Advanced Tools for Simulation and Design of Oscillators/PLLs

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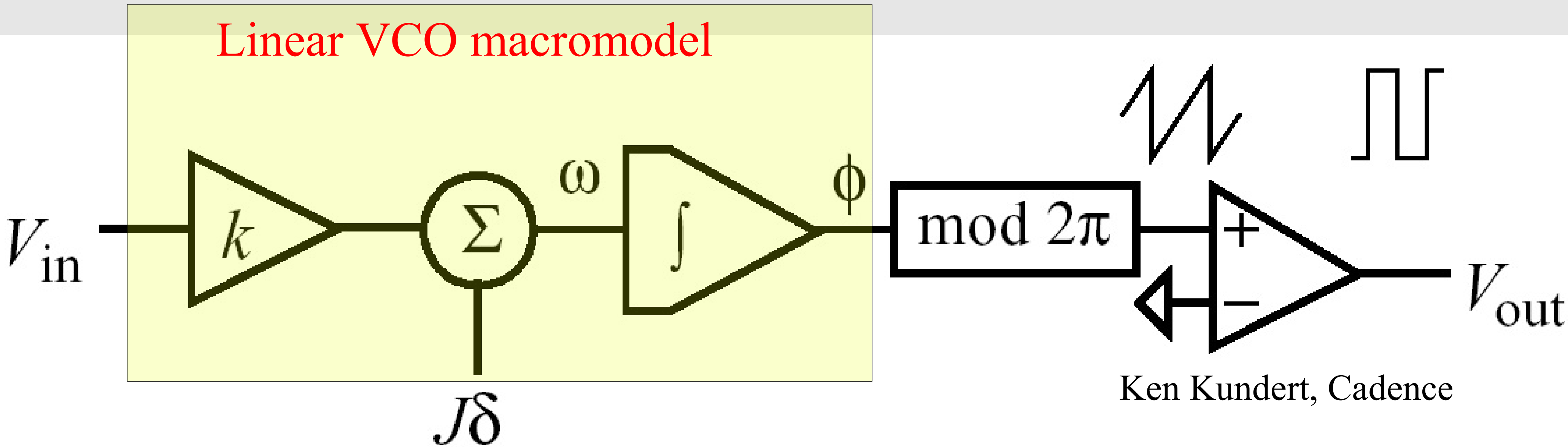
Oscillators: A Special Simulation Challenge

- **Computation/size/accuracy**: much greater than for amps/mixers
  - inefficient for even 1-transistor oscillators
    - long startups: many cycles
    - tiny timesteps needed per cycle
  - integrated RF: 100s to 1000s of transistors
  - errors dependent on size of timesteps, integration method, **size of perturbations**
  - fundamental cause: **marginal phase stability** of all oscillators
    - numerical errors integrate over time

SPICE-based perturbation analysis of oscillators is not a good idea

Alternatives to SPICE-level simulation

- Use simplified phase macromodels
  - Obtain effects of external perturbations on phase directly without simulating the full circuit
  - (Linear Time-Invariant (LTI) models)

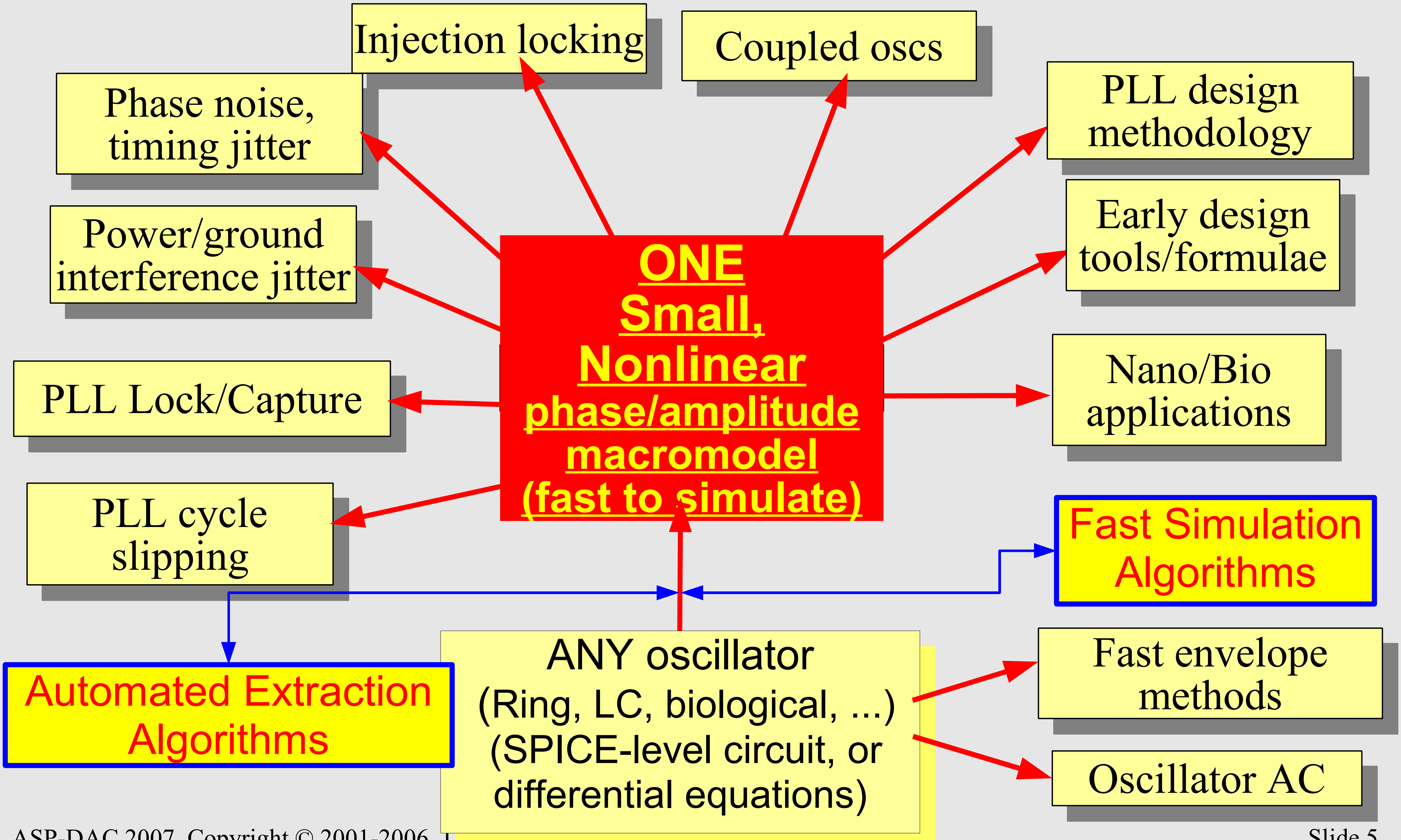


Ken Kundert, Cadence

Limitations of Linear Phase Macromodels

- Linear models are **not generally applicable** for all effects
  - LTI model: **narrow applicability**
  - LPTV models, including:
    - Kaertner's LPTV IRF
    - Hajimiri's closed-form ISF
    - better, but validity depends on circuit/dynamical effects
- Eg, cannot capture nonlinear phenomena
  - injection locking, jitter, cycle slips, power grid noise effects, ...

