# System-level Analysis and Verification of Mixers

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# Outline

- The big picture: system-level simulation of portable/RF front-ends
- Automated macromodelling and its role
- Automated macromodelling techniques for mixers (and other linear time-varying systems)

# Market and Circuit Trends

# Market Trend: Portable Devices

- Proliferation of small, cheap, ubiquitous devices
  - ☛ cellphones, PDAs, wireless LANs, Bluetooth, two-way paging, SMS
  - ☛ 802.11g/a, 2.5G networks
  - ☛ next: 3G, UMTS

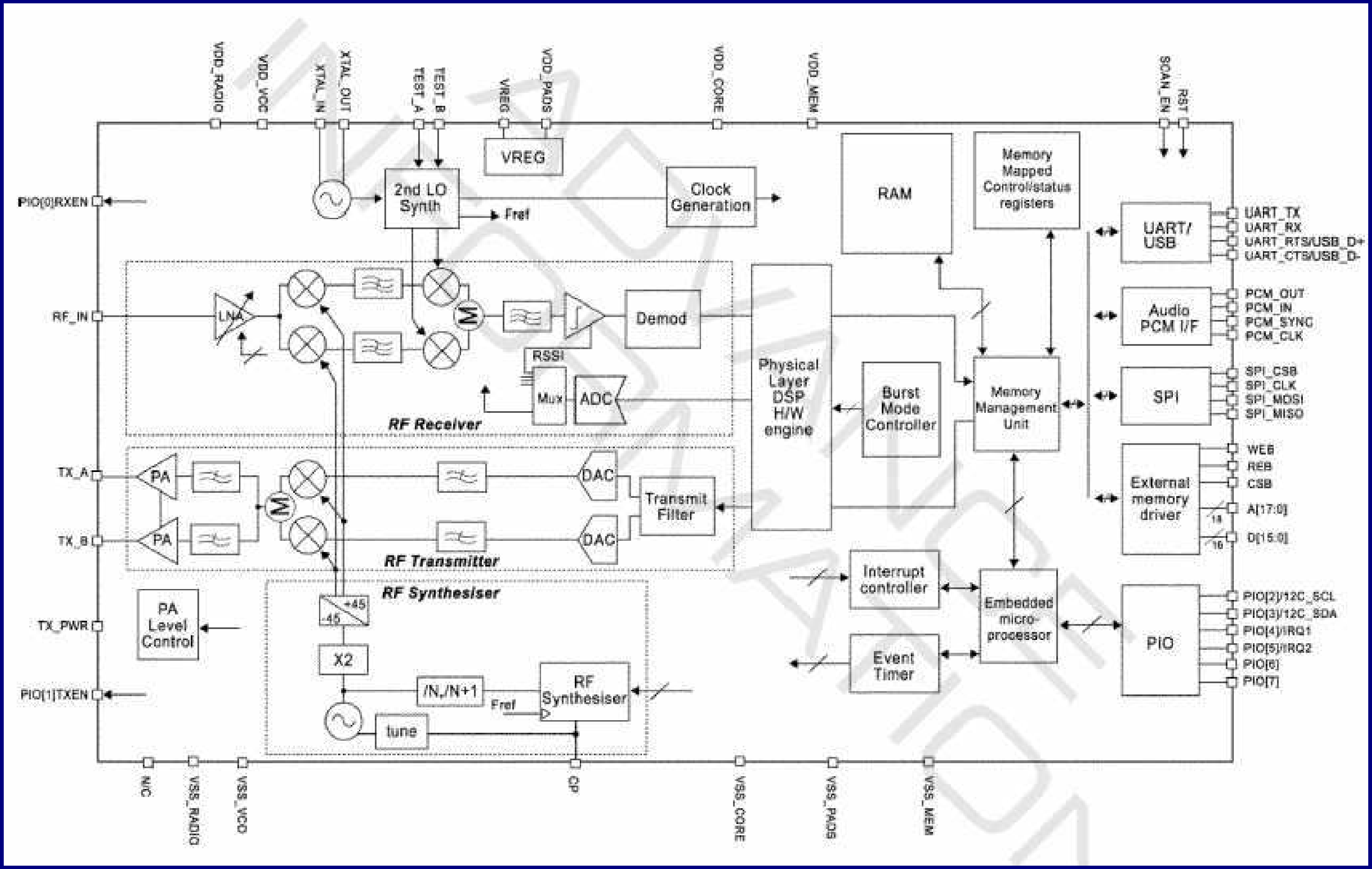
# Demand for Portable Commns.

- 2 billion users worldwide by 2007
  - ☛ Maximum growth: SE Asia and China
  - ☛ India: 28M users (Dec 2003); 100M projected, 2005
- US: Tenfold growth by 2005 (200x?)
  - ☛ \$22–\$140b (IDC, Merrill-Lynch)
  - ☛ exceed PC growth over last decade: Intel

# Drivers for Demand

- Price
  - India: 2.1M new subscribers, Dec 2003
    - *"driven by some of the lowest tariffs in the world"*
- Competitive pressures
  - rapid time to market of new designs
- Design challenge: mixed-signal/RF blocks
  - the *main* design bottleneck

