.762	6.3×10^{-4}

χ^4 minimum: $f_{\rm NL}(t_e) = -48.29$, $n_s(t_e) = 0.770$, $r(t_e) = 7.2 \times 10^{-3}$			
Γ_χ	$f_{\rm NL}^{\rm final}$	$n_s^{\rm final}$	$r^{\rm final}$
$\sqrt{10^{-8}}$	-54.40	0.772	9.7×10^{-3}
$\sqrt{10^{-6}}$	-60.32	0.778	1.2×10^{-2}
$\sqrt{10^{-4}}$	-65.80	0.776	1.5×10^{-2}

For both potentials, notice that f_{NL} seems to be more sensitive to the value of Gamma
In this sense, the spectral index is a more robust observable

Why more robust?

- Interesting to look at no reheating case
- Note how f_{NL} slowly creeps towards zero



Scaling relations

- We find the scaling relation $N_{\varphi\varphi} \simeq N_\varphi/\phi_*$ remains valid even during reheating – derived during slow roll by Elliston et al '11

- Leads to $f_{NL} \approx \frac{5}{6|\varphi_*|}\frac{N_\varphi^3}{[N_\varphi^2 + g_*^2]^2}$

  where $g_* = N_\chi \simeq (2\epsilon_\chi^*)^{-1/2}$

- As reheating takes longer, $N_\varphi \to -\infty \;\Rightarrow\; f_{NL} \to 0$

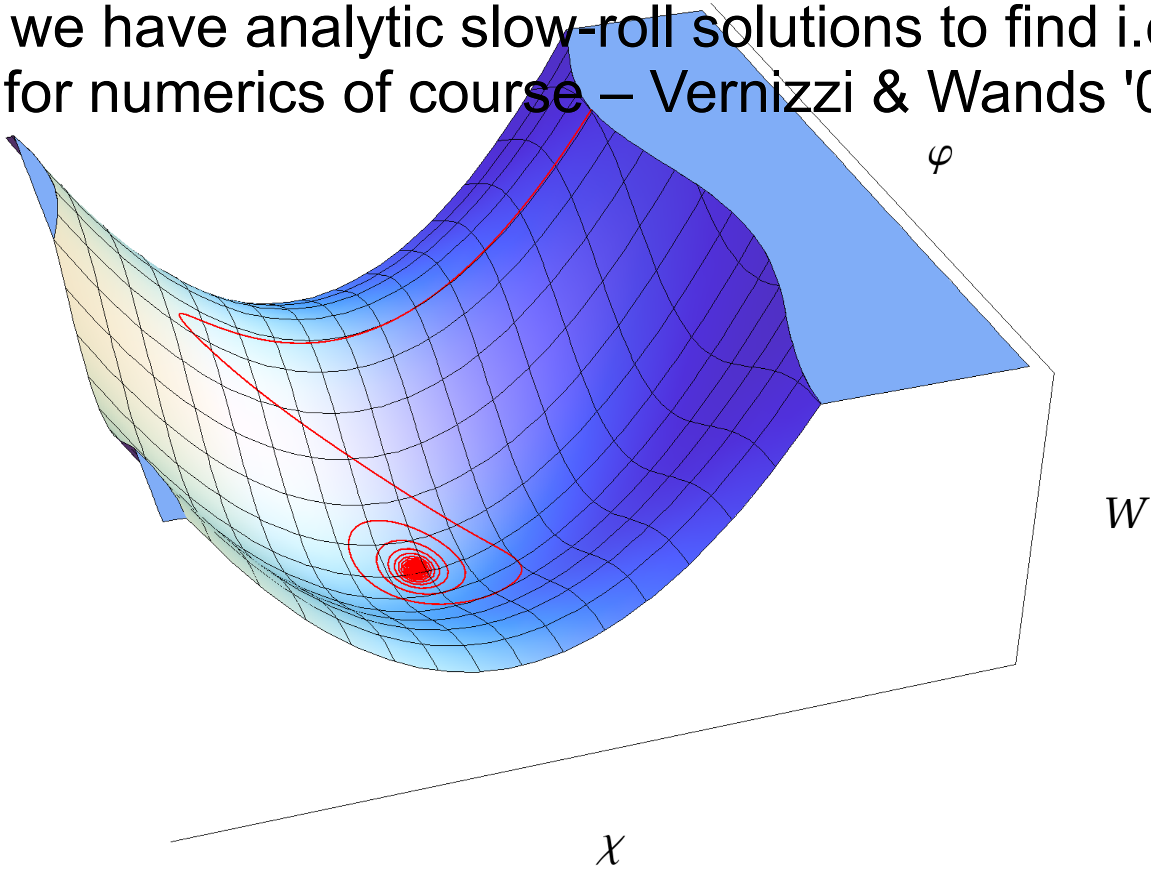
$$n_\zeta - 1 \approx -2\epsilon_* - 4\lambda \frac{N_\varphi^2}{N_\varphi^2 + g_*^2} \simeq -2\epsilon_* - 4\lambda$$