Automatically-extracted Oscillator Macromodel works for ALL effects, ALL oscillators



Automatically Extracted Nonlinear Oscillator Macromodel

$$\dot{\alpha}(t) = v_1^T(t + \alpha(t)) \cdot b(t)$$

Phase error/ jitter

Perturbation Projection Vector (PPV/NISF)

Noise "Input"

Phase macromodel is **nonlinear** and **scalar**
(nonlinear = captures complex dynamics)
(scalar = small, fast to evaluate)

Drop-in replacement for linear phase models

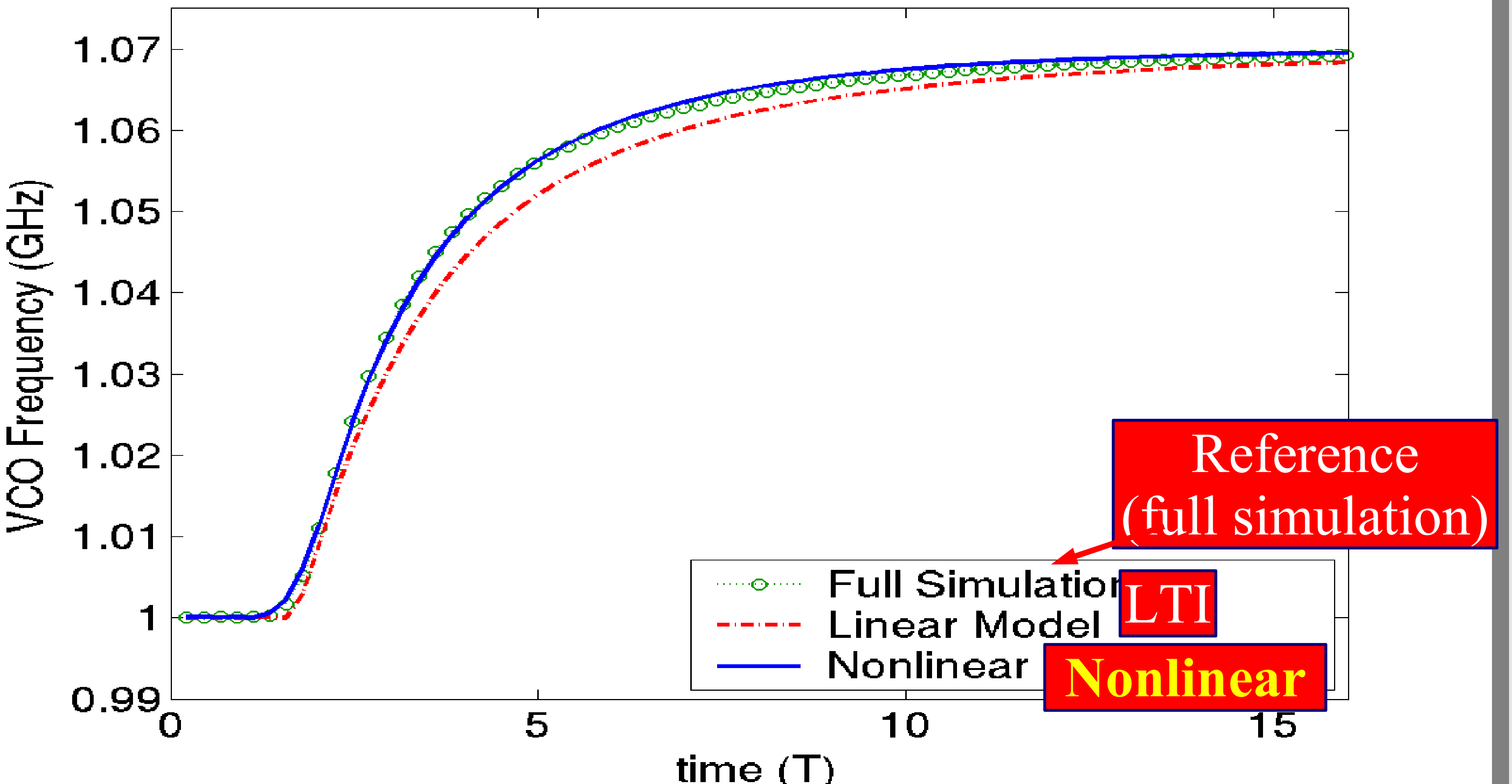
Feature Comparison with Existing Methods

	LTI	LPTV	Our approach
Jitter from white noise	✗	✓ ✗ ⓘ	✓
Flicker/coloured jitter	✗	?	✓
Supply interference jitter	✗	✗ ✓ ⓘ	✓
VCO frequency control	✓ ✗ ⓘ	✓ ⓘ	✓
Injection locking	✗	✗	✓
PLL lock/capture	✓ ⓘ	✓ ⓘ	✓
Cycle slipping	✗ ⓘ	?	✓
Amplitude effects	NA	NA	✓
Model generation speed	Poor ⓘ	Poor	Excellent
Model gen. robustness	Poor	Mediocre	Good ⓘ
Model simulation speed	Excellent	Excellent	Excellent

