Title: Preheating after Multi-Field Inflation

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Abstract: We investigate the feasibility of explosive particle production via parametric resonance or tachyonic preheating in multi-field inflationary models by means of lattice simulations. We observe a strong suppression of resonances in the presence of four-leg interactions between the inflaton fields and a scalar matter field,

leading to insufficient preheating when more than two inflatons couple to the same matter field. This suppression is caused by a dephasing of the inflatons that increases the effective mass of the matter field. Including three-leg interactions leads to tachyonic preheating, which is not suppressed by an increase in the number of fields. If four-leg interactions are sub-dominant, we observe a slight enhancement of tachyonic preheating. Thus, in order for preheating after multi-field inflation to be efficient, one needs to ensure that three-leg interactions are present. If no tachyonic contributions exist, we expect the old theory of reheating to be applicable.

Perimeter Institute 2009

Pre-heating after Multi Field Inflation

0904.2778 (follow up to 0803.0321)

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In collaboration with:

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J. T. Giblin Jr., Bates College and Perimeter Institute
S. Kawai, Helsinki Institute of Physics

(P)re-heating:

Energy needs to be transferred from the inflationary sector to ordinary matter:

- Old Theory of reheating (field decays once the decay rate ~ H)
  Abbot et. al (82), Dolgov and Linde (82), …

Or Preheating (subsequent phase of thermalization needed)

- Resonances (explosive particle production)
  Brandenberger and Traschen (90), Dolgov and Kirilova (90), Kofman, Linde, Starobinsky (98), …

- Tachyonic Instabilities (i.e. in hybrid inflation)
  Dufaux, Felder, Kofman, Peloso and Podolsky (06), …

Remarks on Preheating:

- High temperatures after preheating are common:
  good for GUT-baryogenesis, but problematic w.r.t. relics (gravitino problem).

- Unrelated (important) application:
  moduli trapping near loci of enhanced symmetry.

- Preheating models are phenomenological, since the couplings of the inflaton(s) to other fields are generally unknown.

- Preheating in multi-field inflationary models is largely unexplored (a brief review follows).

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> **Question:**
> Under what conditions does preheating take place if multiple inflatons contribute?

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Review: Wands (07)

Why consider more inflatons?

"Natural" in string theory (presence of many moduli fields etc.)

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

- possible avoidance of super-Planckian field values
- increased Hubble friction, steeper potentials work, reduced fine tuning

Examples are

- Inflation from axions (N-flation), Dimopolus, Kachru, McGreevy, Wacker (05),
- Inflation from multiple M5-branes, Becker, Becker, Krause (06),
- Inflation from tachyons (D-branes), Majumdar, Davis (03),
- Inflation on the landscape (staggered inflation; inflation from random potentials), Battefeld, Battefeld, Davis (08); Tye, Xu, Zhang (09)
- ...

Outline

Setup

Review
- single inflaton, parametric resonance (PR)
- two inflatons, Cantor preheating (enhanced PR)
- hundreds of inflatons, suppressed PR due to dephasing

Lattice simulations (including backreaktion), N=1,2,3,4 and 5
- Case A: four-leg interactions (PR case)
- Case B: three- and four-leg interactions
- Case C: three-leg interactions (tachyonic instability)

Conclusions

Setup

N inflatons, one additional scalar field, canonical kinetic terms

$$W = \sum_{i=1}^{\mathcal{N}} \left(\frac{m_i^2}{2}\varphi_i^2 + \frac{\sigma}{2}\varphi_i\chi^2 + \frac{g}{2}\varphi_i^2\chi^2 \right) + \frac{\lambda}{4}\chi^4$$

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Inflaton potential, expanded around minimum.

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Three-leg interaction (Yukawa coupling), leads to a tachyonic instability/preheating in single field models.

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↑

four-leg interaction, leads to PR and stochastic preheating in single field models.

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Added for stability in our lattice simulations. (No effect on preheating)

Single Inflaton: N=1, sigma=0, no backreaction

Kofman, Linde, Starobinsky (97)

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + g\ \varphi^2\right)\chi_k = 0$$

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Oscillating effective mass ⟶ resonances,
explosive particle production

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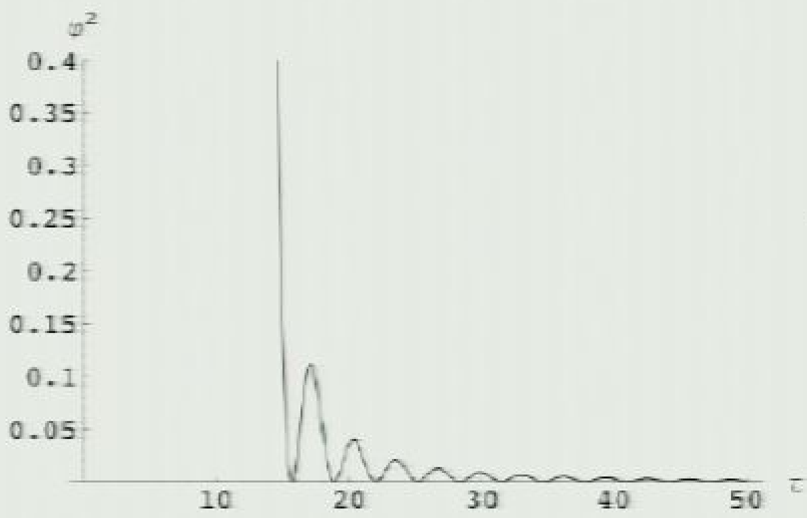
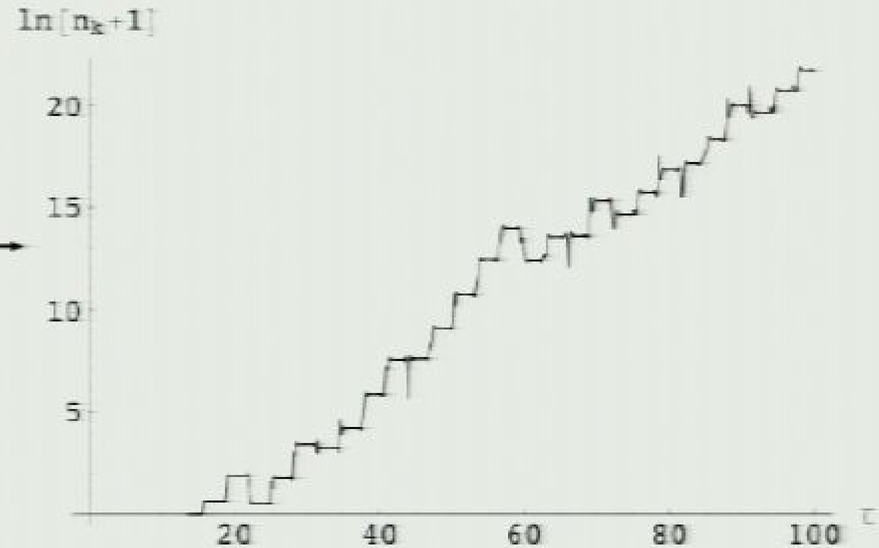


⟶



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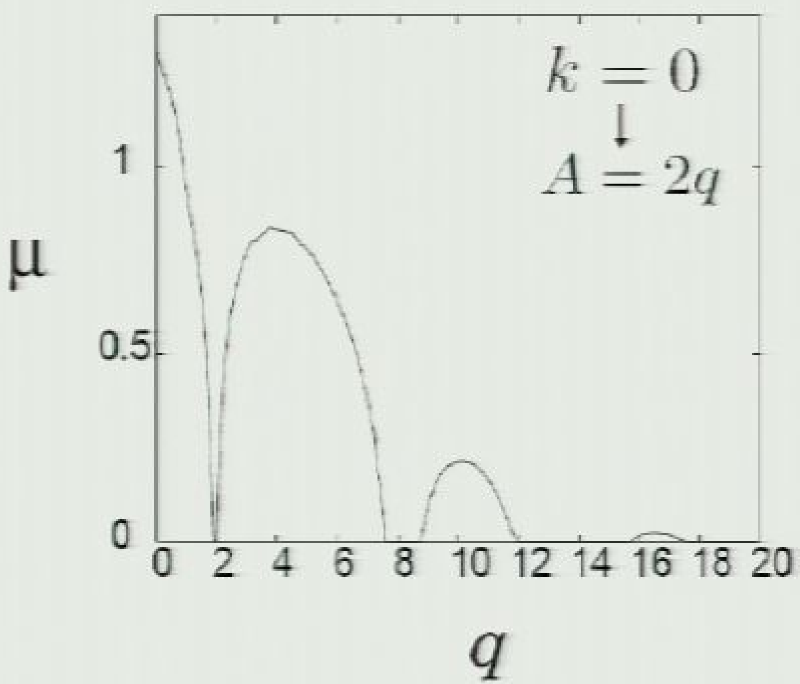
Analytic understanding: stability/instability bands; modes shift through bands as the universe expands: ``stochastic resonance''

$$q = \frac{g\ \Phi_0^2}{4m_\varphi^2}, \qquad A = \frac{k^2}{a^2 m_\varphi^2} + 2q \qquad a^{3/2}\chi_k \propto e^{\mu_k \tau}$$



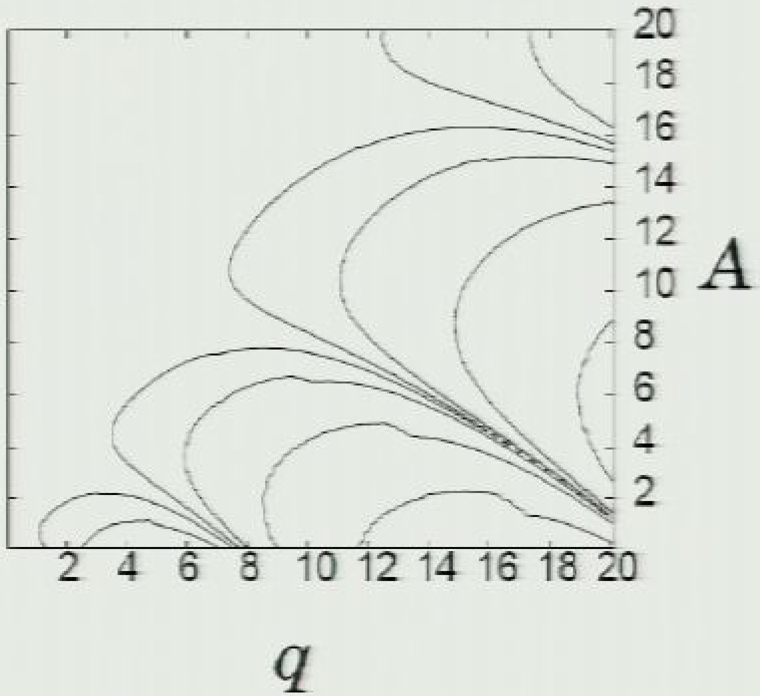


Figure from Bassett, Tamburini (98)

Cantor Preheating: N=2, sigma=0, no backreaction

Bassett, Tamburini (97,98)

- Analytic result (spectral theory): stability bands dissolve into a nowhere dense set if the oscillation frequency of the inflatons differ (quasi periodic modulation of chi's effective mass).

- Expectation: almost all modes should get amplified (no prediction for the magnitude).