# Integrated Bluetooth Transceiver




- Cheap
- Low margins
- <u>**Must work first time**</u>

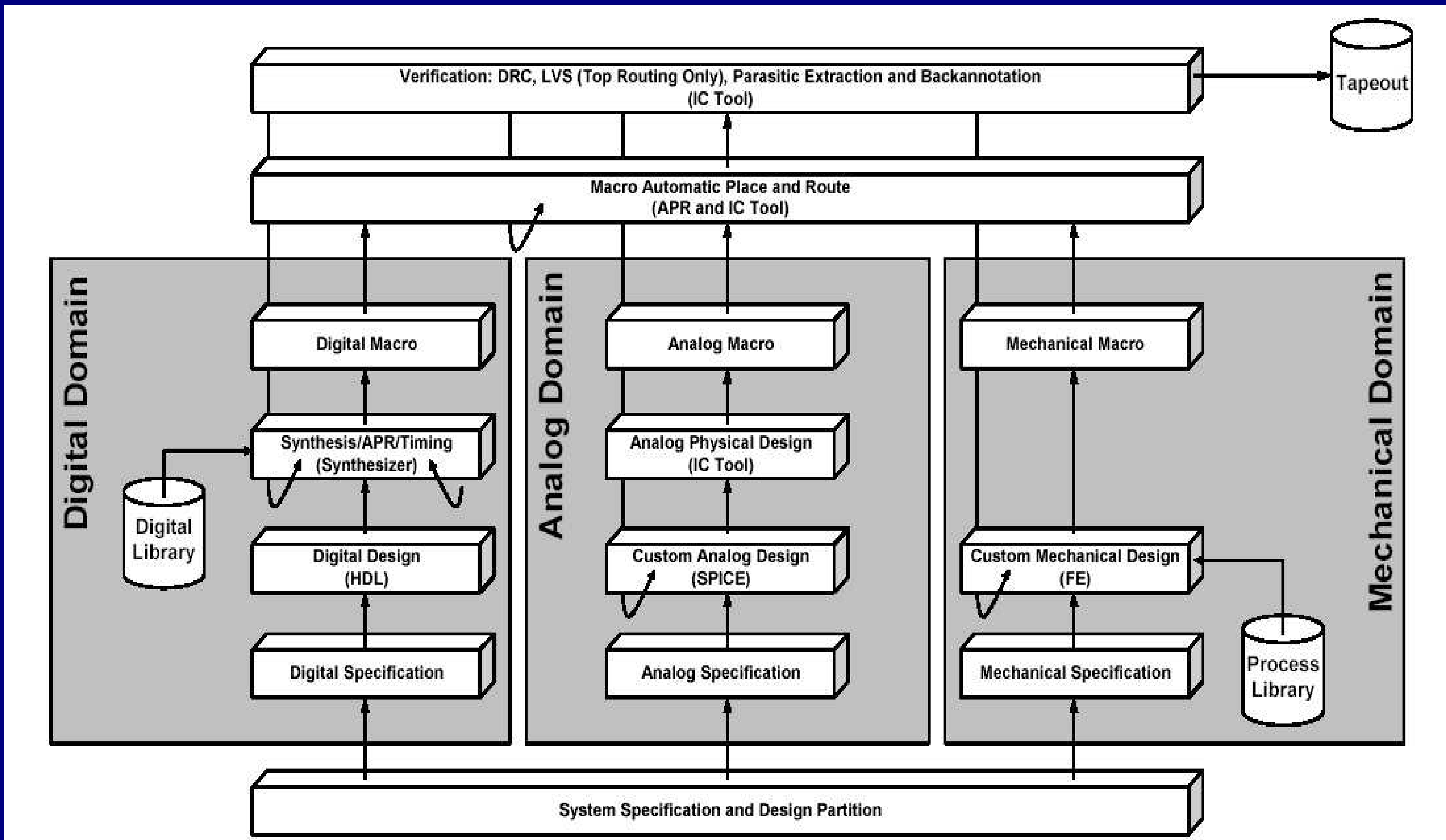
# Important Mixed-Signal Blocks

- **Mixers**, phase detectors, frequency dividers, VCOs, PLLs
- LNAs, power amps
- ADCs, ΣΔs, DACs
- z-domain switched-capacitor ckts: baseband filtering
- DC-DC power converters
- System focus: deliver everything working together

# Mixed-Signal Simulation Needs

- Correct, speedy noise simulation
  - ☛ mixers, oscillators, PLLs
  - ☛ issues: nonlinearity, cyclostationarity
- Faster basic time- and frequency-domain simulation
  - ☛ VCOs, PLLs, mixers, ...
  - ☛ issues: fast-slow dynamics, strong nonlinearities
- Research to production tool: “Time-to-market”
  - ☛ need effective transition path
  - ☛ issue: traditionally extremely slow
- **Automated macromodelling techniques**
  - ☛ enabler for effective hierarchical system verification
  - ☛ issues: nonlinearity, time-variation; oscillator dynamics

# Today's Design Flow

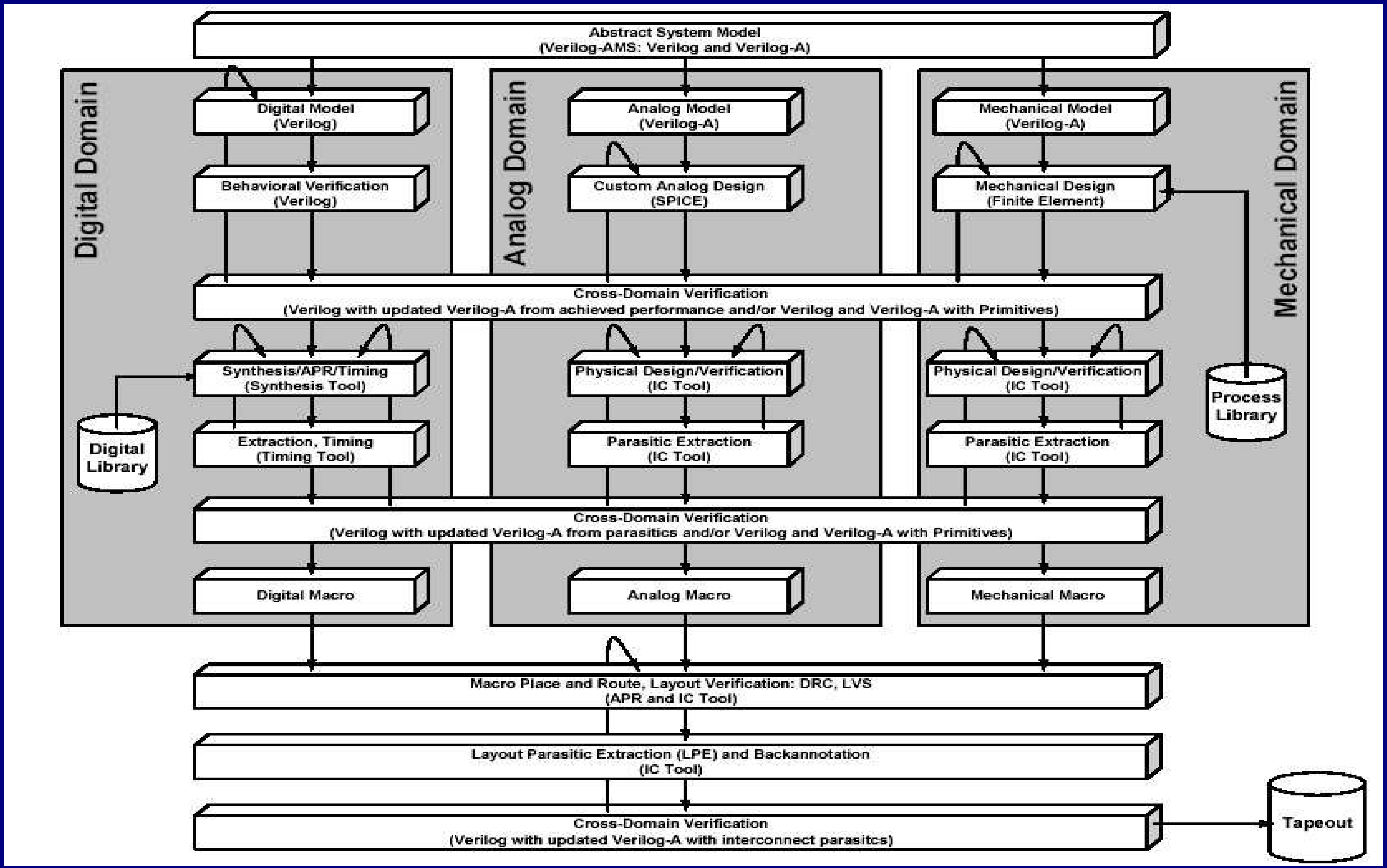



Credits: McCorquodale et al, Univ Michigan

- 3-5 spins = cutting edge; (10 at Lucent)