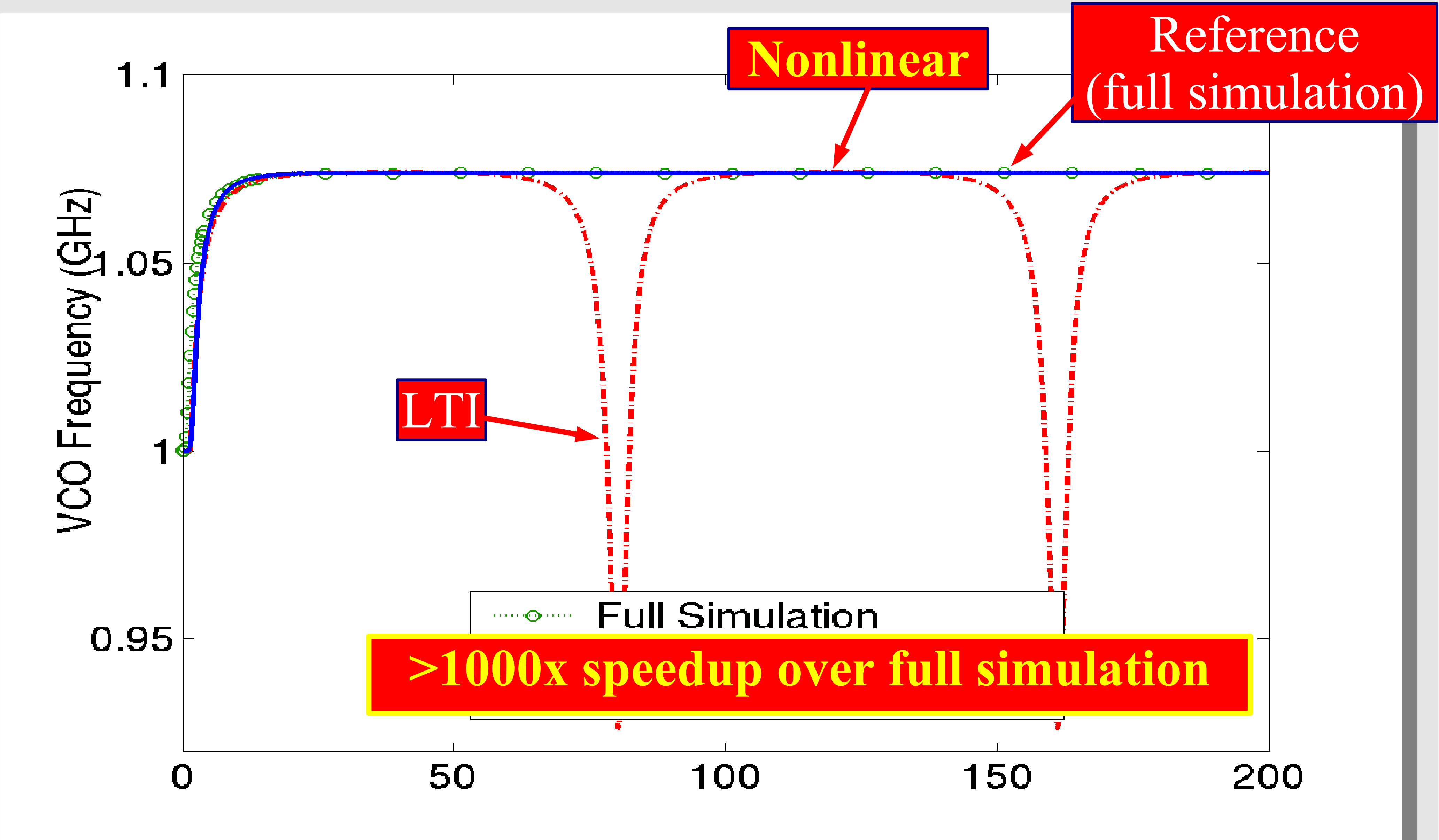
PLL Capture and Lock Transients

PLL Capture/Lock: fref=1.07f0

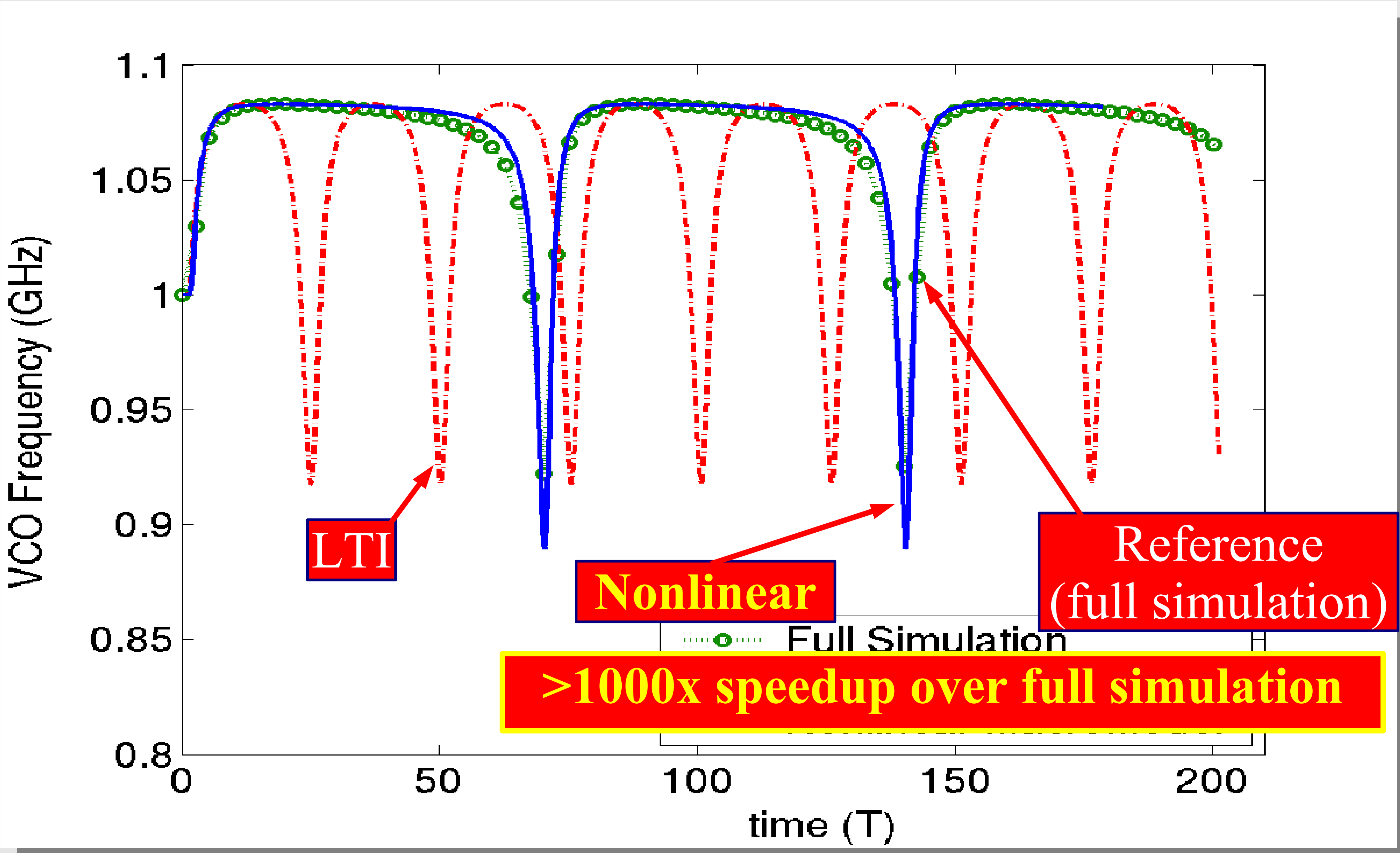
>1000x speedup over full simulation