- Numerical study: 2 inflatons, 1 matter field: dissolution of stability bands and amplification of almost all modes is observed, enhanced particle production

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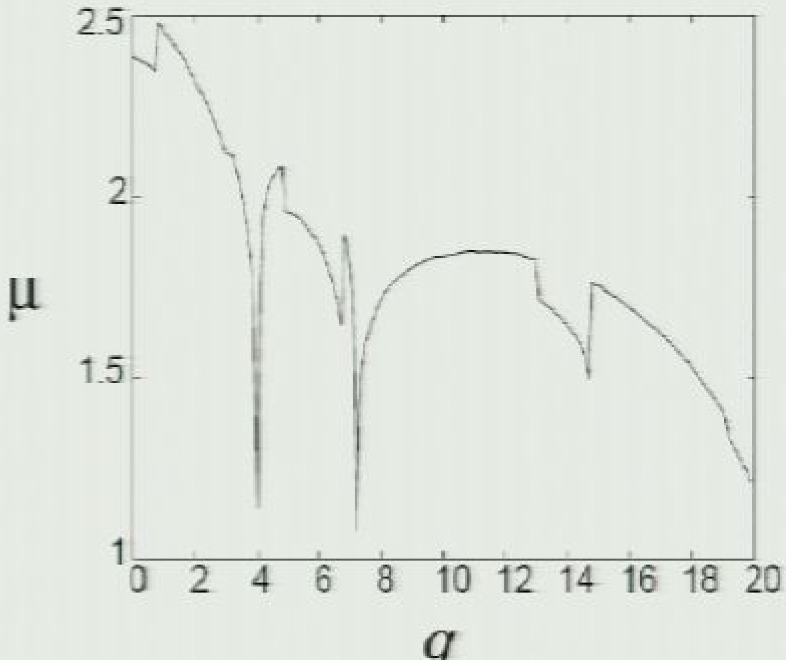

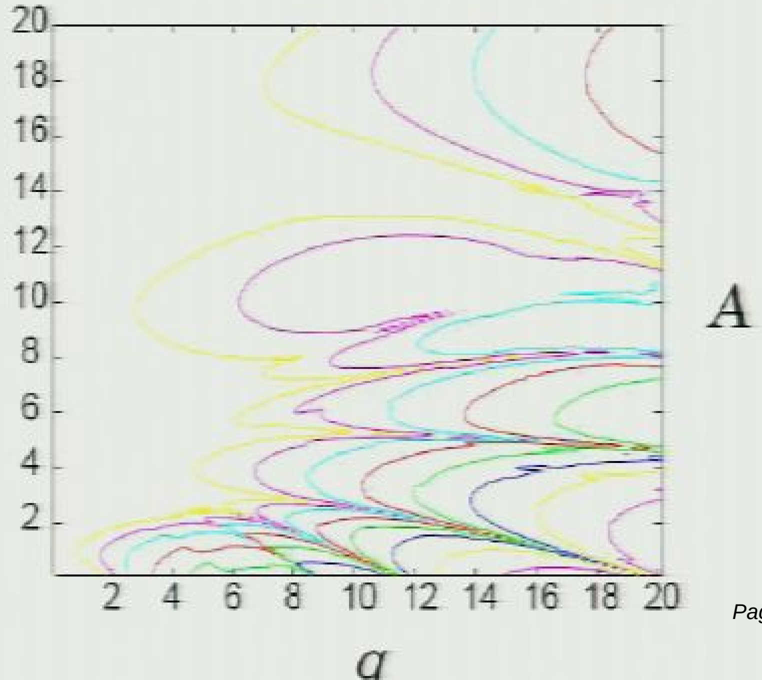

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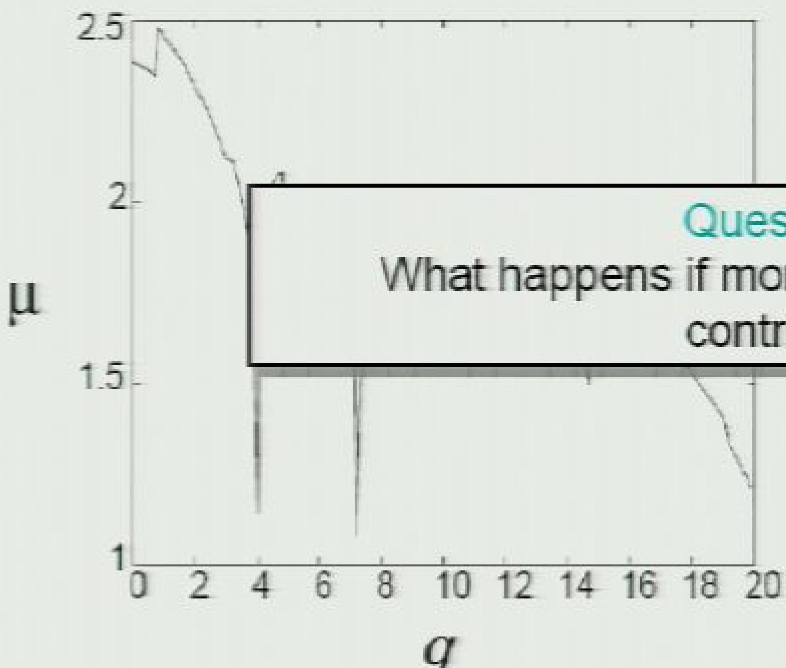

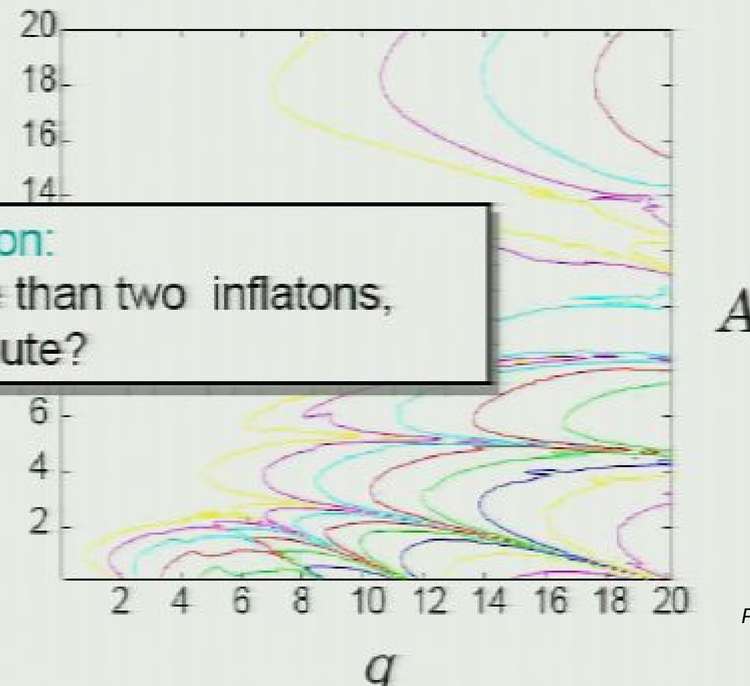

Question:
What happens if more than two inflatons, contribute?

N=large, sigma=0, no back-reaction

D. Battefeld, S. Kawai (08)

Consider

$$\mathcal{L} = -\frac{1}{2}\sum_{i=1}^{\tilde{N}}\left(g^{\mu\nu}\nabla_\mu\varphi_i\nabla_\nu\varphi_i + m_i^2\varphi_i^2 + g\ \varphi_i^2\chi^2\right) - \frac{1}{2}g^{\mu\nu}\nabla_\mu\chi\nabla_\nu\chi$$

Many fields $\tilde{N} = 150$ (arises i.e. in N-flation.)

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Many fields $\tilde{N} = 150$ (arises i.e. in N-flation.)

Equations of motion: $$\ddot{\varphi}_i + 3H\dot{\varphi}_i + m_i^2\varphi_i = 0,$$

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + g\ \sum_i \varphi_i^2\right)\chi_k = 0,$$

$$6H^2 = \sum_i \dot{\varphi}_i^2 + \sum_i m_i^2\varphi_i^2$$

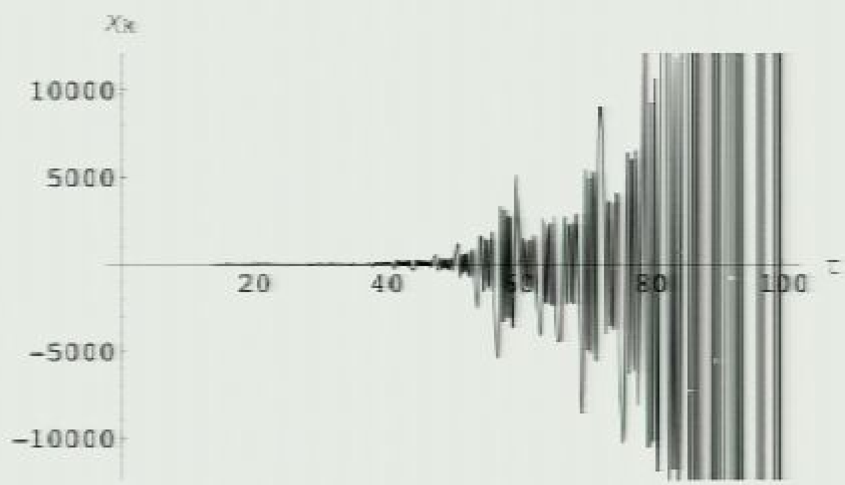
Equal masses

The fields' collective behavior is coherent; indistinguishable from a single field model:

$$\varphi = \sqrt{\tilde{N}}\varphi_i$$

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + g\ \varphi^2\right)\chi_k = 0$$

System exhibits resonances:



Particle number:

$$n_k = \frac{1}{2}\left(\frac{|\dot{X}_k|^2}{\omega_k} + \omega_k |X_k|^2\right) - \frac{1}{2}$$

Where $X_k = a^{3/2}\chi_k$ and $\omega_k = \sqrt{\frac{k^2}{a^2} + g\ \varphi^2}$

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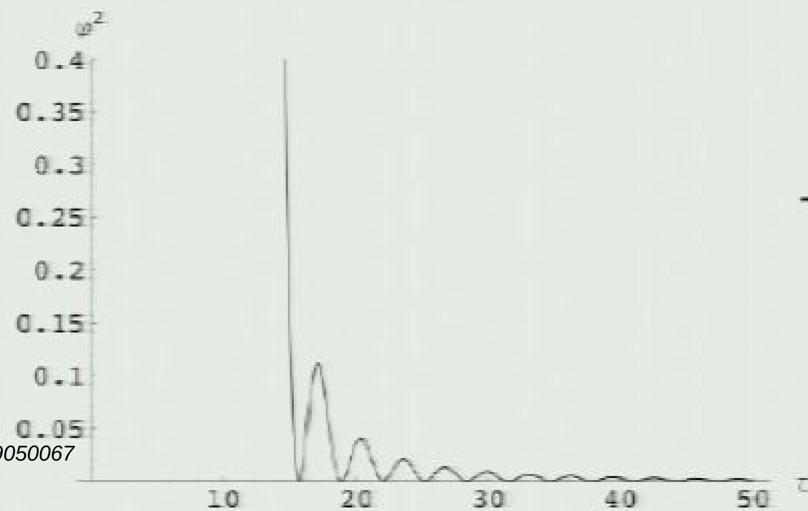
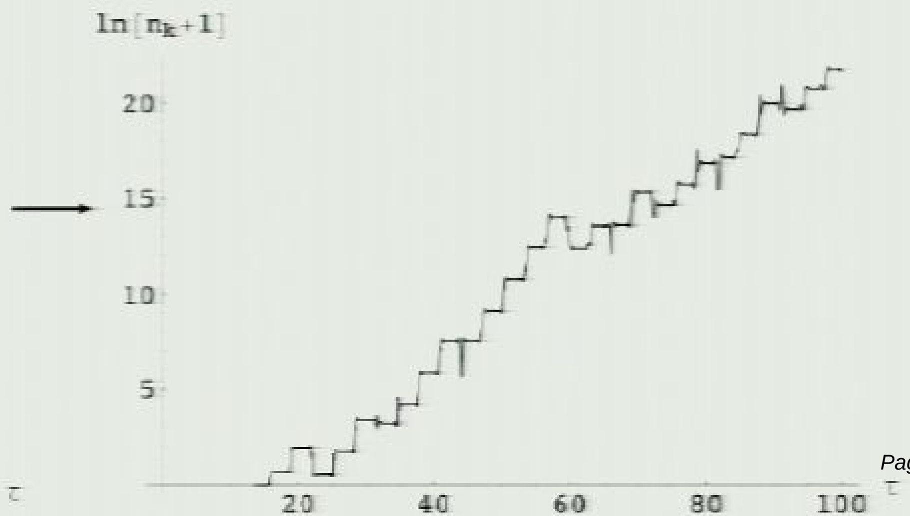
System exhibits explosive particle production:

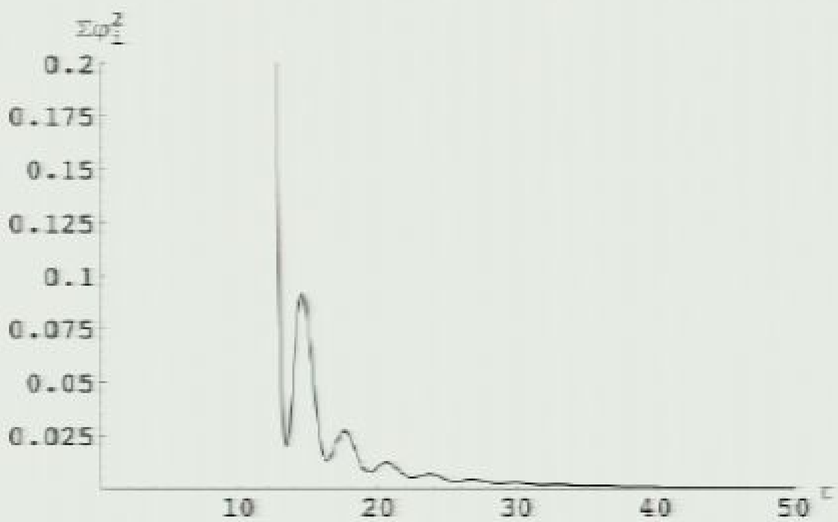




Different masses

Use mass distribution of N-flation

The inflatons' collective behavior is not coherent due to de-phasing. Effective mass of chi is bigger (non-adiabaticity parameter remains small).