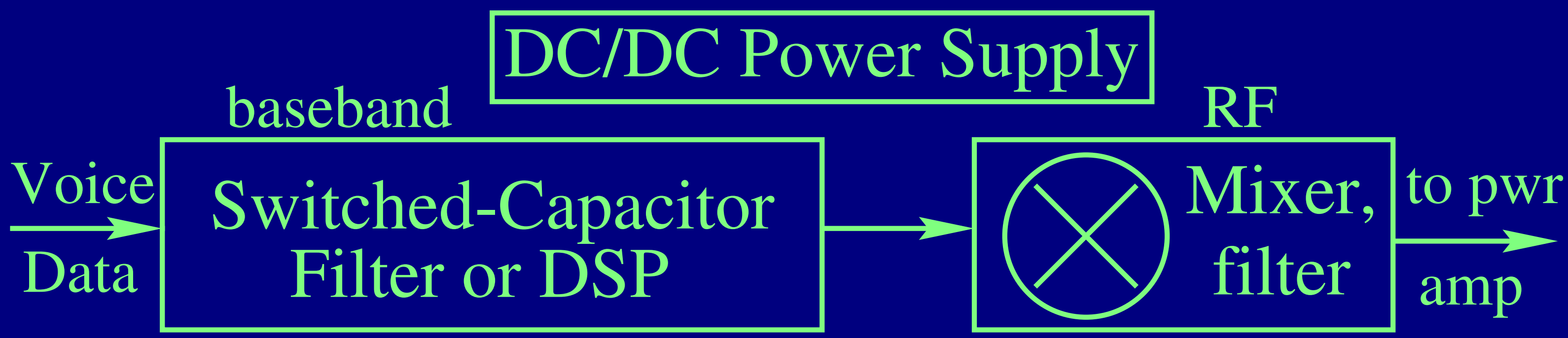
# System-Verification-Based Design Flow

Credits: McCorquodale et al, Univ Michigan



# Automated Macromodel Generation

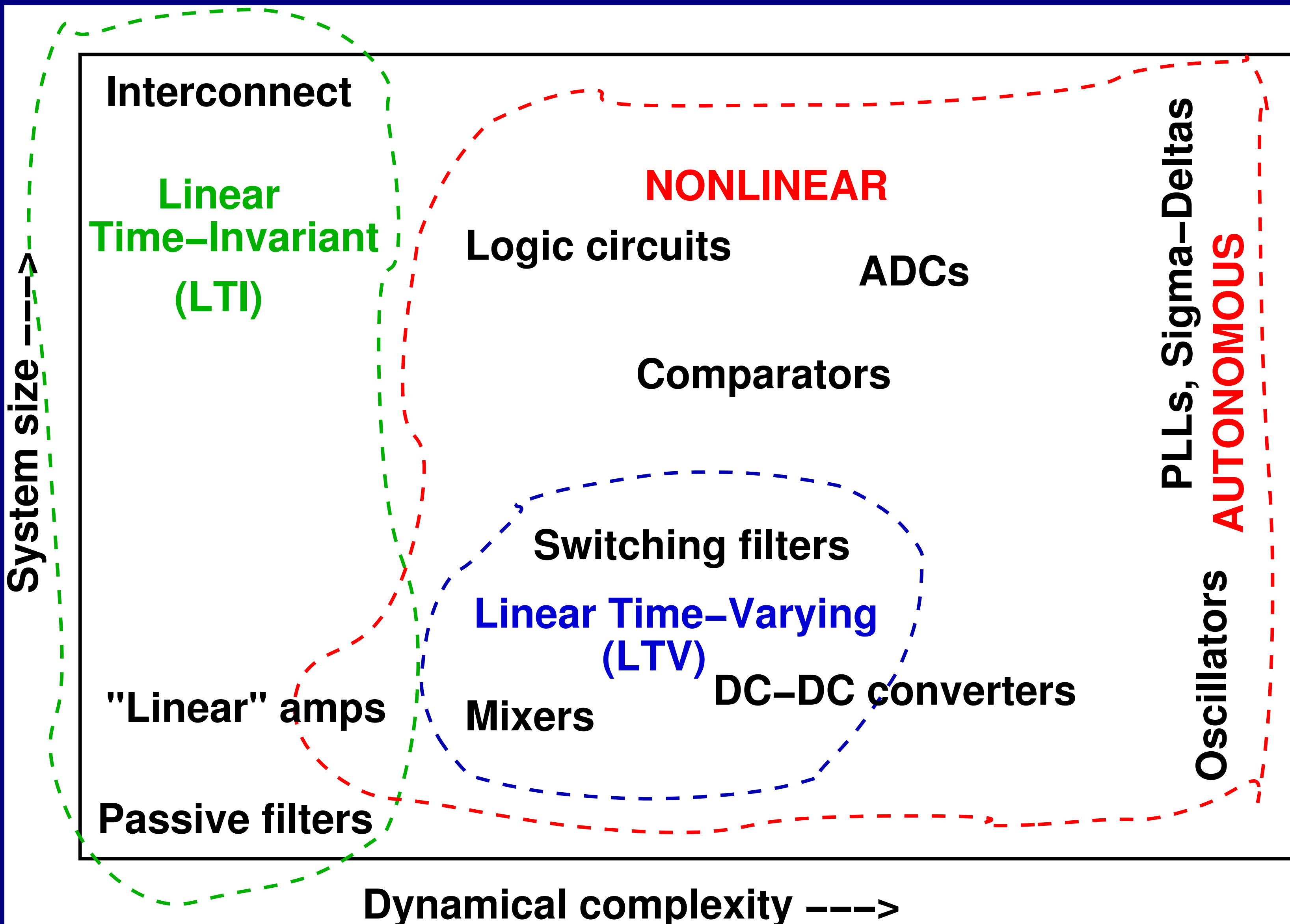
# Macromodelling Mixed-Signal Blocks




- Substitute big block by small
  - preserve I/O relationship
- Speed system verification
  - simulate connection of macromodels
- Automated macromodel generation
  - Input: (large) SPICE deck
  - Output: (small) SPICE/Matlab macromodel
  - Fast/convenient: "Computers made of iron, let them work"[a]
  - Applicable to *general classes* of circuits