PLL Capture/Lock: fref = 1.074 f0

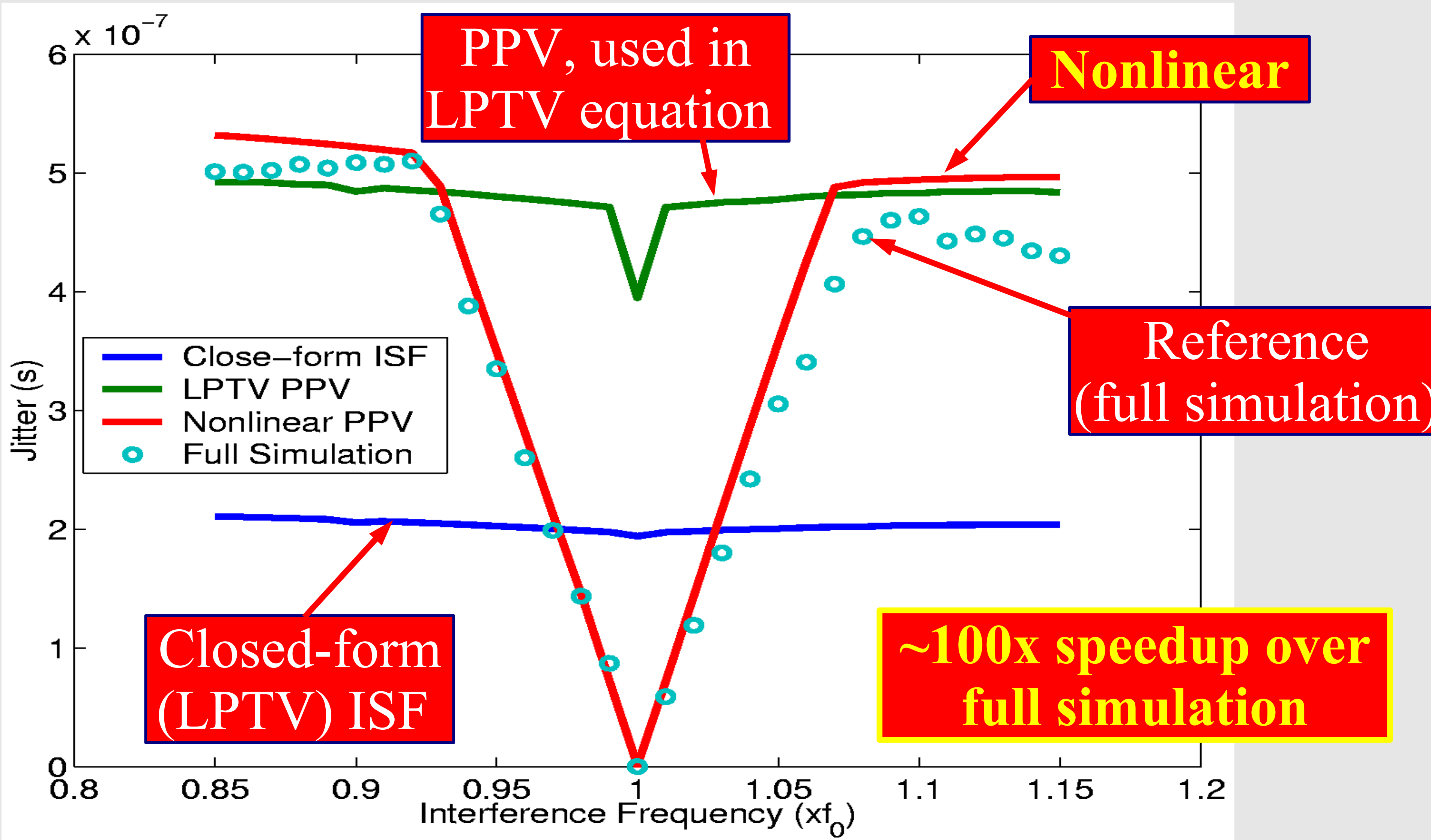


PLL Capture/Lock: fref = 1.083 f0

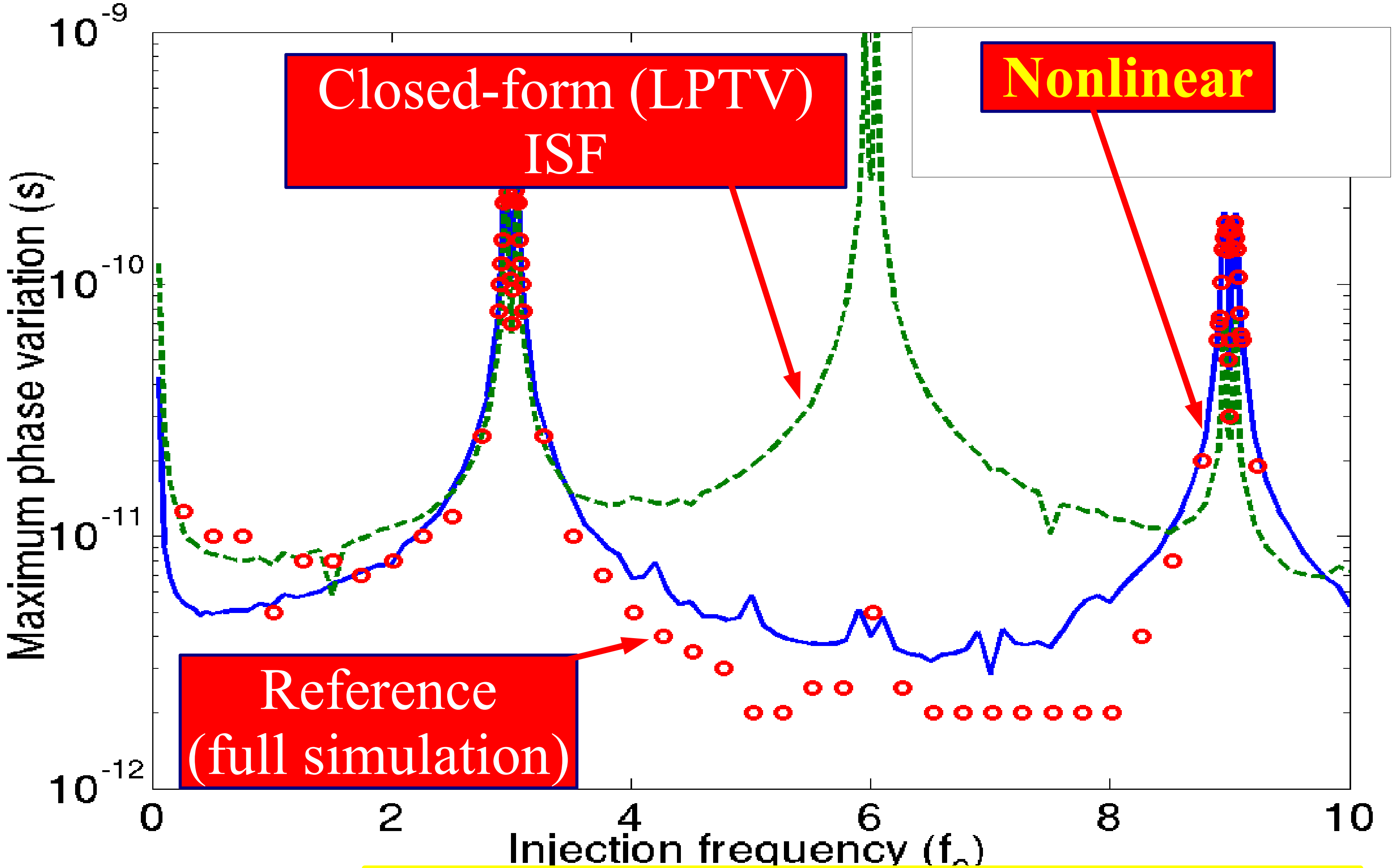


Oscillator and PLL jitter due to Supply Interference