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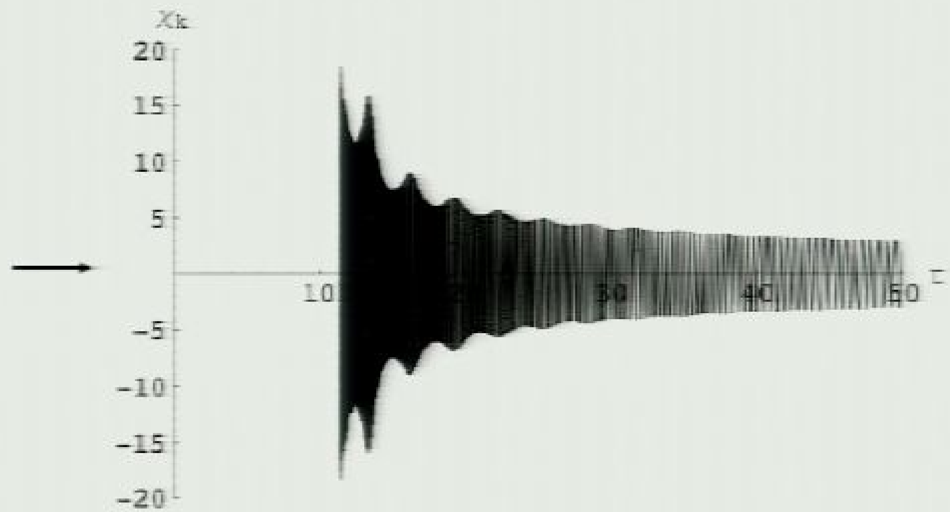

Note: Beats (and a some minor particle production) are possible if fields start out in phase and one waits long enough.

Conflicting Results

F. Tamburini and B. Basset (98), 2 inflatons – increased particle production

D. Battefeld and S. Kawai (08), 150 inflatons – strong suppression
(Also: J.Braden at COSMO08)

What is the dominant effect for a few field?

D. Battefeld, T. Battefeld and T. Giblin (09):

- incorporate backreaction (lattice simulation)

- simulate N=1,2,3,4 and 5.

- consider three- and four-leg interactions

Several fields, with back-reaction

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- Using the LATTICEEASY-code, we solve for N=1,2,3,4 and 5:

$$\ddot{a} + 2\frac{\dot{a}^2}{a} - \frac{8\pi}{a}\left(\frac{1}{3}\sum_{i=1}^{\mathcal{N}} |\nabla\varphi_i|^2 + \frac{1}{3}|\nabla\chi|^2 + aW\right) = 0$$

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- Mass distribution: $m_i^2 = \frac{\mathcal{N} + 2i - 3}{2(\mathcal{N} - 1)} m^2 \equiv \beta_i m^2$

- Equal energy initial conditions (for zero mode):

$$\varphi_i(0) = \sqrt{\frac{1}{\mathcal{N}}\frac{1}{\beta_i}}\varphi_0$$

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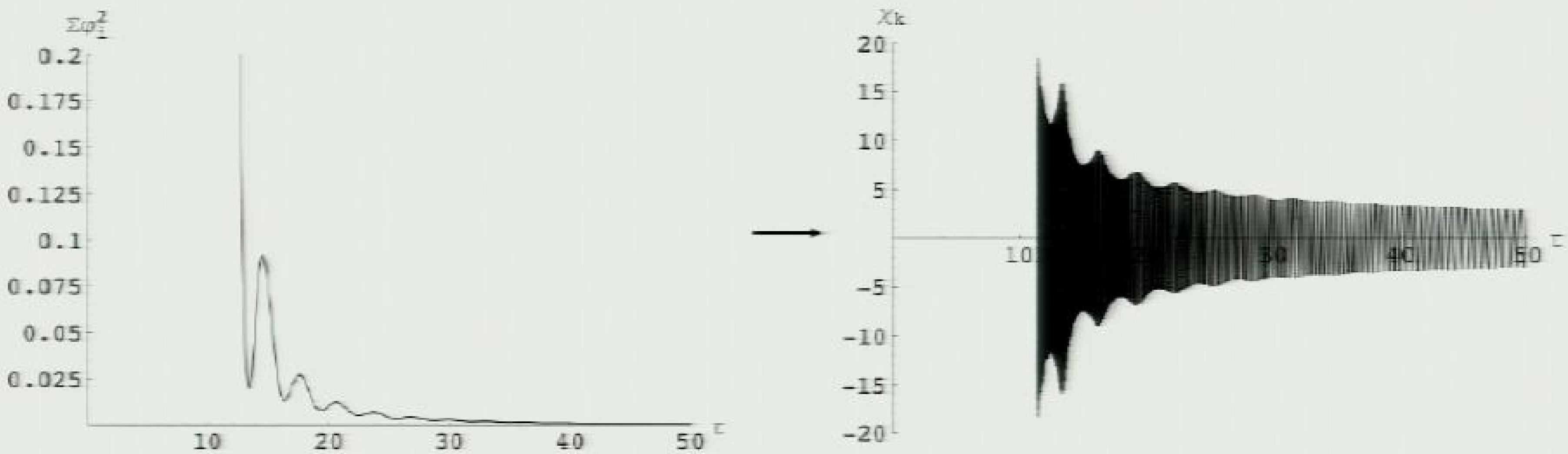

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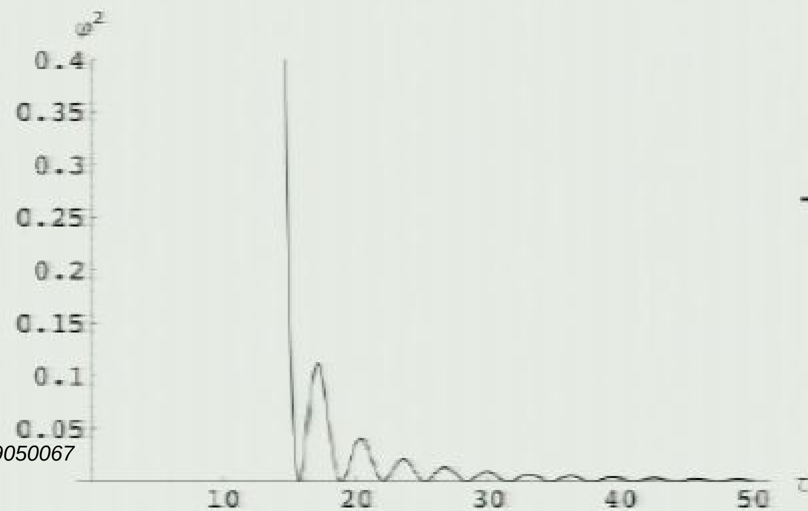
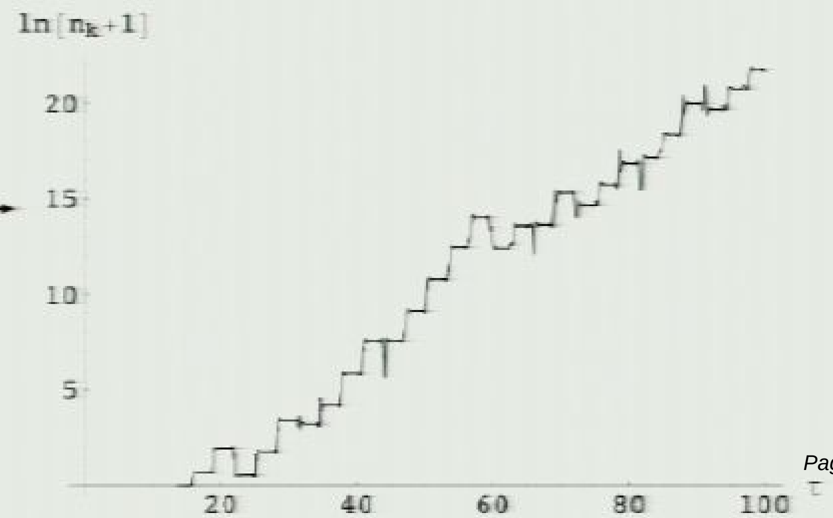
System exhibits explosive particle production:





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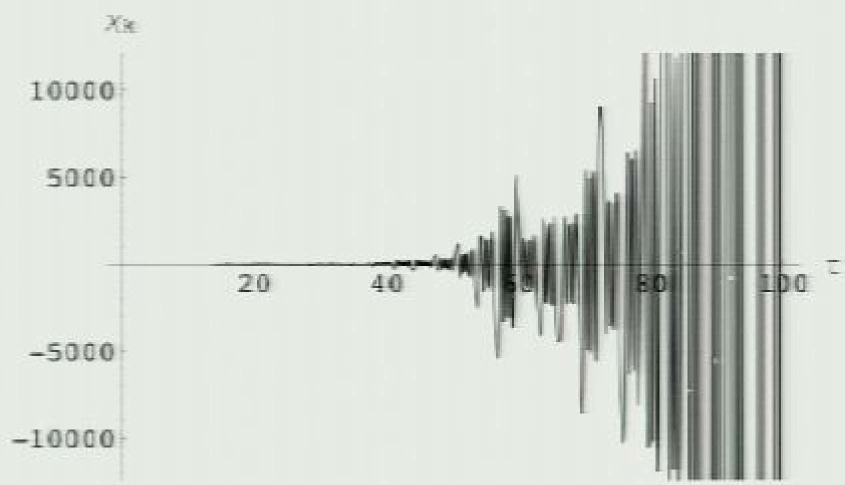

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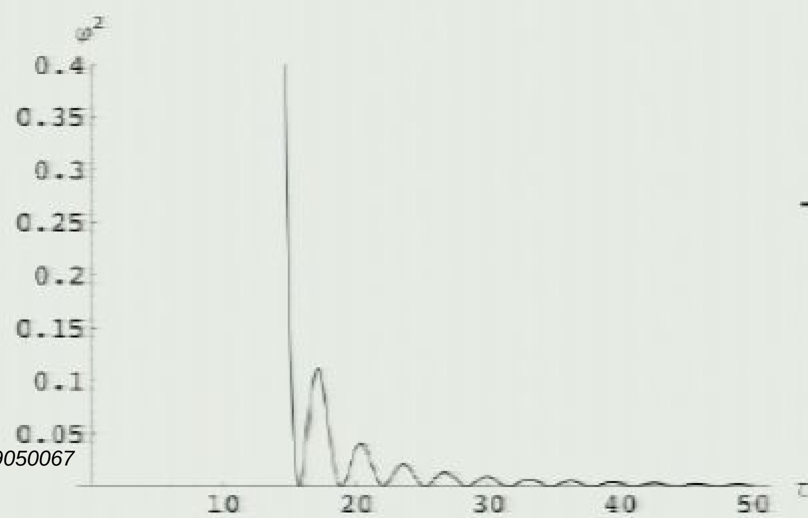

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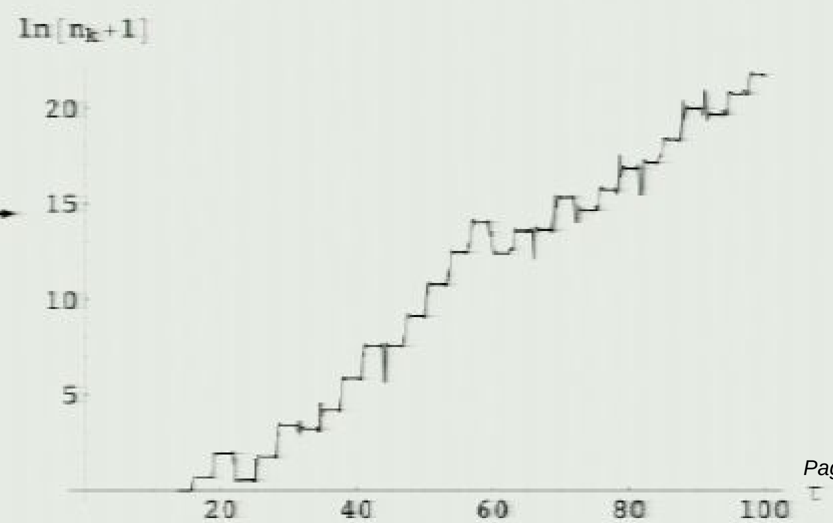

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- Initial inhomogeneities are specified natively by LATICEEASY in momentum space.