[a] Vladimir Rokhlin, ~1997

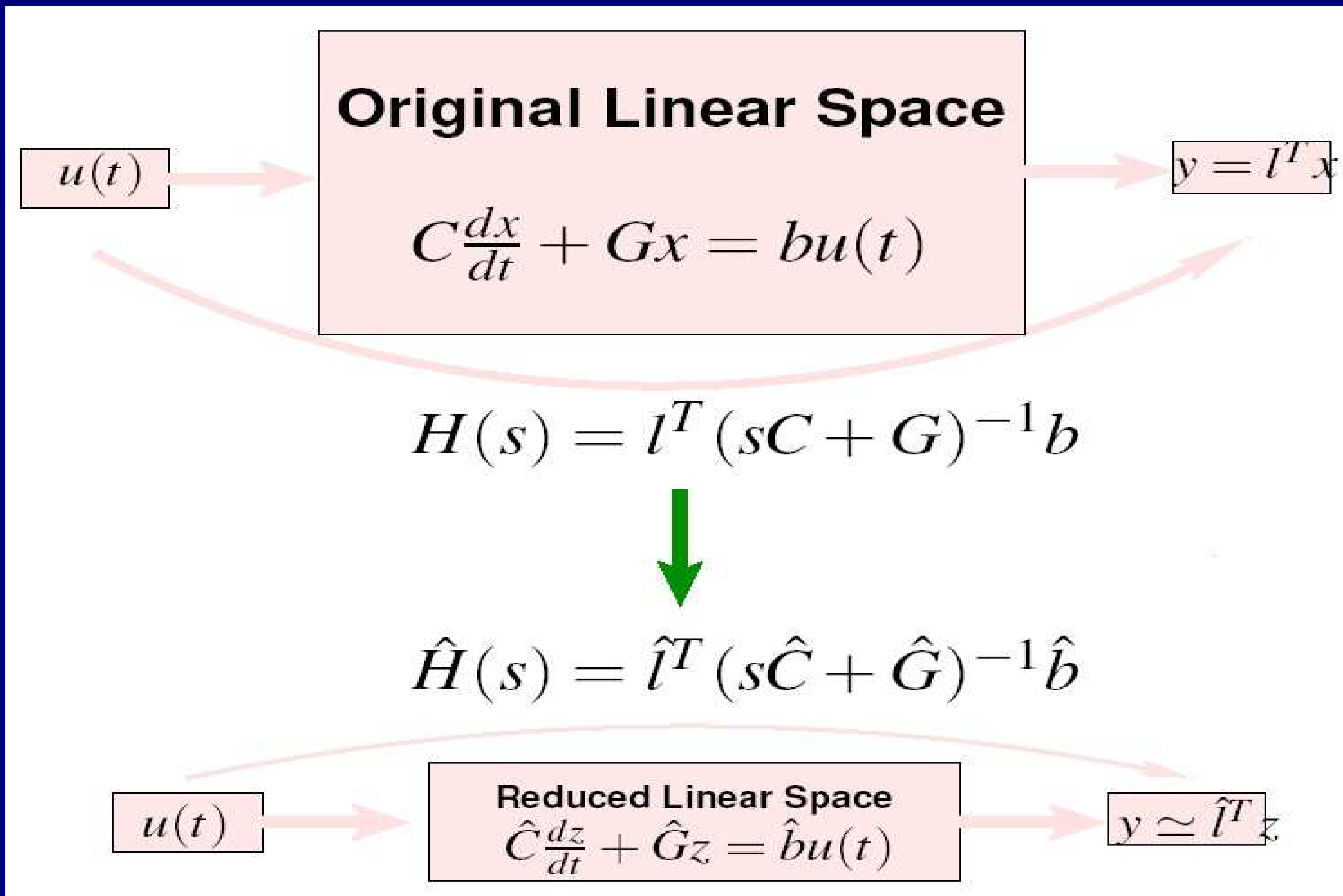
# Classifying systems for Macromodelling



# Types of Algorithmic Macromodelling

- Linear Time Invariant (LTI) macromodelling
  - ☛ application: interconnect networks (delay, crosstalk)
  - ☛ AWE, PVL, PRIMA: moment-matching, Krylov subspace methods
- Linear Time Varying (LTV) macromodelling
  - ☛ mixers, sampling/switching circuits
  - ☛ TVP (Time-Varying Padé)
- Weakly nonlinear macromodelling
  - ☛ companding circuits, amplifier/mixer gain compression
  - ☛ Low-order polynomial-based reduction
- Strongly nonlinear macromodelling
  - ☛ Piecewise polynomial (PWP): comparators, switching

# Linear Time-Invariant MM



# Macromodelling LTV Systems

- First obtain time-varying transfer function
- Problem: interaction of “system” and “input” time variations
- Solution: separate using multiple time scales

$$\boxed{\begin{gathered}\frac{\partial[C(t)x(t)]}{\partial t} + G(t)x(t) = bu(t)\\ y(t) = d^T x(t)\end{gathered}} \rightsquigarrow \boxed{\begin{gathered}\left[\frac{\partial}{\partial t_1} + \frac{\partial}{\partial t_2}\right](C(t_1)\hat{x}) + G(t_1)\hat{x} = bu(t_2)\\ \hat{y}(t_1,t_2) = d^T \hat{x}(t_1,t_2)\end{gathered}}$$

- Time-varying operator form of transfer function

$$H(t_1,s) = d^T \left(\frac{\partial}{\partial t_1}C(t_1) + sC(t_1) + G(t_1)\right)^{-1}[b]$$

# From LTV to Artificial MIMO LTI System

- Expand $t_1$ dependence in basis (eg, Fourier)
  - operator expression $\rightsquigarrow$ MIMO LTI form
  - $H_{FD}(s) = D^T \left(sC_{FD} + J_{FD}\right)^{-1} B_{FD}$
- Apply any (eg, Krylov-subspace-based) LTI model reduction method
  - Arnoldi, Lanczos methods reduce to size $q$ system
- Map reduced LTI system back to LTV form
  - reduced model: $-T_q \frac{\partial x_q}{\partial t} + x_q = r_q u(t), \quad y(t) \approx l_q^T(t) x_q(t)$
  - $u(t) \mapsto y(t)$ relation approximated well