Ring Oscillator: Per-cycle jitter as a function of sinusoidal supply interference frequency



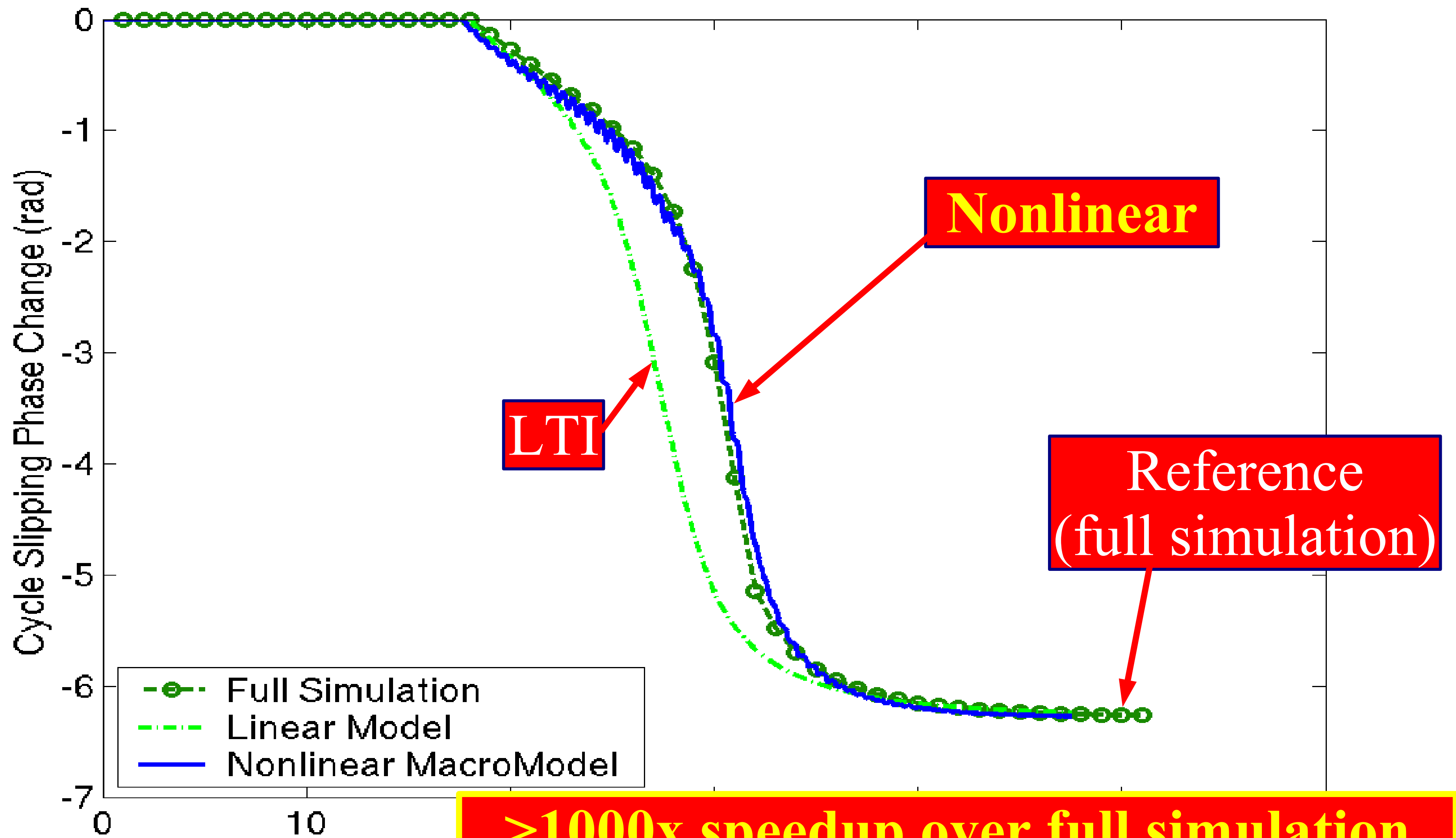
PLL: Max jitter as function of supply interference frequency