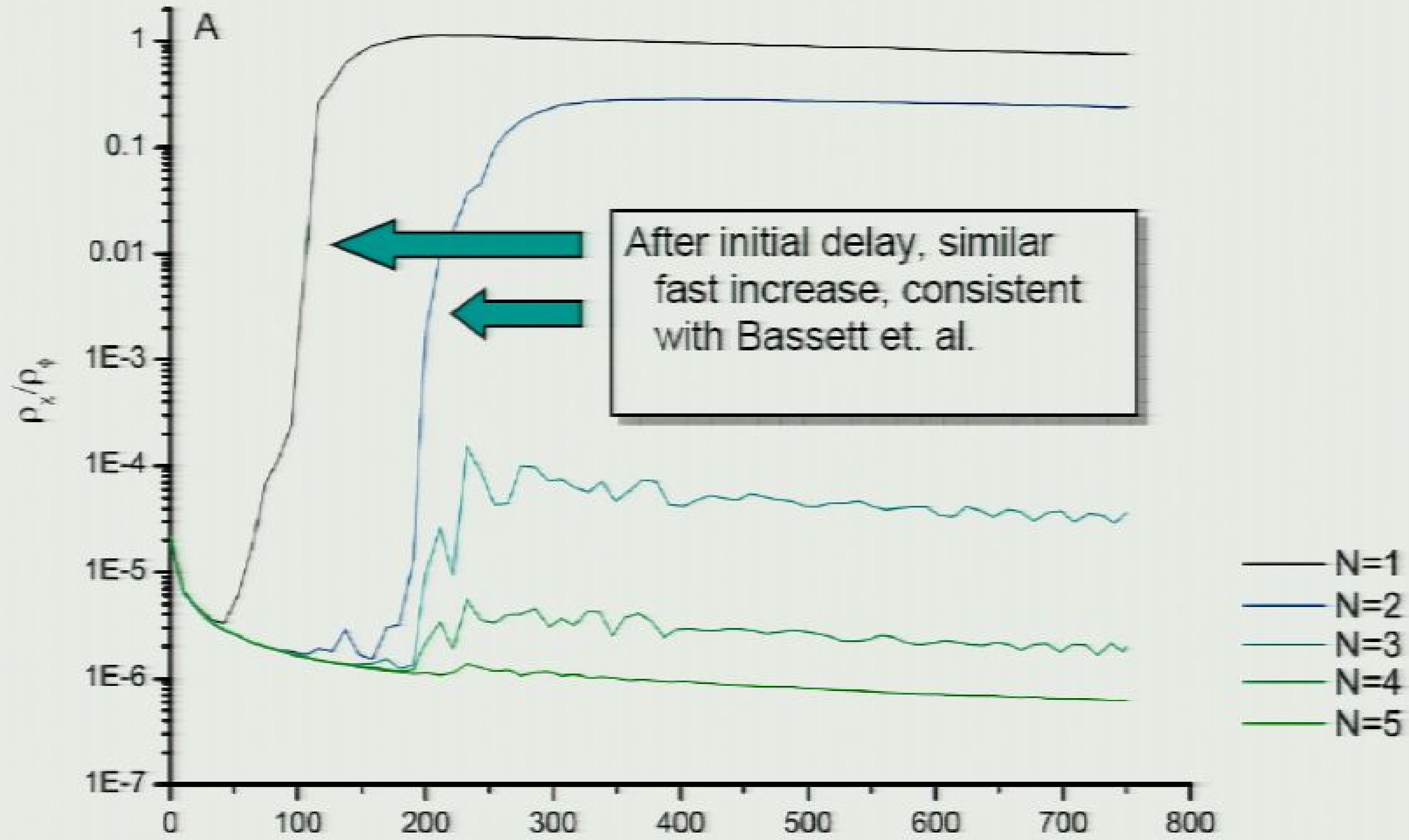
- Use: $n^3 = 128^3$ lattice, box size: $L = 5/m$; cover: $2\pi/L < k < 2\pi\sqrt{3}n/(2L)$

- Investigate three cases:

Case	$g \times (0.193)^2/m^2$	$\sigma \times 0.193/m^2$	$\lambda \times (0.193)^2/m^2$
A	10^4	0	5×10^3
B	10^4	100	5×10^3
C	100	100	10^4

$$W = \sum_{i=1}^{N} \left(\frac{m_i^2}{2}\varphi_i^2 + \frac{\sigma}{2}\varphi_i\chi^2 + \frac{g}{2}\varphi_i^2\chi^2 \right) + \frac{\lambda}{4}\chi^4$$

Case A, four-leg interactions (Parametric resonance case)



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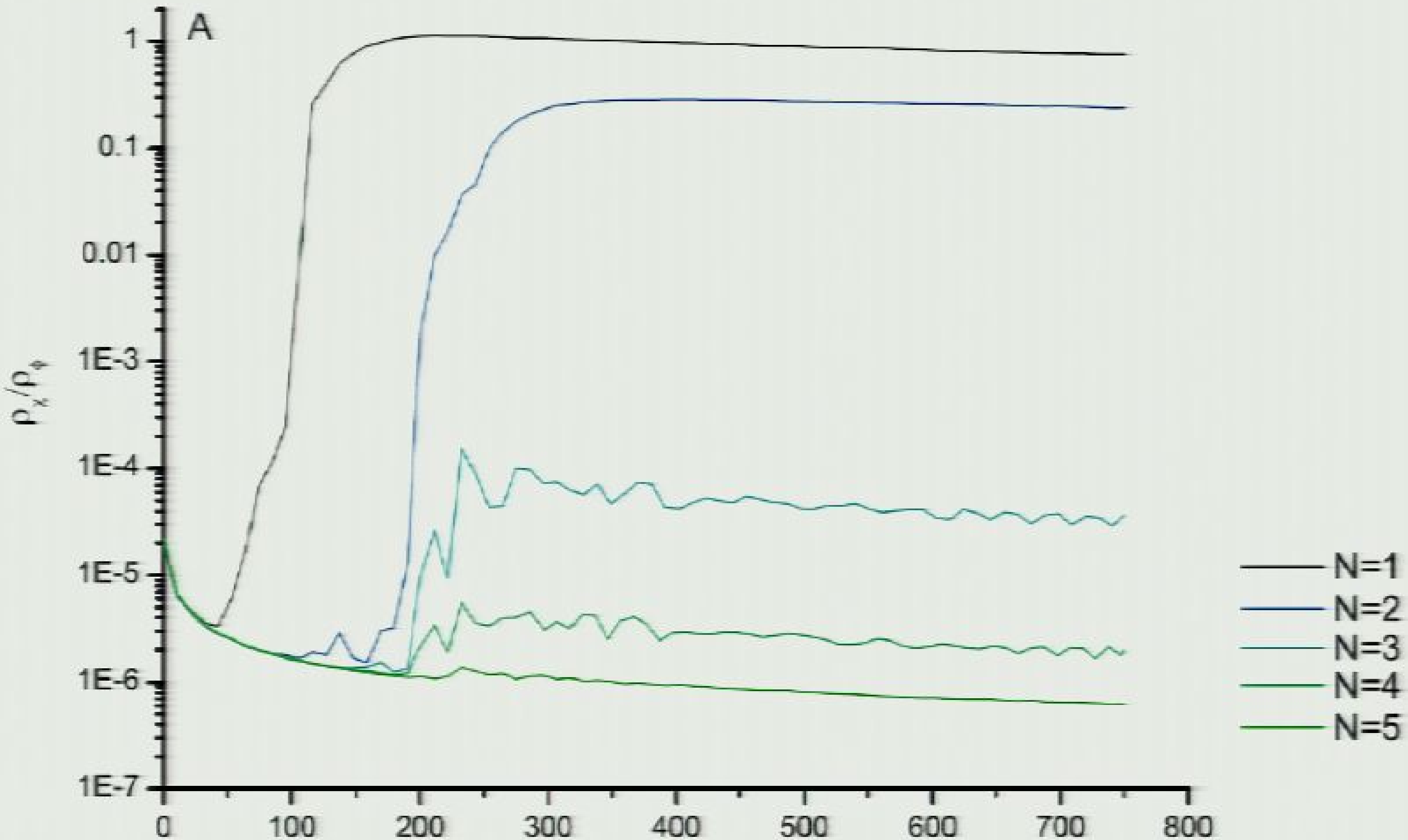

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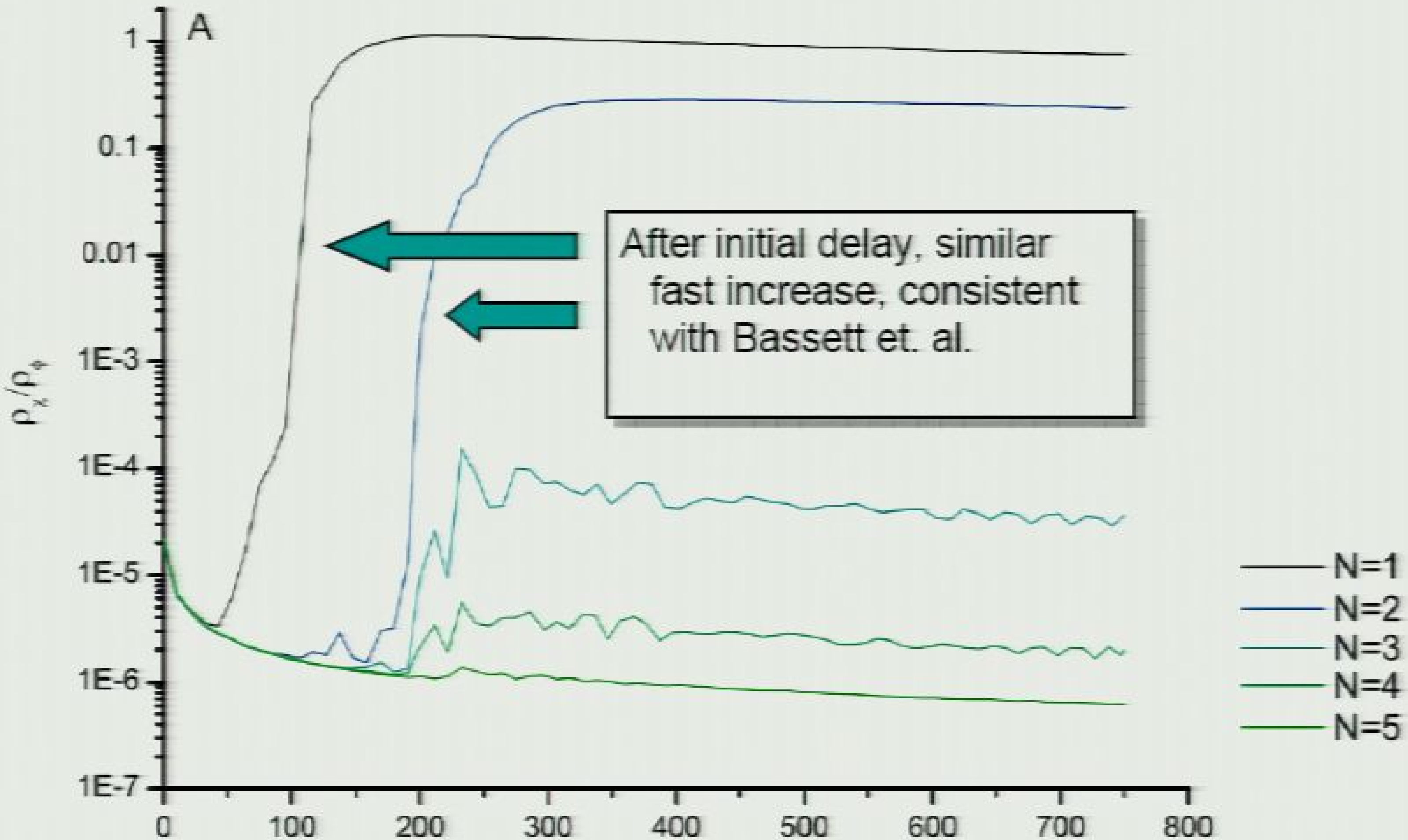