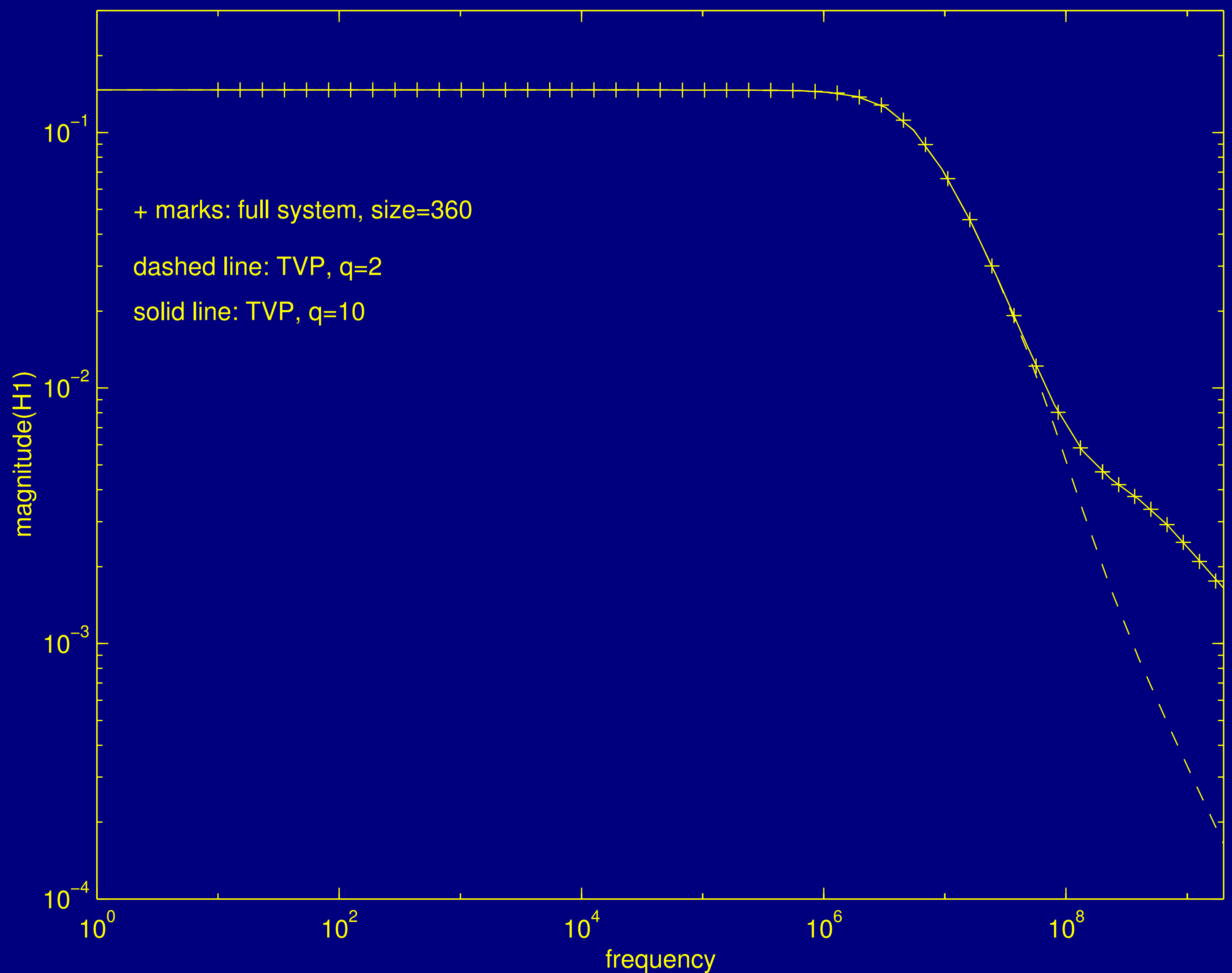
# TVP: Time-Varying Padé

- Prerequisites
  - any SPICE-type circuit description, can be large
  - nonlinear periodic steady-state (by HB or shooting)
- Main steps and features
  - choice of model-reduction algorithm (explicit/Arnoldi/Lanczos)
  - choice of time-domain / frequency-domain computations
  - solve $Jx = b$ ($J$ = steady-state Jacobian)
  - iterative methods essential for linear solution
  - size of macromodel = $q$ = # of solns
  - macromodel in LTI + memoryless form
  - poles/residues/transfer-plots produced

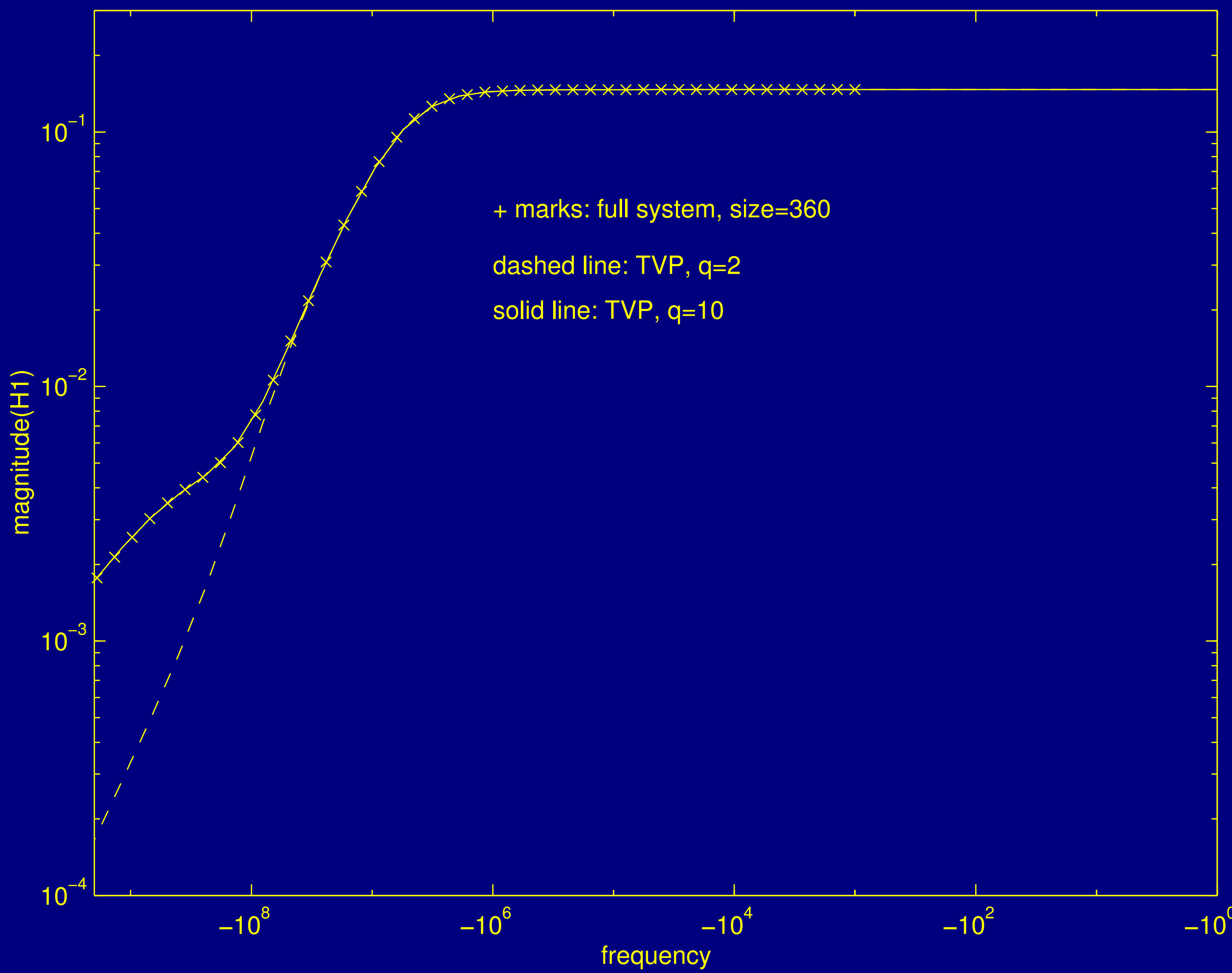
# Application to RF mixer block

- I-channel mixer and buffer block (Lucent ME W2013 RFIC)
  - 360 nodes, RF$\approx$80kHz, LO=178MHz
  - Steady-state: Harmonic Balance with 10 LO harmonics, zero RF input
- TVP: Lanczos process on frequency-domain Jacobian
  - $q = 2$: provides reasonable macromodel
  - $q = 10$: matches xfer fn upto twice LO frequency
  - size reduction: 30–100; macromodel evaluation speedup: $> 500$