>1000x speedup over full simulation

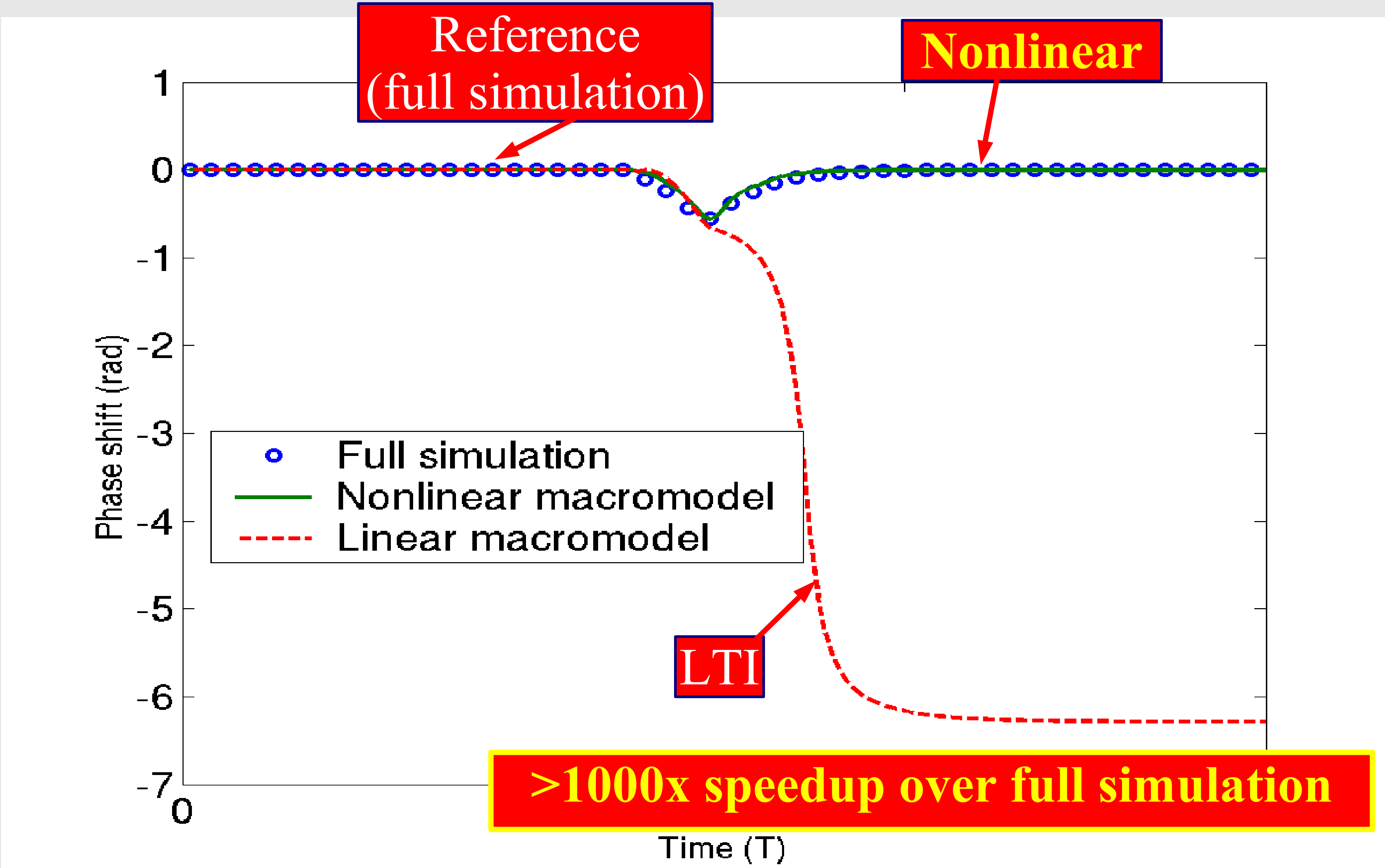
PLL Cycle Slipping

PLL: cycle slipping (5mA, 10T shock)



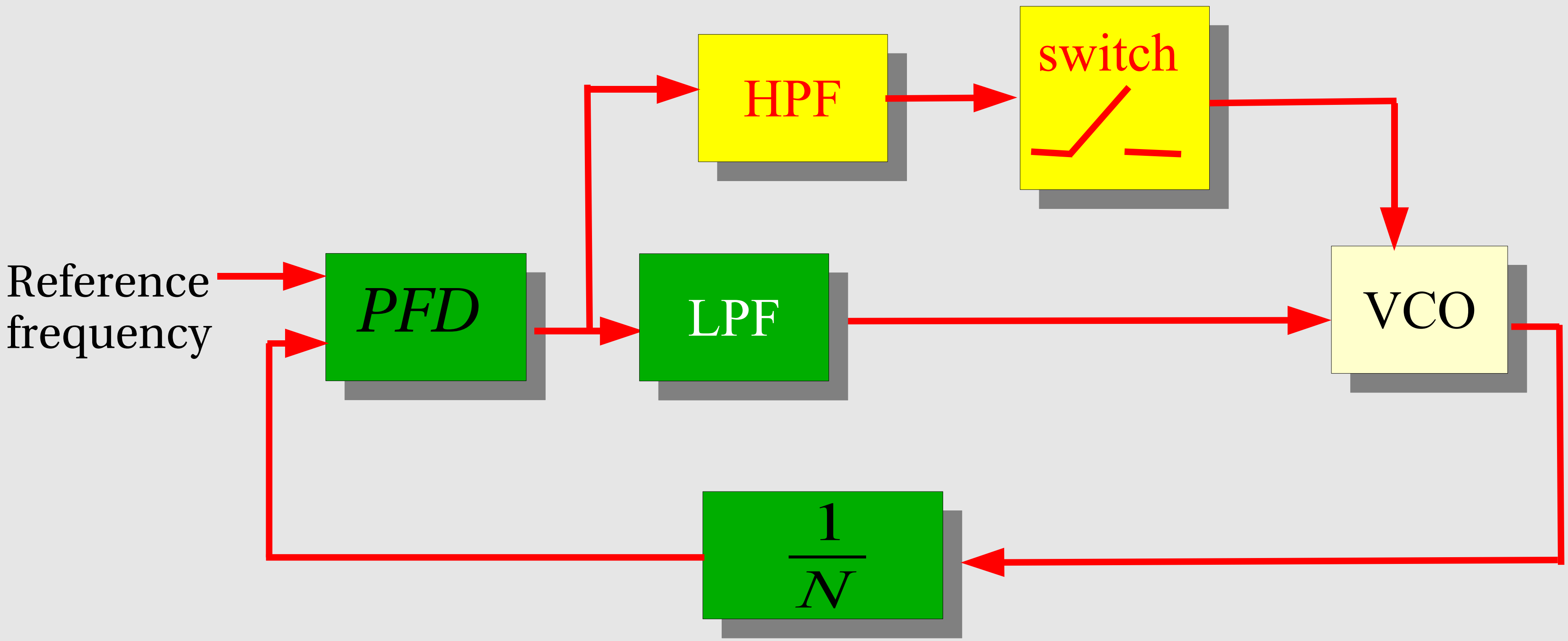
>1000x speedup over full simulation

PLL: cycle slipping (3mA, 10T shock)