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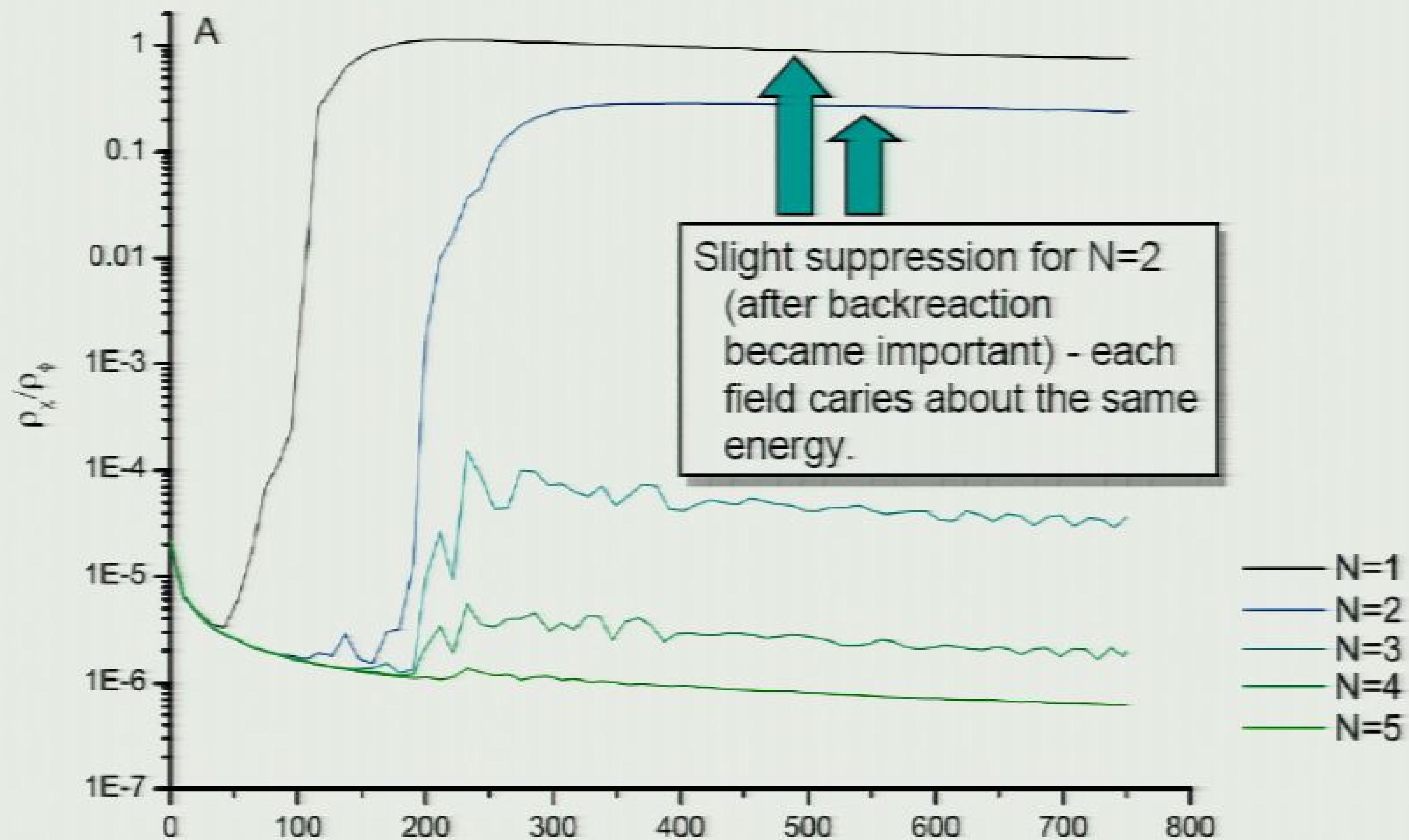

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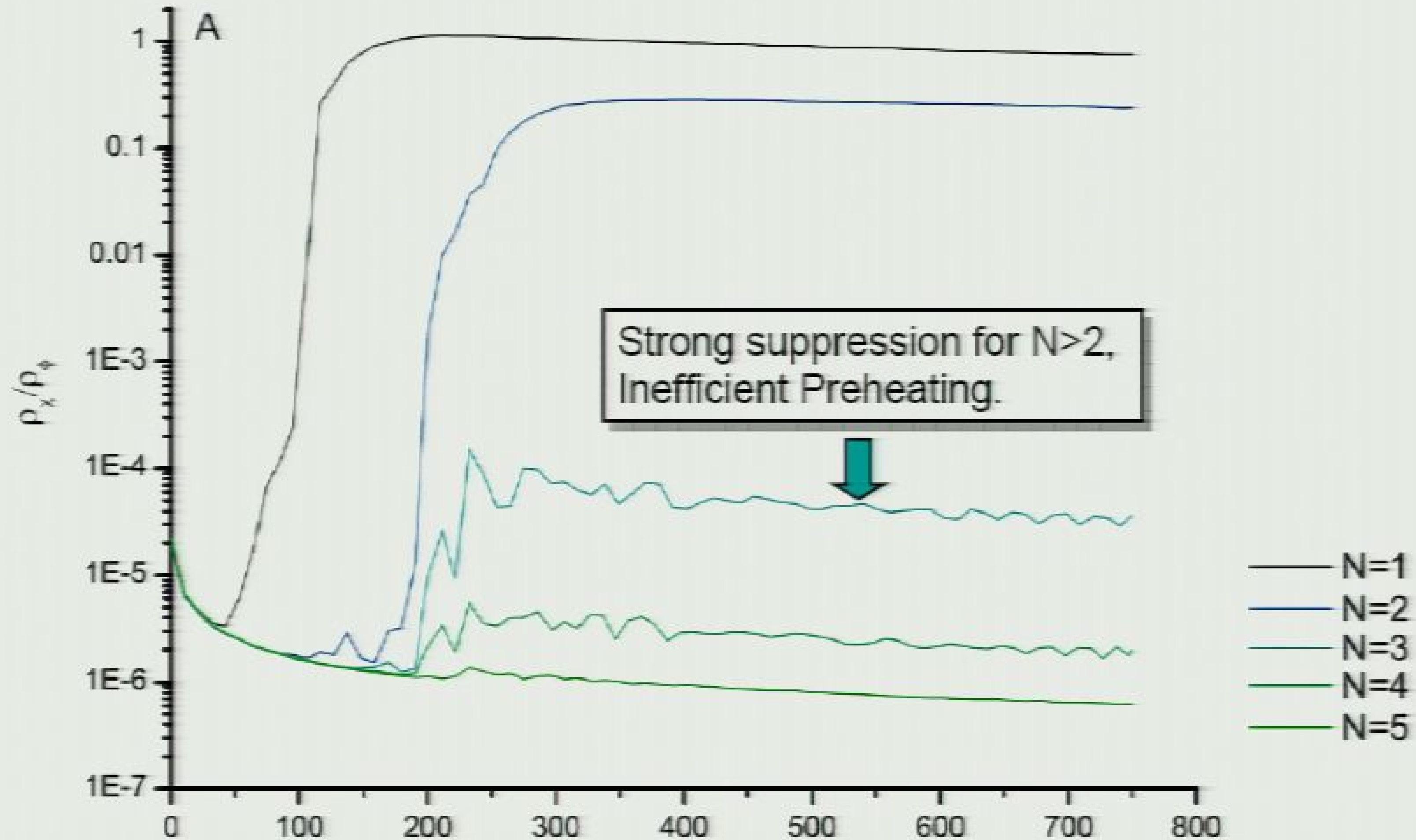
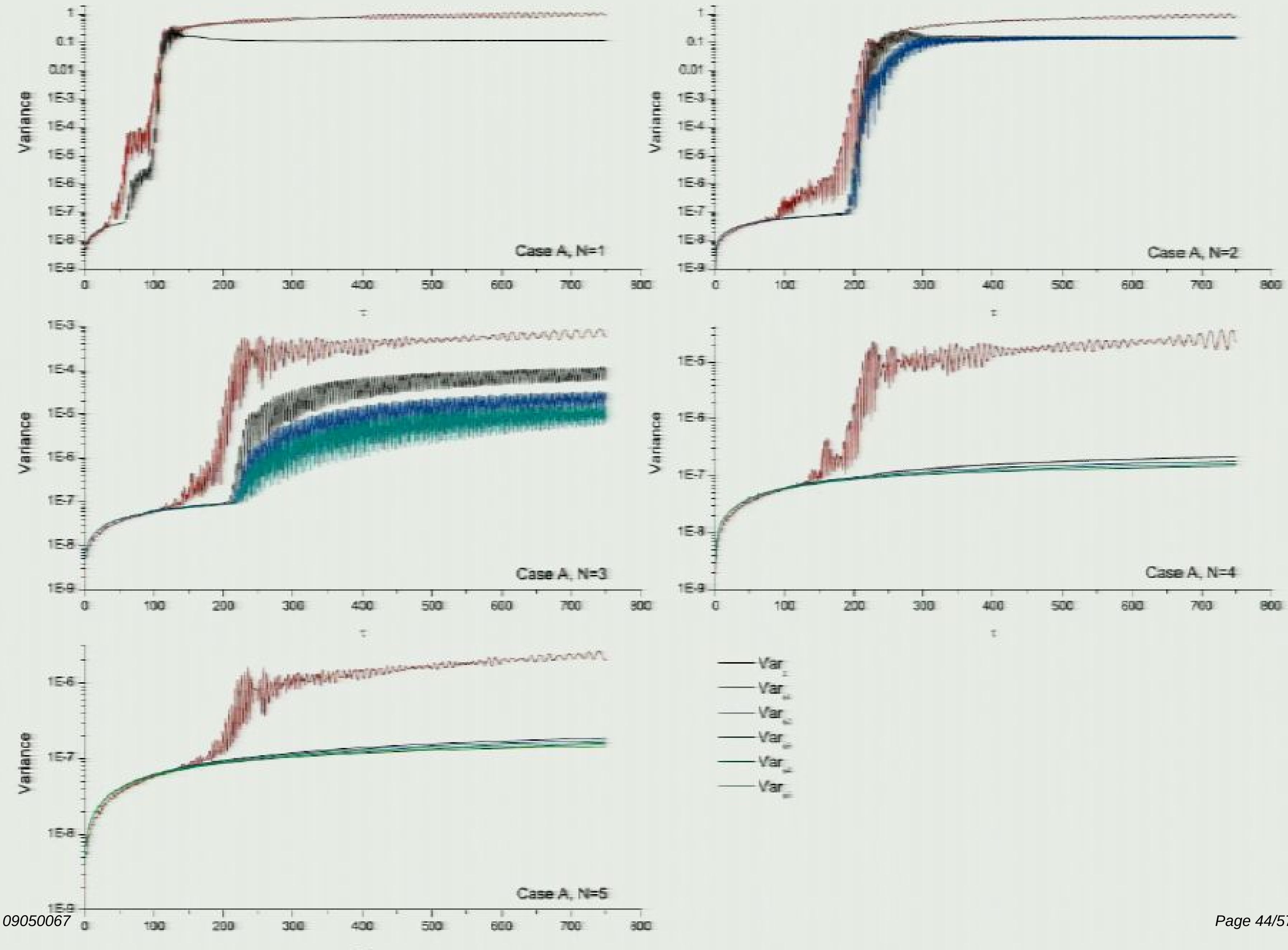
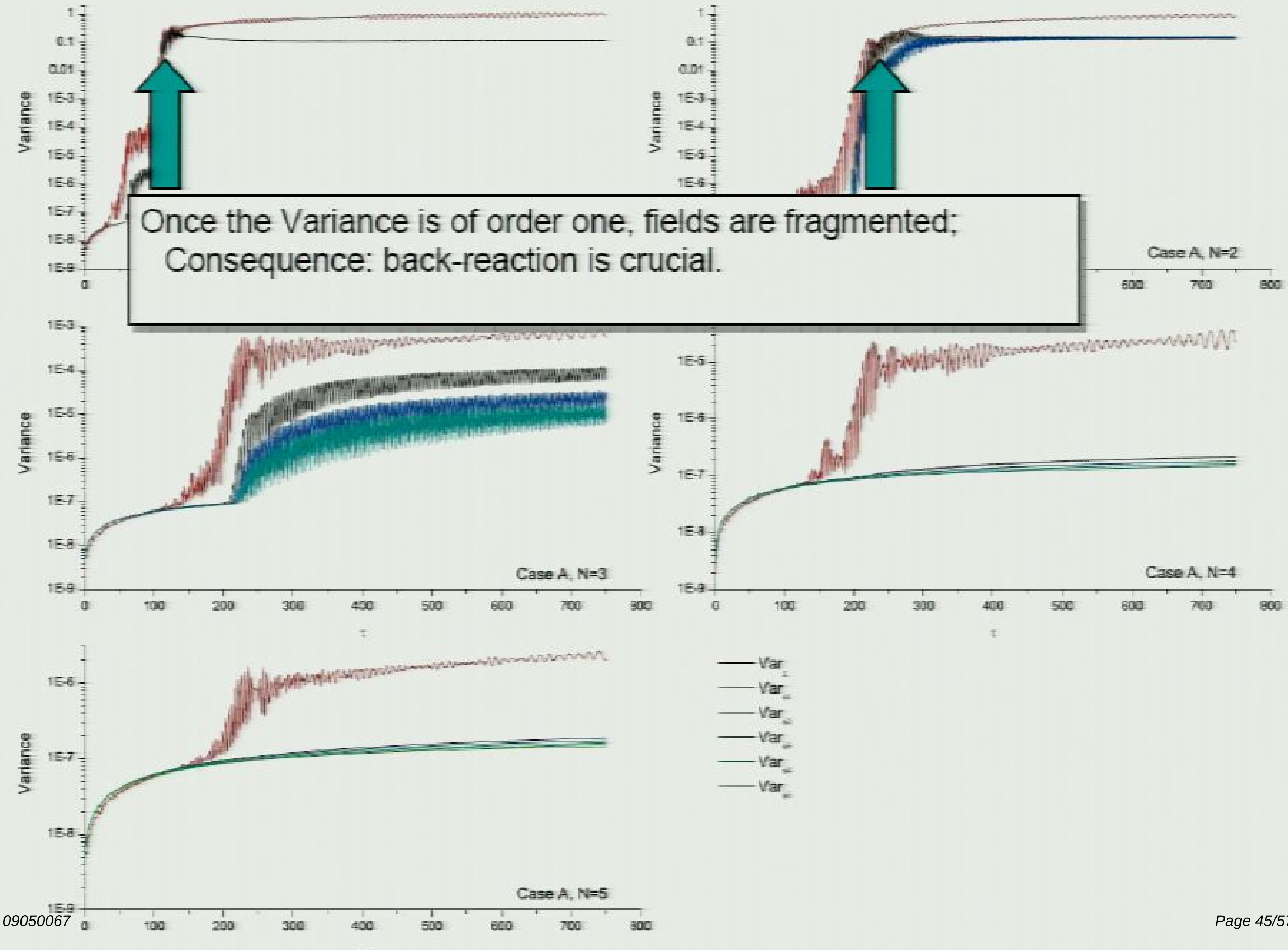
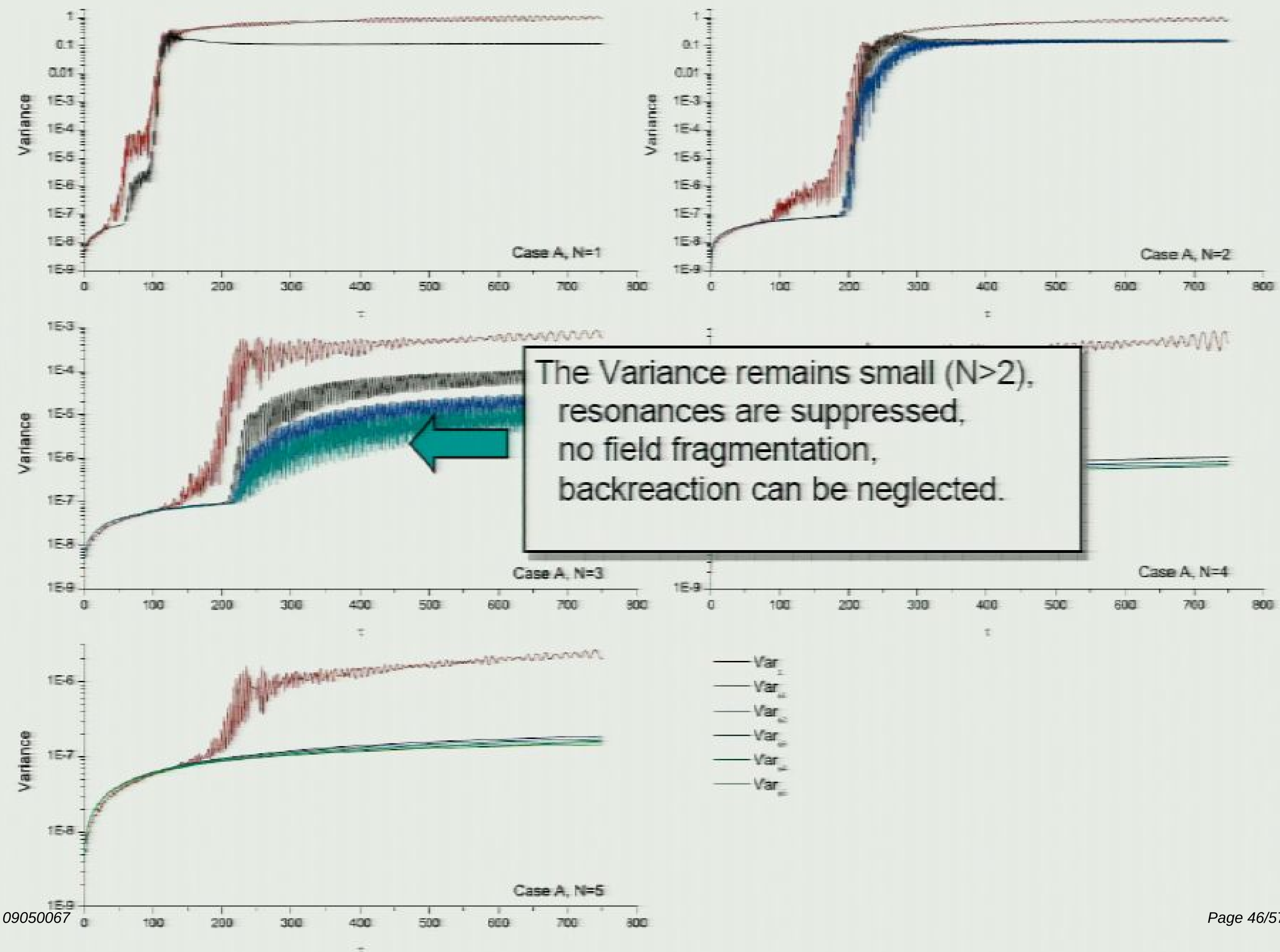