Case Study: two minima model

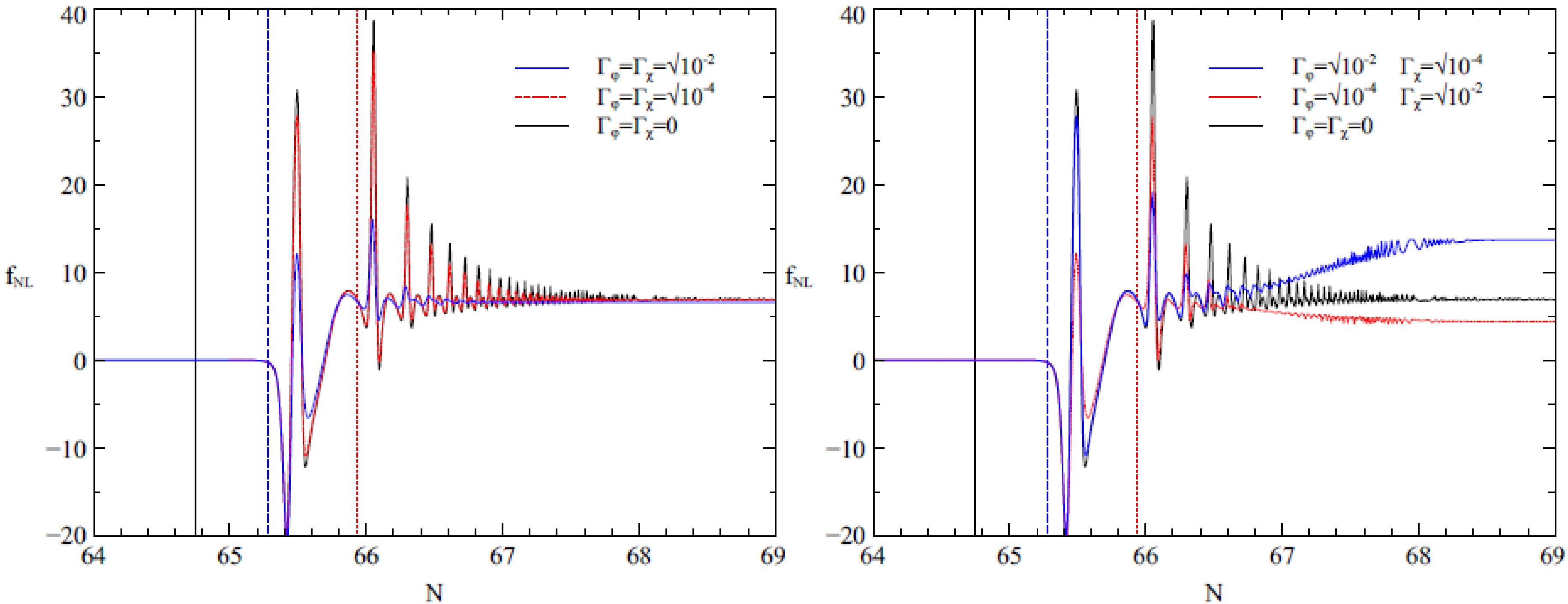
$$W = W_0 \left[\frac{1}{2}m^2\chi^2 + \Lambda^4\left(1 - \cos\left(\frac{2\pi}{f}\varphi\right)\right)\right]$$

Elliston et al '11

- Note product separable, previous model was sum separable (chosen because we have analytic slow-roll solutions to find i.c.'s), not required for numerics of course – Vernizzi & Wands '06



f_{NL} evolution



Solution diverges slowly from zero gamma case, suggests our assumption of constant gamma is reasonably good
Notice that in equal gamma case, the final value of f_{NL} is always the same
Strong contrast to the unequal gamma case (right hand plot)
Also interesting that $f_{NL}=0$ until reheating in this model, a calculation during inflation would give the impression of Gaussian perturbations

More observables

χ^2 minimum: $f_{\rm NL}(t_e) \approx 0$, $n_s(t_e) = 0.969$, $r(t_e) = 0.124$				
Γ_φ	Γ_χ	$f_{\rm NL}^{\rm final}$	$n_s^{\rm final}$	$r^{\rm final}$
0	0	6.88	0.935	4.6×10^{-4}
$\sqrt{10^{-2}}$	$\sqrt{10^{-2}}$	6.59	0.969	4.3×10^{-4}
$\sqrt{10^{-4}}$	$\sqrt{10^{-4}}$	6.83	0.965	4.6×10^{-4}
$\sqrt{10^{-2}}$	$\sqrt{10^{-4}}$	13.66	0.963	1.0×10^{-3}
$\sqrt{10^{-4}}$	$\sqrt{10^{-2}}$	4.37	0.974	2.7×10^{-4}

χ^4 minimum: $f_{\rm NL}(t_e) \approx 0$, $n_s(t_e) = 0.951$, $r(t_e) = 0.263$				
Γ_φ	Γ_χ	$f_{\rm NL}^{\rm final}$	$n_s^{\rm final}$	$r^{\rm final}$
0	0	5.04	0.966	2.9×10^{-4}
$\sqrt{10^{-5}}$	$\sqrt{10^{-5}}$	4.99	0.972	3.0×10^{-4}
$\sqrt{10^{-4}}$	$\sqrt{10^{-4}}$	5.06	0.966	3.0×10^{-4}
$\sqrt{10^{-1}}$	$\sqrt{10^{-5}}$	5.39	0.967	3.3×10^{-4}
$\sqrt{10^{-2}}$	$\sqrt{10^{-4}}$	5.28	0.967	3.2×10^{-4}

Notice tensor-to-scalar ratio decreases dramatically in this model from the end of inflation and f_{NL} grows from nearly zero
Estimates based on the end of inflation would be very wrong

Conclusions

- If f_{NL} is large at the end of inflation, it typically remains large (reverse not always true)
- Large local f_{NL} does rule out single field and "uninteresting" multifield models
- However amplitude of non-zero f_{NL} has limited power to discriminate between models
- Except its sign which seems to be preserved
- Spectral index is less sensitive to reheating

Many open issues

- More potentials (how generic are our conclusions?)
- Best way to scan large parameter space
- Progress on analytics...
- More than two fields (but many parameters)
- Different kinetic terms (go beyond local non-G)
- Higher order observables (eg trispectrum and scale dependence of f_{NL})
- More realistic (p)reheating models (but hard even in single-field inflation)