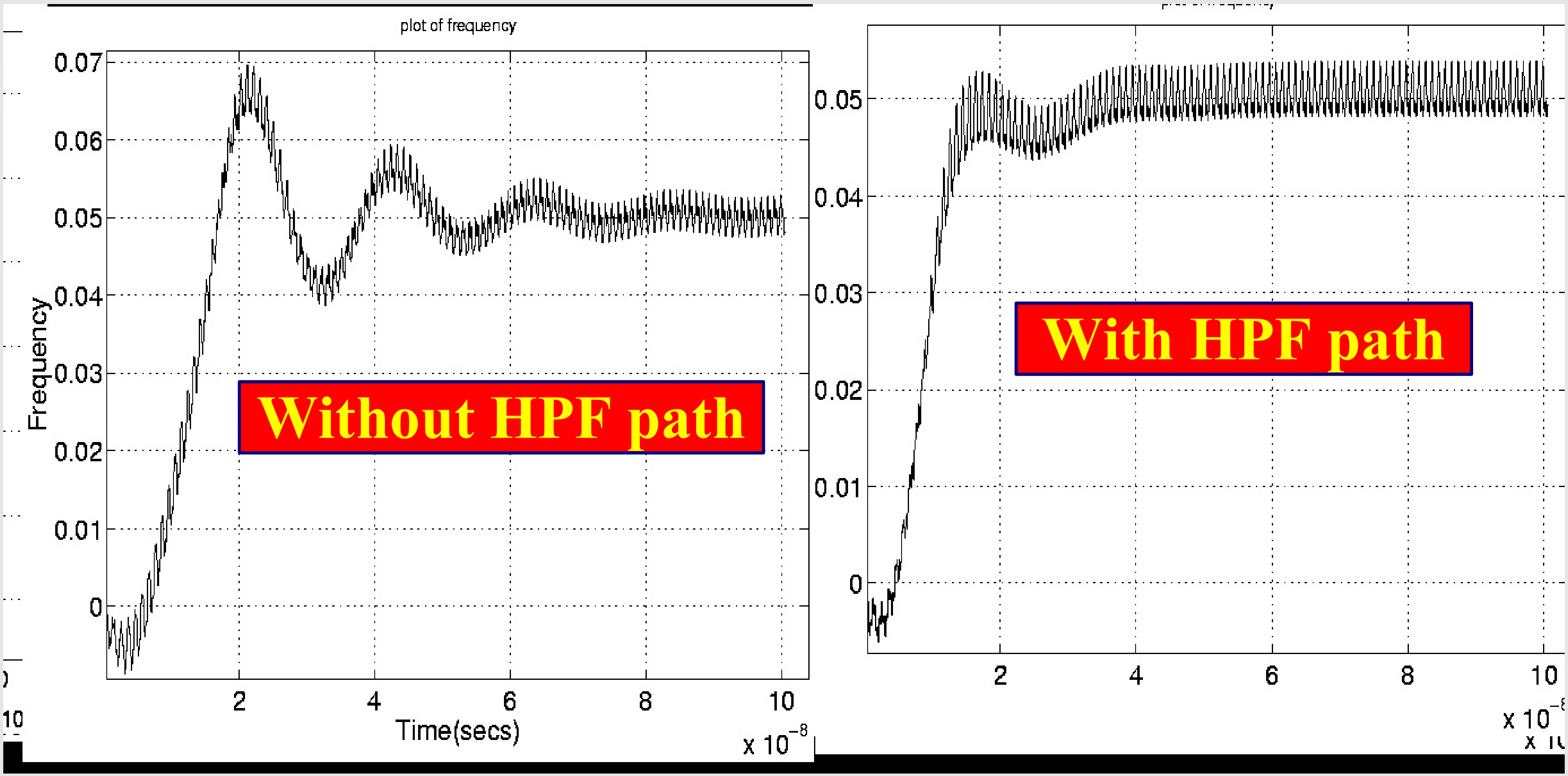
Impact of Nonlinear Macromodels on PLL Design Process

Injection-aided PLL structure



- **Lock acquisition time reduction is important**
- High-pass path: induces **injection locking**
  - **speeds lock acquisition**
- Once locked, **HPF path is switched out of the loop**
  - **to lower phase noise in lock**

PLL Capture (freq shift vs time)



- ~3x faster lock acquisition due to injection aiding

Nonlinear PLL Macromodel: Benefits for Design

- **Linear macromodels: wrong results (though fast)**
  - can mislead, waste design time
- **Nonlinear macromodels: can be trusted during design**
  - sanity checking via SPICE-level simulation: <u>still indispensable</u>
    - ~80 simulations in all
    - ~5 full SPICE-level simulations
    - macromodel offers **100-1000x speedup** over full
      - few minutes/simulation (including macromodel generation)
  - Enables much more thorough exploration of design space
    - **many combinations of parameters, injection paths, ...**
    - **Impractical using full simulation alone**
  - Design exploration completed in ~1 week
    - Estimate: 10x saving in design time vs prior methodologies
      - (with much more complete exploration)