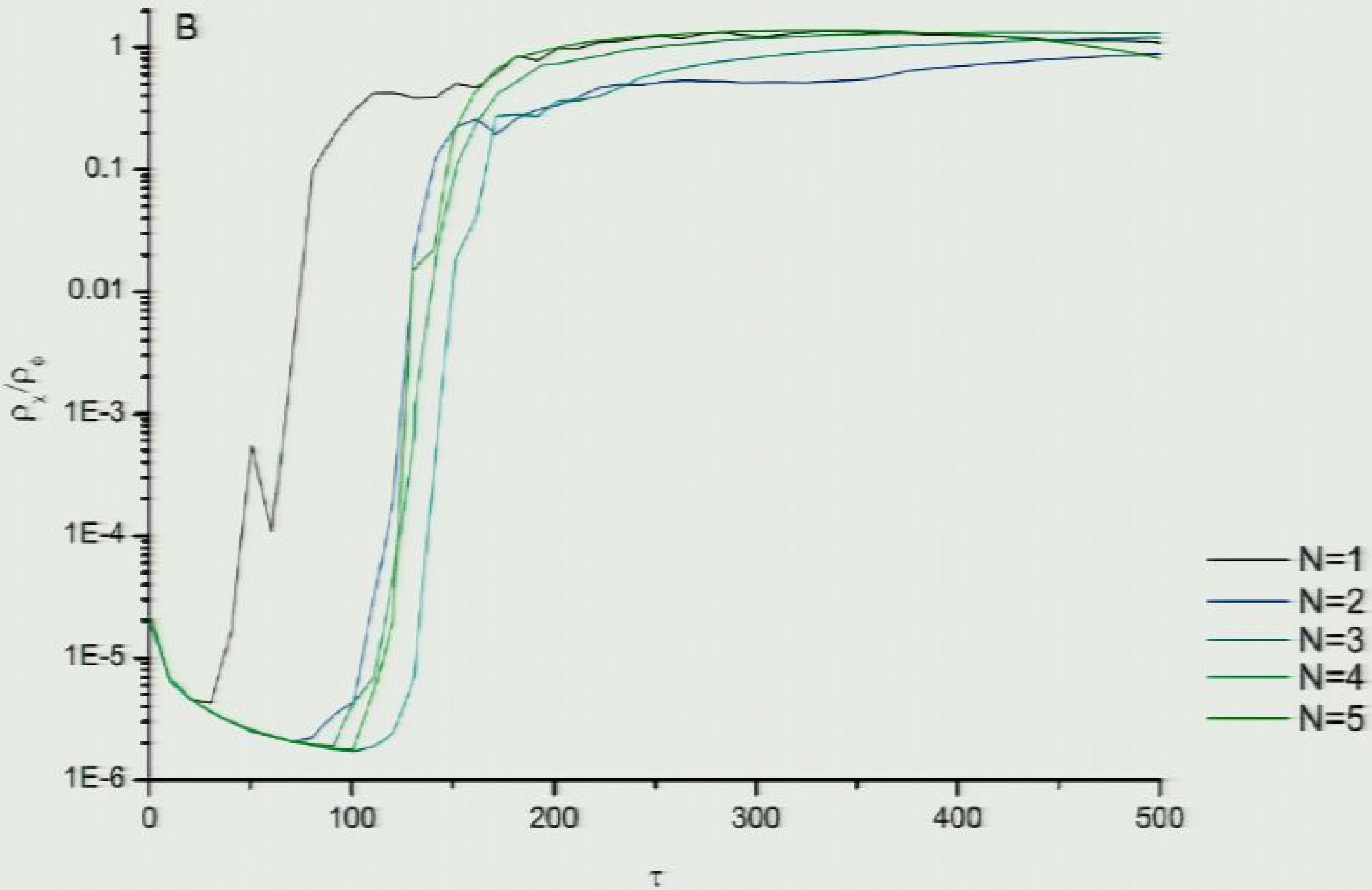

Variance
τ
Case A, N=1
Case A, N=2
Case A, N=3
Case A, N=4
Case A, N=5
Var
Var
Var
Var
Var
Var



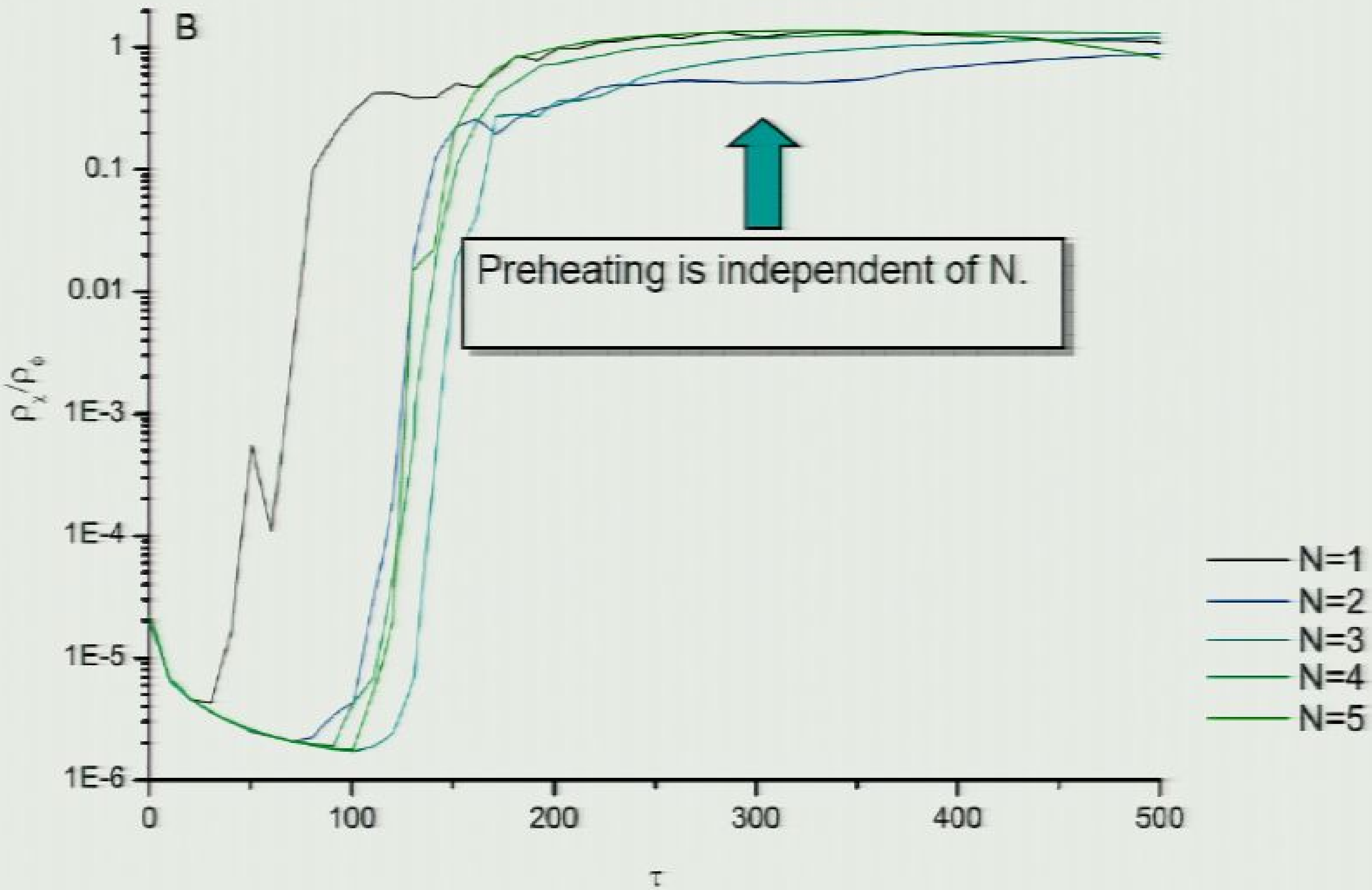
Once the Variance is of order one, fields are fragmented;
Consequence: back-reaction is crucial.