# W2013 mixer: upconversion transfer function, +ve frequencies



# W2013 mixer: upconversion transfer function, -ve frequencies



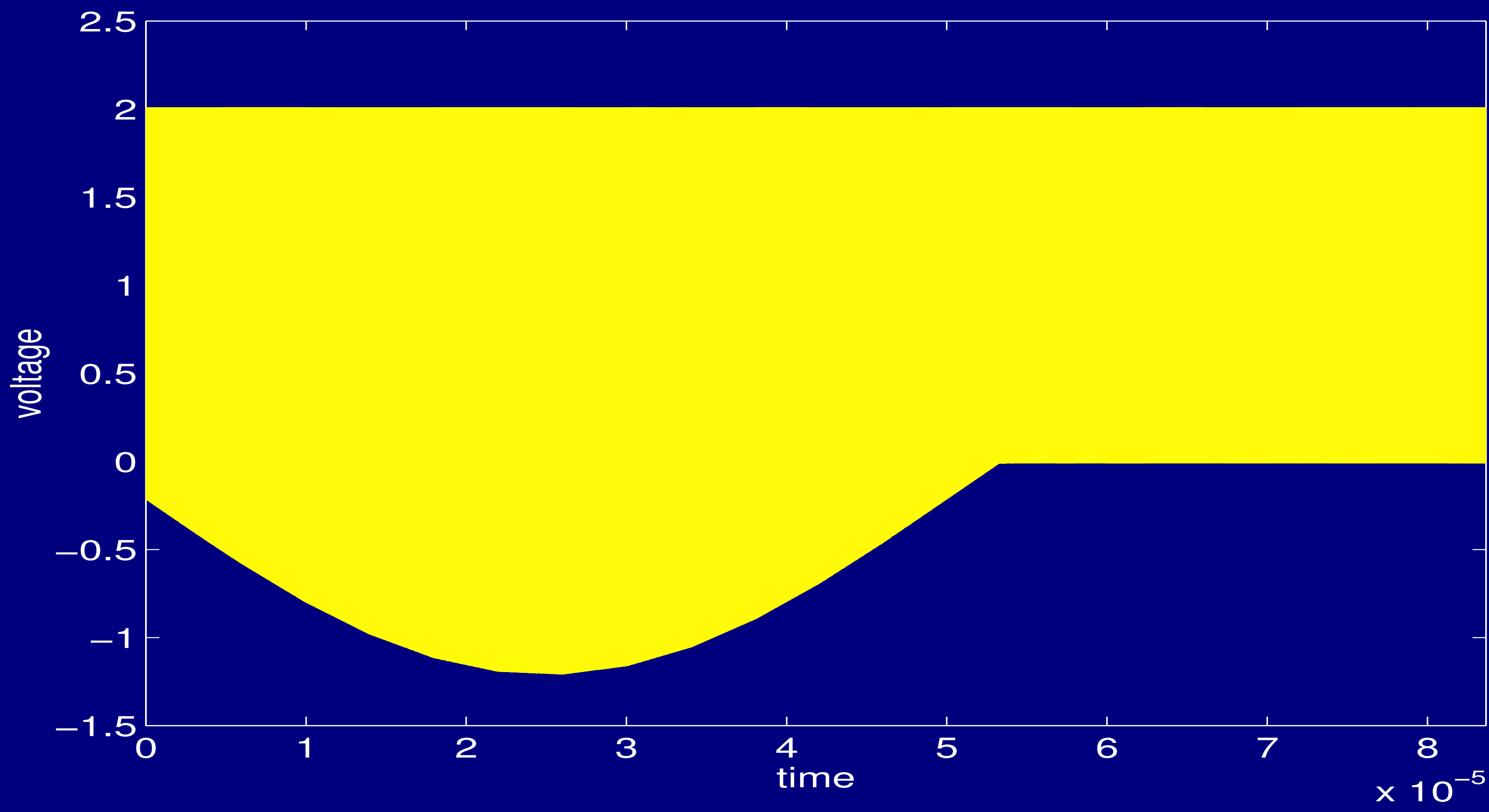
# W2013 mixer: poles of macromodel

| TVP, $q = 2$ | TVP, $q = 10$ |
|---|---|
| -5.3951e+06 | -5.3951e+06 |
| -6.9196e+07 - $j$3.0085e+05 | -9.4175e+06 |
| | -1.5588e+07 - $j$2.5296e+07 |
| | -1.5588e+07 + $j$2.5296e+07 |
| | -6.2659e+08 - $j$1.6898e+06 |
| | -1.0741e+09 - $j$2.2011e+09 |
| | -1.0856e+09 + $j$2.3771e+09 |
| | -7.5073e+07 - $j$1.4271e+04 |
| | -5.0365e+07 + $j$1.8329e+02 |
| | -5.2000e+07 + $j$7.8679e+05 |