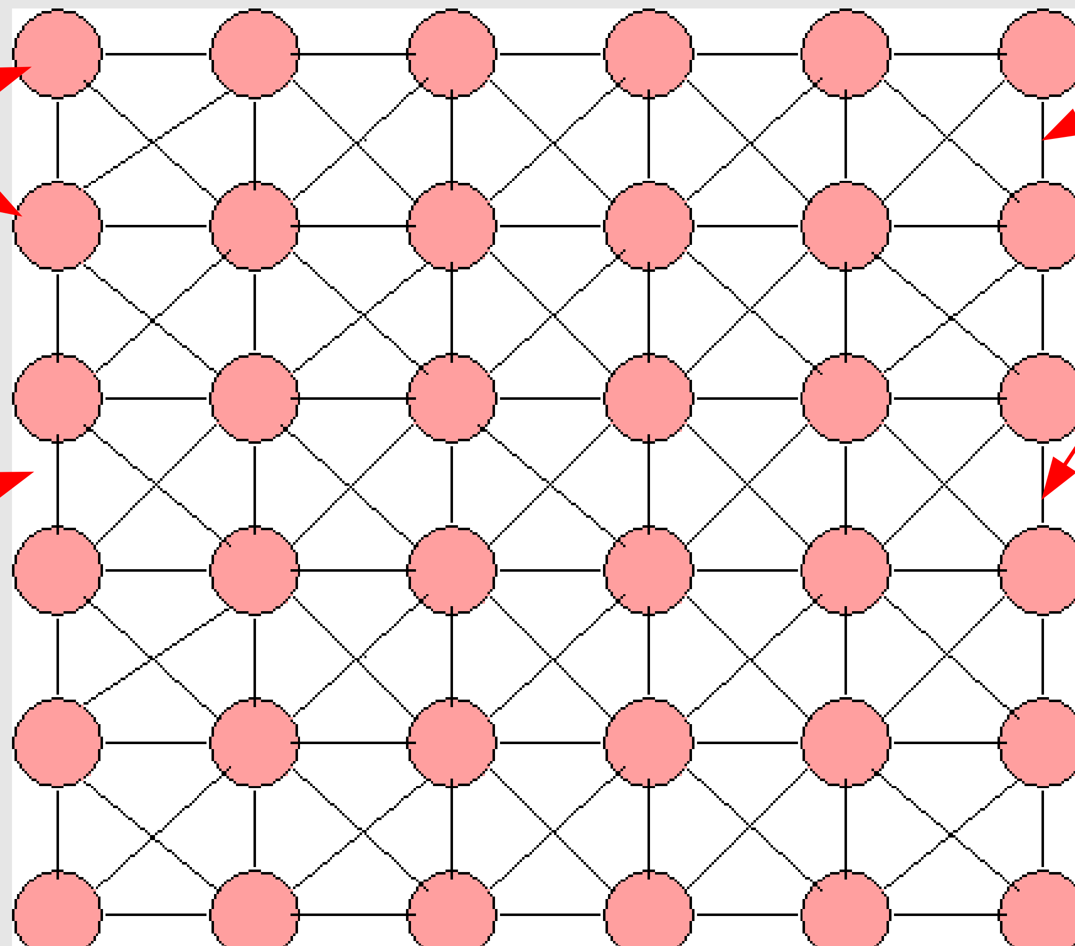
Coupled Oscillator Systems

Brusselator biochemical oscillators

$$\begin{cases} \boxed{\dfrac{\partial u}{\partial t} = A - (B+1)u + (1 + \gamma \cdot \sin(2\pi f t))u^2 v} + D_u \nabla^2 u \\ \boxed{\dfrac{\partial v}{\partial t} = Bu - u^2 v} + D_v \nabla^2 v, \end{cases}$$

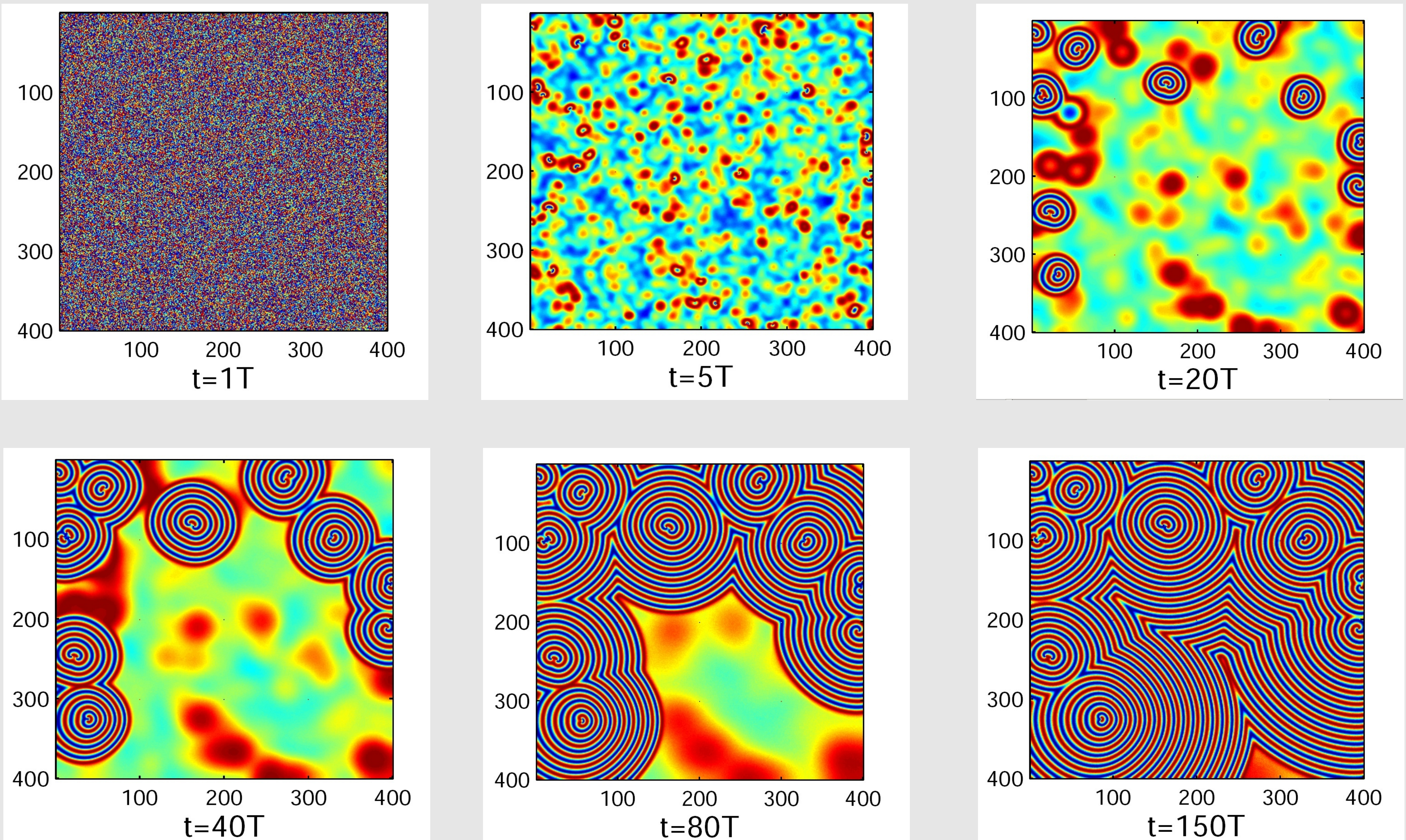
Coupling (diffusion) terms

Brusselator biochemical oscillators



"Network model" of coupled oscillators

Spontaneous Pattern Formation: 160,000 coupled Brusselator oscillators (g=1/15)



Simulation time: 200 minutes for 160 cycles (MATLAB); est speedup 1200x

Summary

- Nonlinear oscillator macromodel captures:
  - injection locking
  - PLL lock and capture
  - PLL cycle slipping
  - phase noise and jitter in oscillators and PLLs
  - pattern formation in biochemistry
- Productivity enhancer for in design flows
  - 10x faster?
  - Better, more completely explored designs