Variance
τ
Case A, N=1
Case A, N=2
Case A, N=3
Case A, N=4
Case A, N=5
Var
The Variance remains small (N>2), resonances are suppressed, no field fragmentation, backreaction can be neglected.

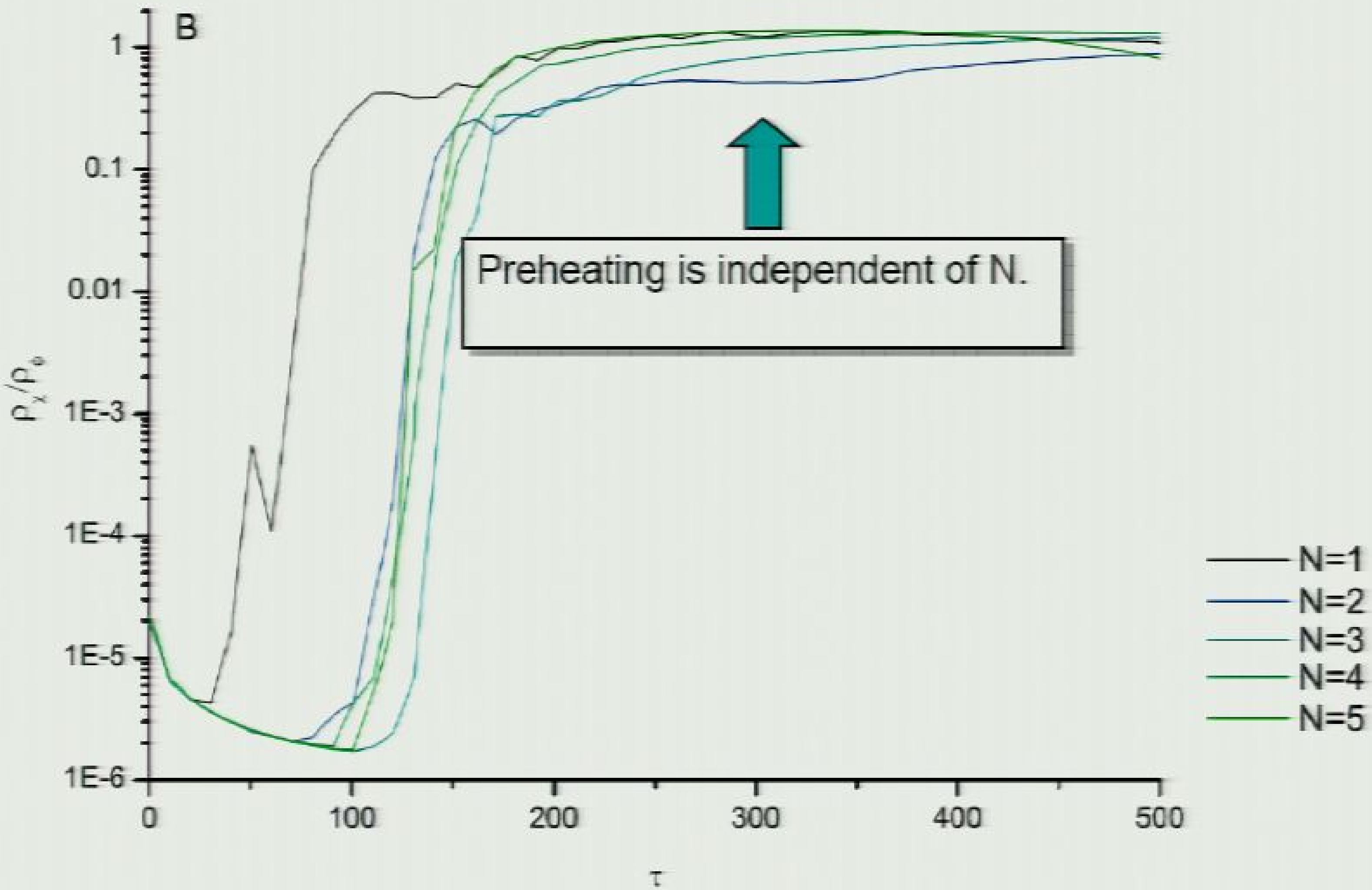
Case B, three and four-leg interactions



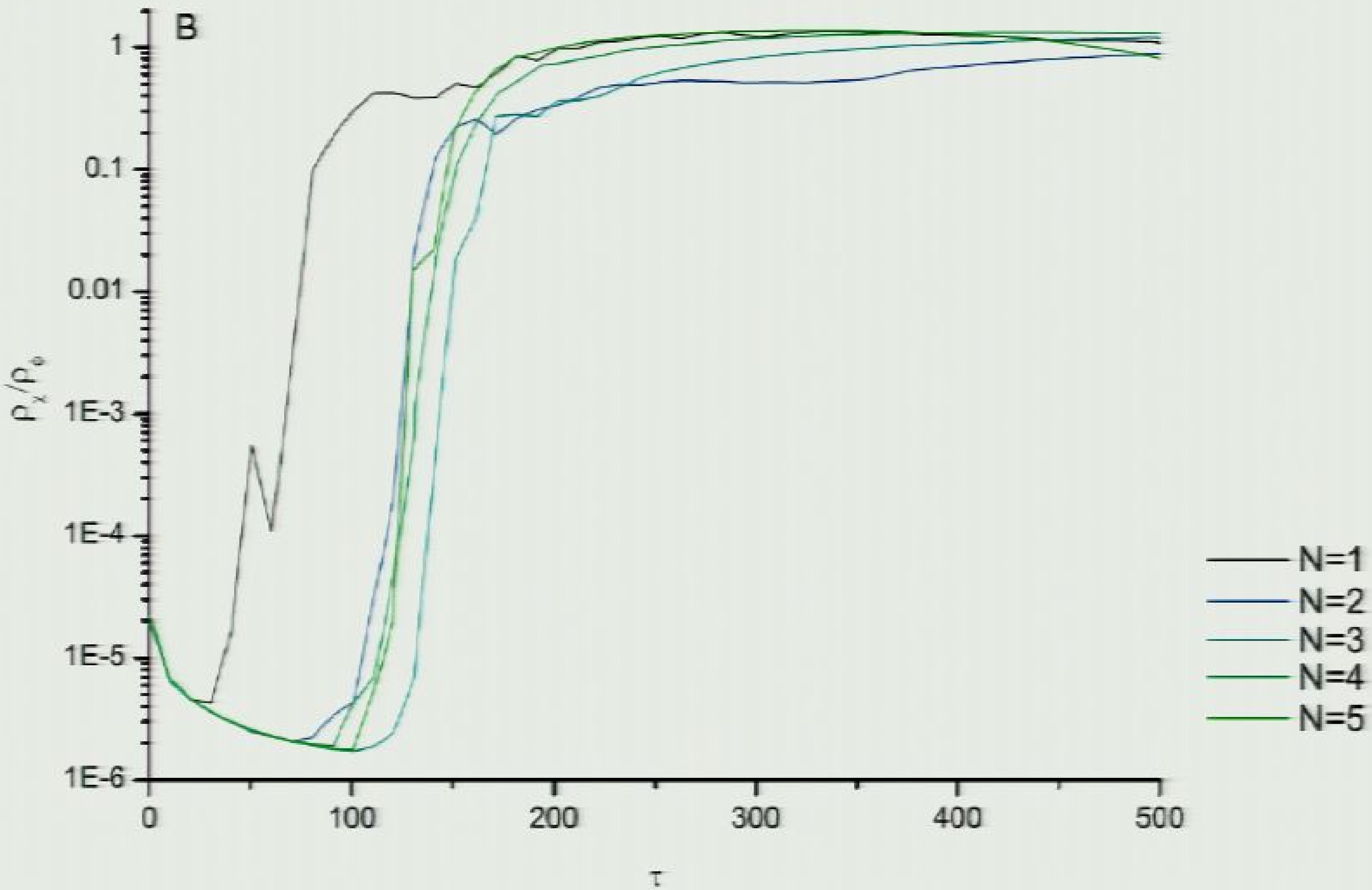
Case B, three and four-leg interactions



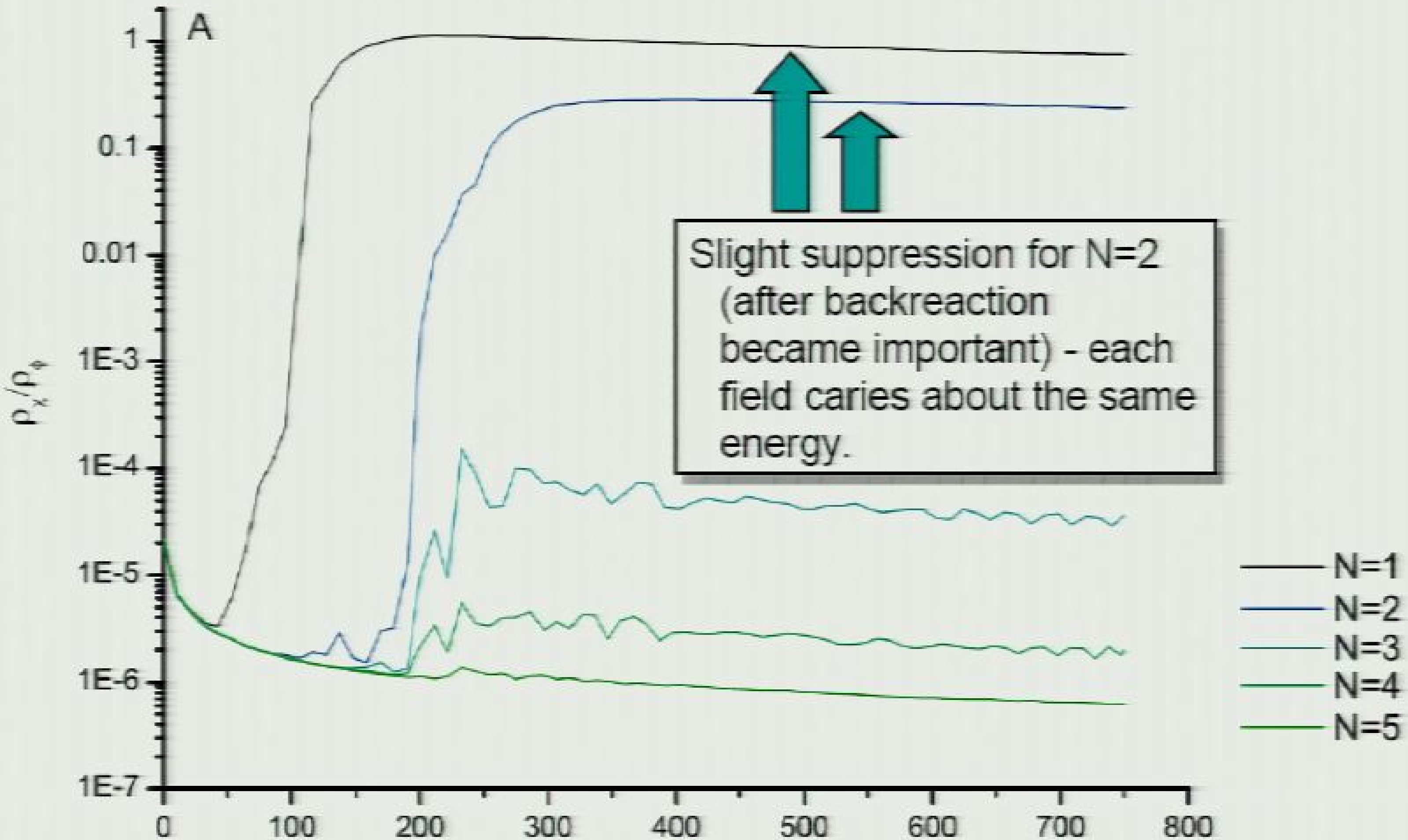
Case B, three and four-leg interactions



Case B, three and four-leg interactions



Case A, four-leg interactions (Parametric resonance case)



- Initial inhomogeneities are specified natively by LATICEEASY in momentum space.