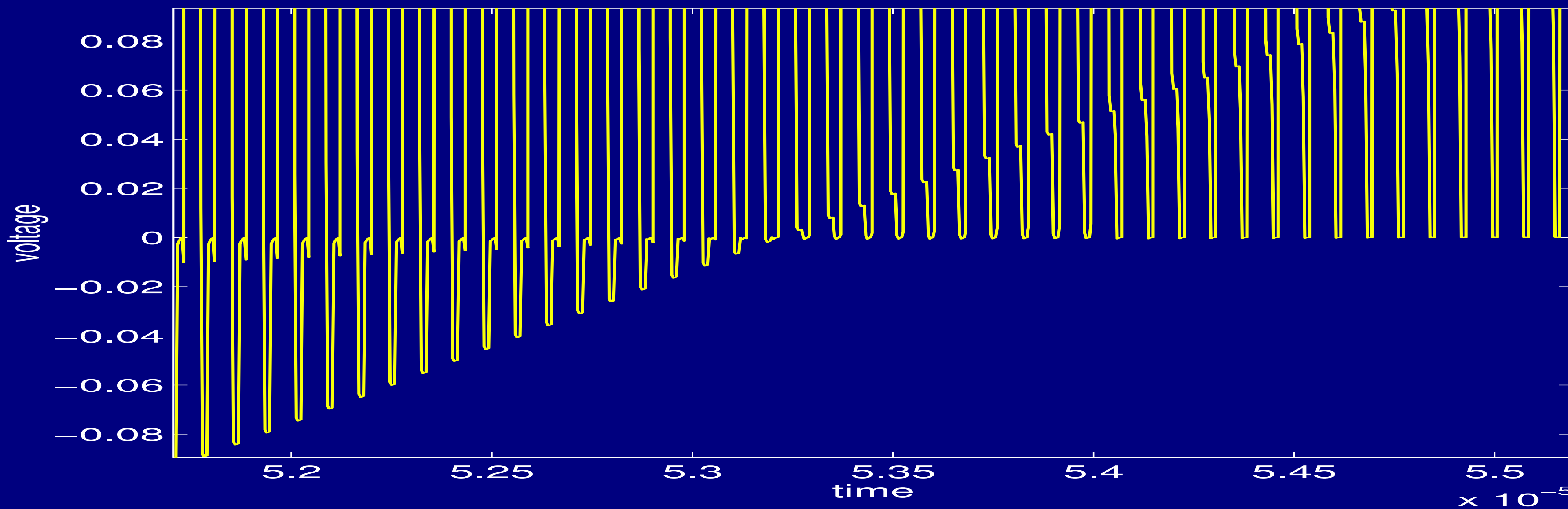
# Switched-Capacitor Integrator

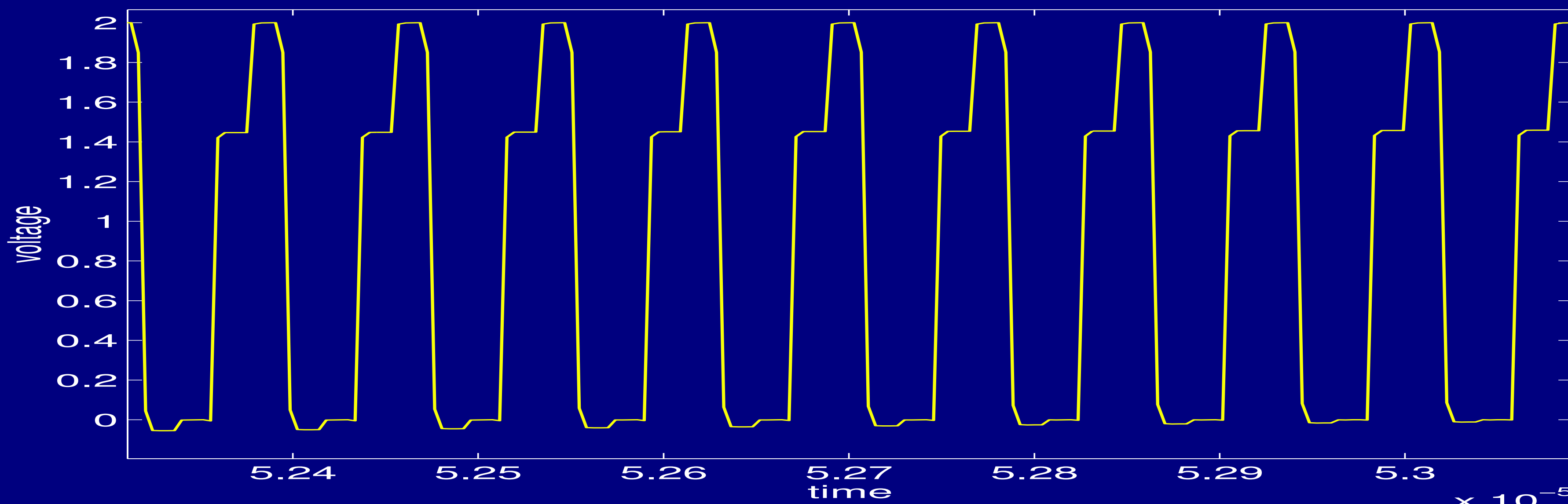
- Lossy balanced design; 350 MOSFETs
- clock: 12.8 MHz; test signal: 10 kHz