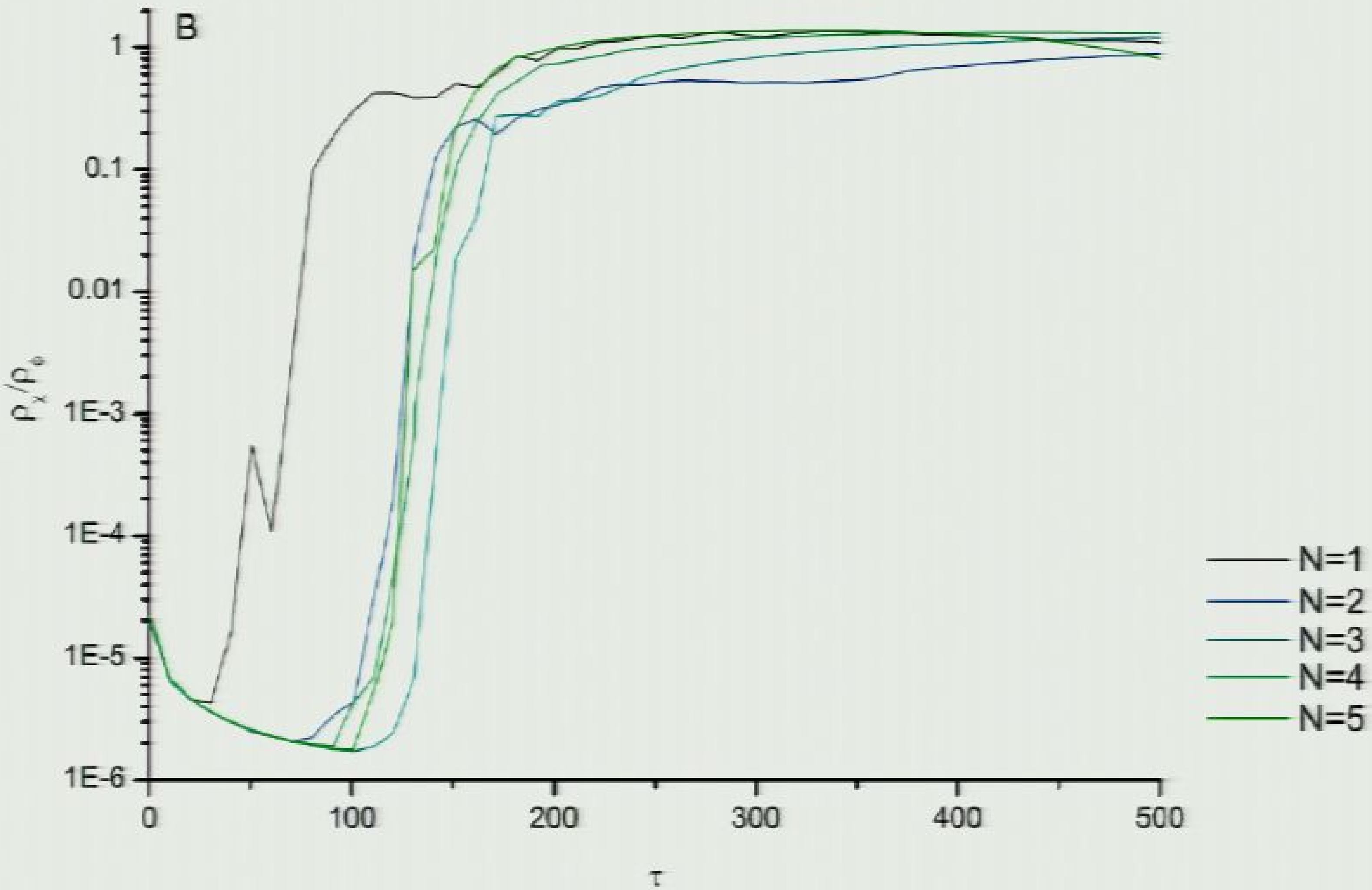
- Use: $n^3 = 128^3$ lattice, box size: $L = 5/m$; cover: $2\pi/L < k < 2\pi\sqrt{3}n/(2L)$

- Investigate three cases:

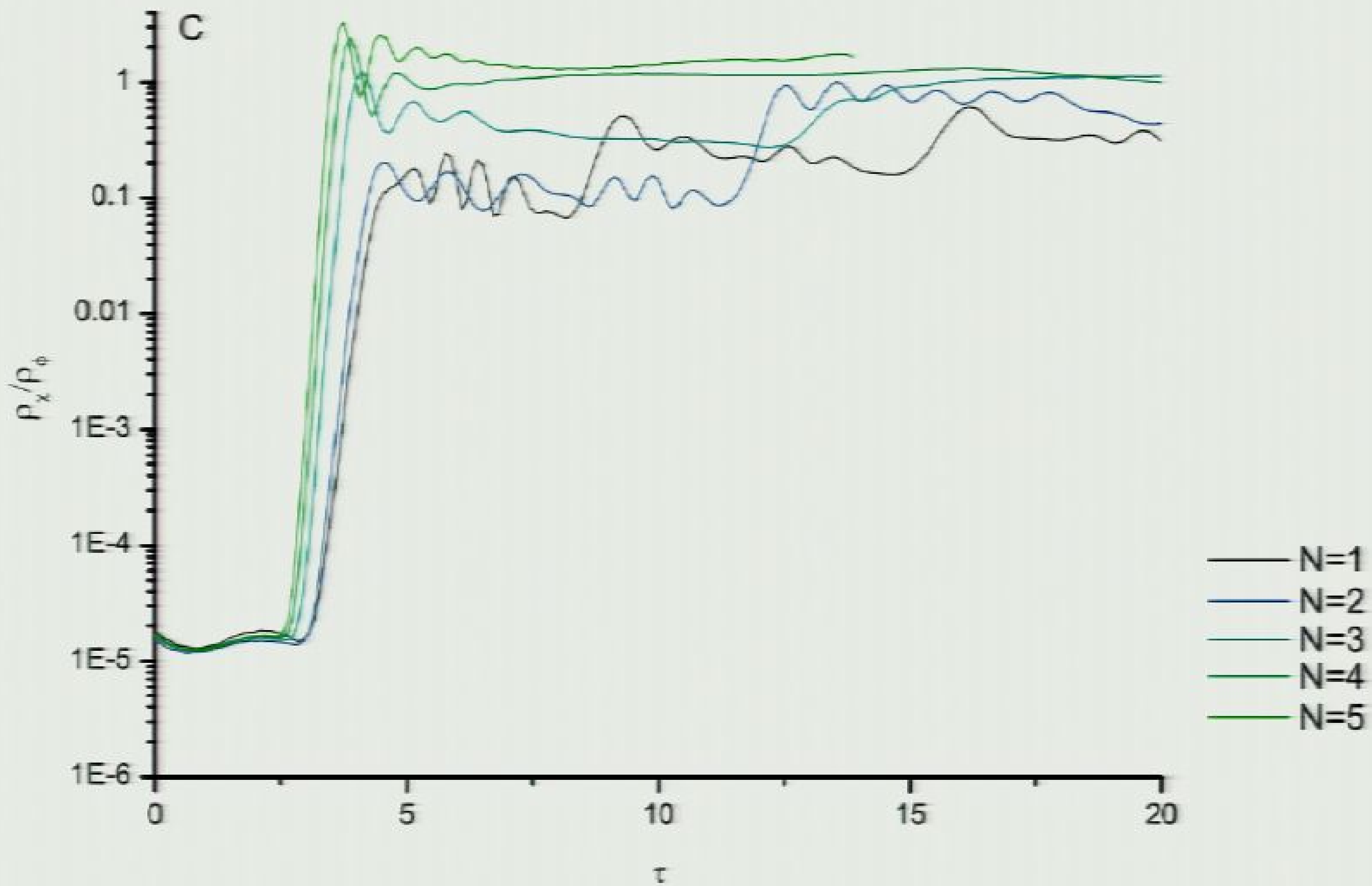
Case	$g \times (0.193)^2/m^2$	$\sigma \times 0.193/m^2$	$\lambda \times (0.193)^2/m^2$
A	10^4	0	5×10^3
B	10^4	100	5×10^3
C	100	100	10^4

$$W = \sum_{i=1}^{N} \left(\frac{m_i^2}{2}\varphi_i^2 + \frac{\sigma}{2}\varphi_i\chi^2 + \frac{g}{2}\varphi_i^2\chi^2 \right) + \frac{\lambda}{4}\chi^4$$

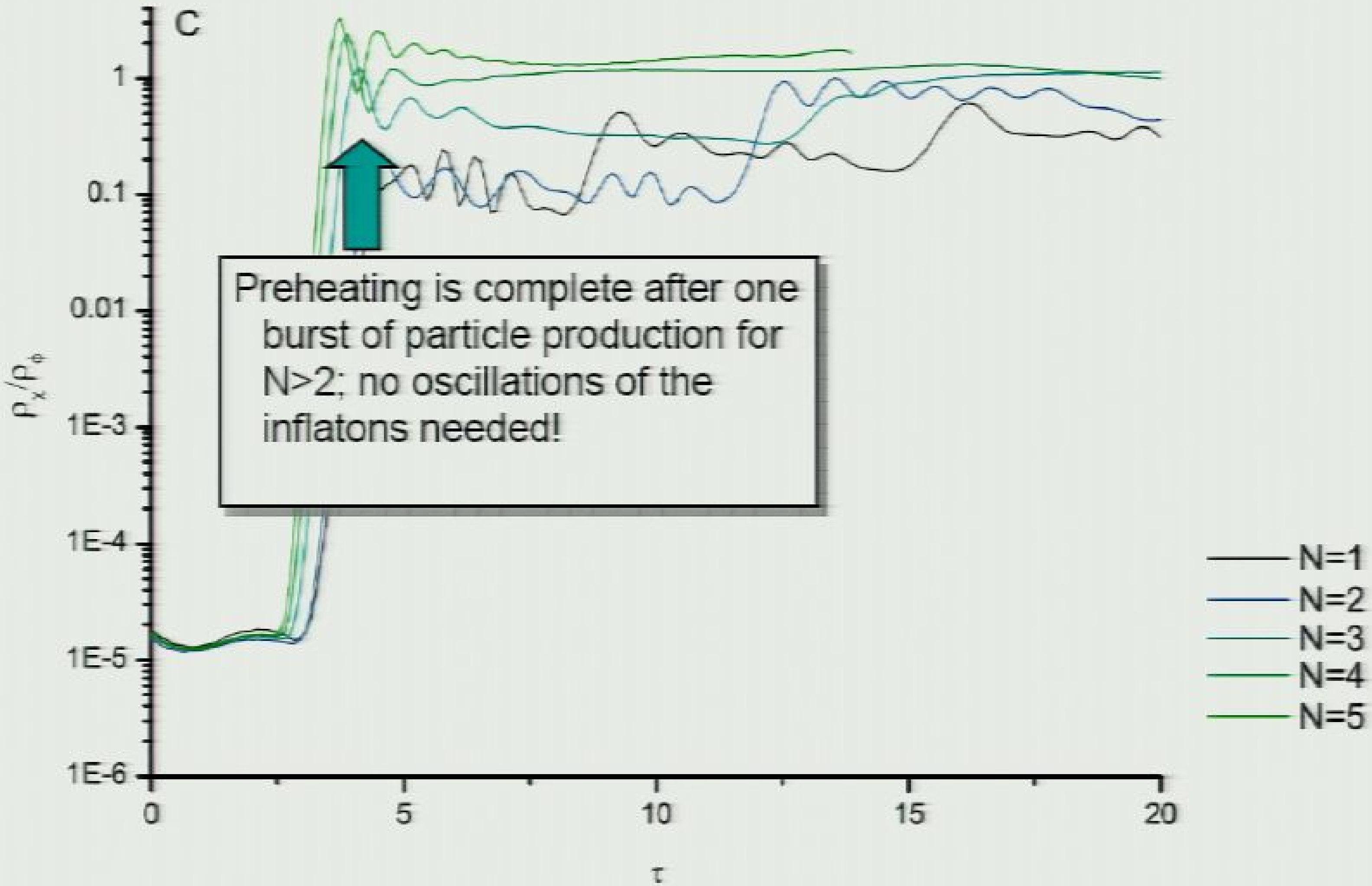
Case B, three and four-leg interactions



Case C, primarily three-leg interactions (tachyonic preheating)



Case C, primarily three-leg interactions (tachyonic preheating)



Summary of Results

Parametric resonance is suppressed for more than one inflaton (absent for N>3), opposite to expectation based on Cantor preheating. As a result, the old theory of preheating is applicable for large N.

Possible way to avoid suppression: couple each inflaton to its own matter field.

Tachyonic Preheating remains efficient (even slightly enhanced), if N is increased, even in the presence of four-leg interactions.

Conclusions

Preheating after multi-field inflation should not be discussed within an effective single field model.

Couplings (type and magnitude) need to be known to assess whether or not preheating occurs.

If preheating occurs, the universe still needs to thermalize and the proper degrees of freedom need to be heated (ordinary matter and radiation), while preventing the overproduction of relics (challenging, but possible i.e. if a second phase of reheating or a few e-folds of thermal inflation follow before nucleosynthesis).

If preheating does not occur (i.e. if several inflatons couple to the same degrees of freedom and no tachyonic contributions exist), the old theory of reheating is applicable; this avoids the overproduction of relics and might be desirable.