# Switched-Capacitor Integrator

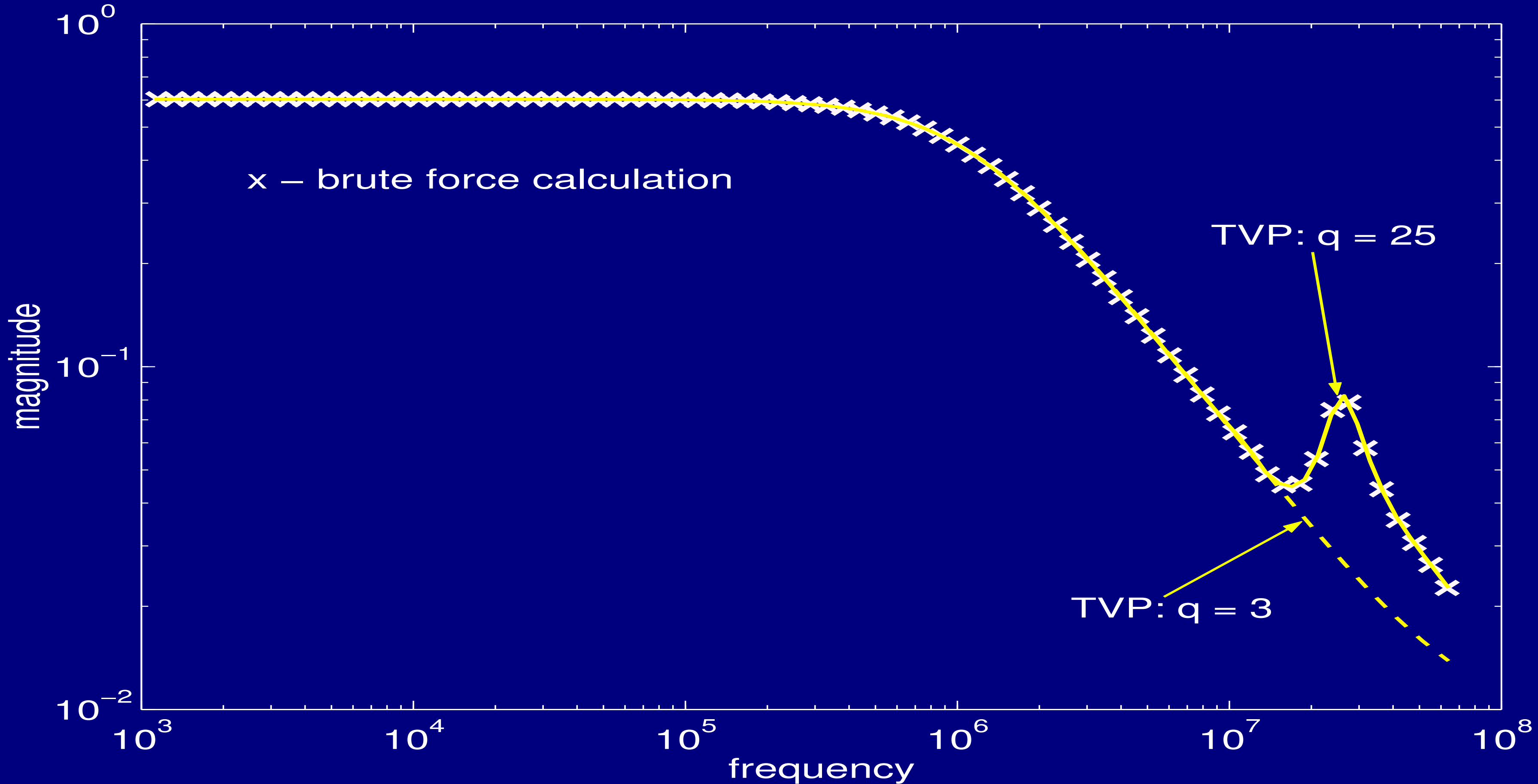


# SC Integrator: transient detail



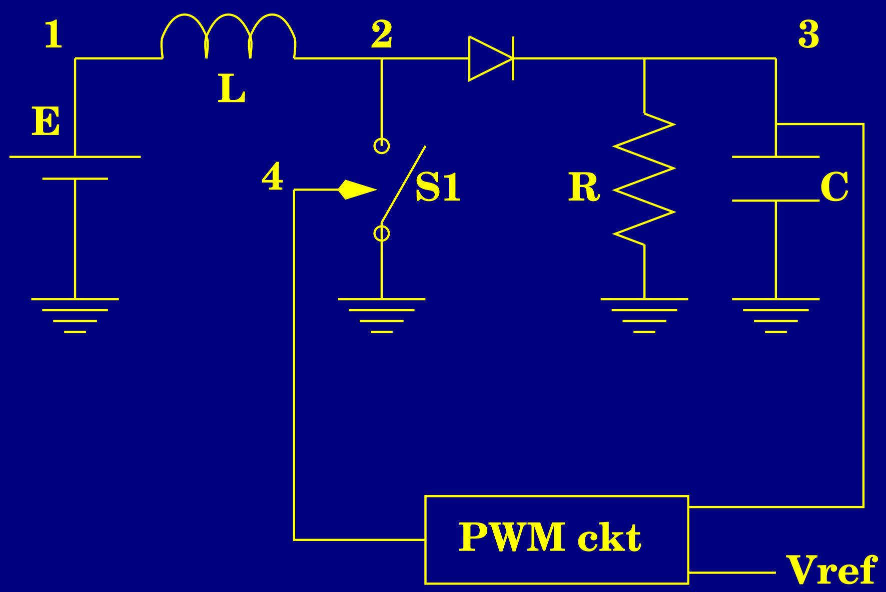



# TVP on SC Integrator



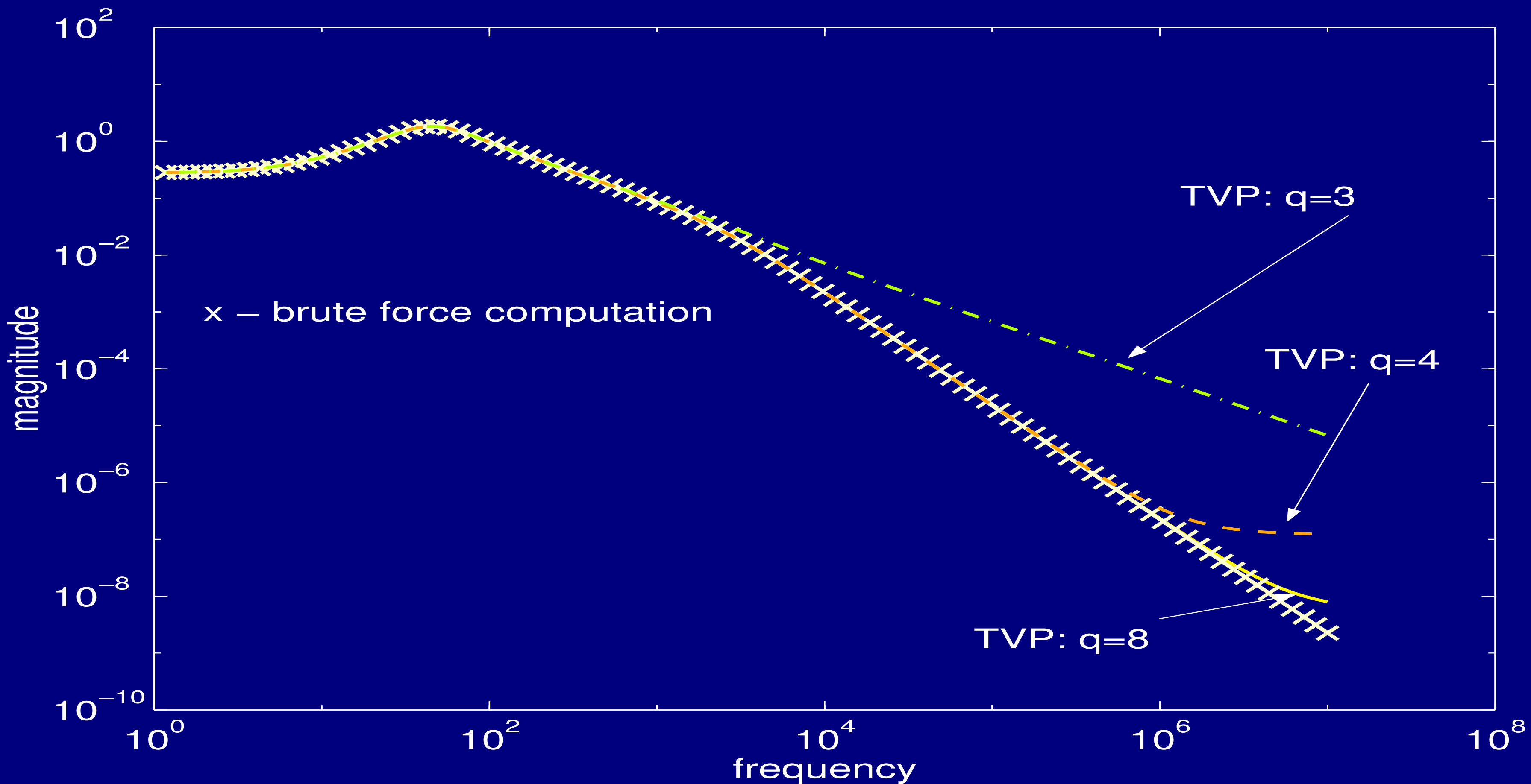

$$\frac{0.613}{j2\pi f-(-1.1e6)}+\frac{1.02e-4}{j2\pi f-(-1.68e5)}+\frac{9.81e-3}{j2\pi f-(-1.2e9)}$$

# DC/DC Switching Power Converter



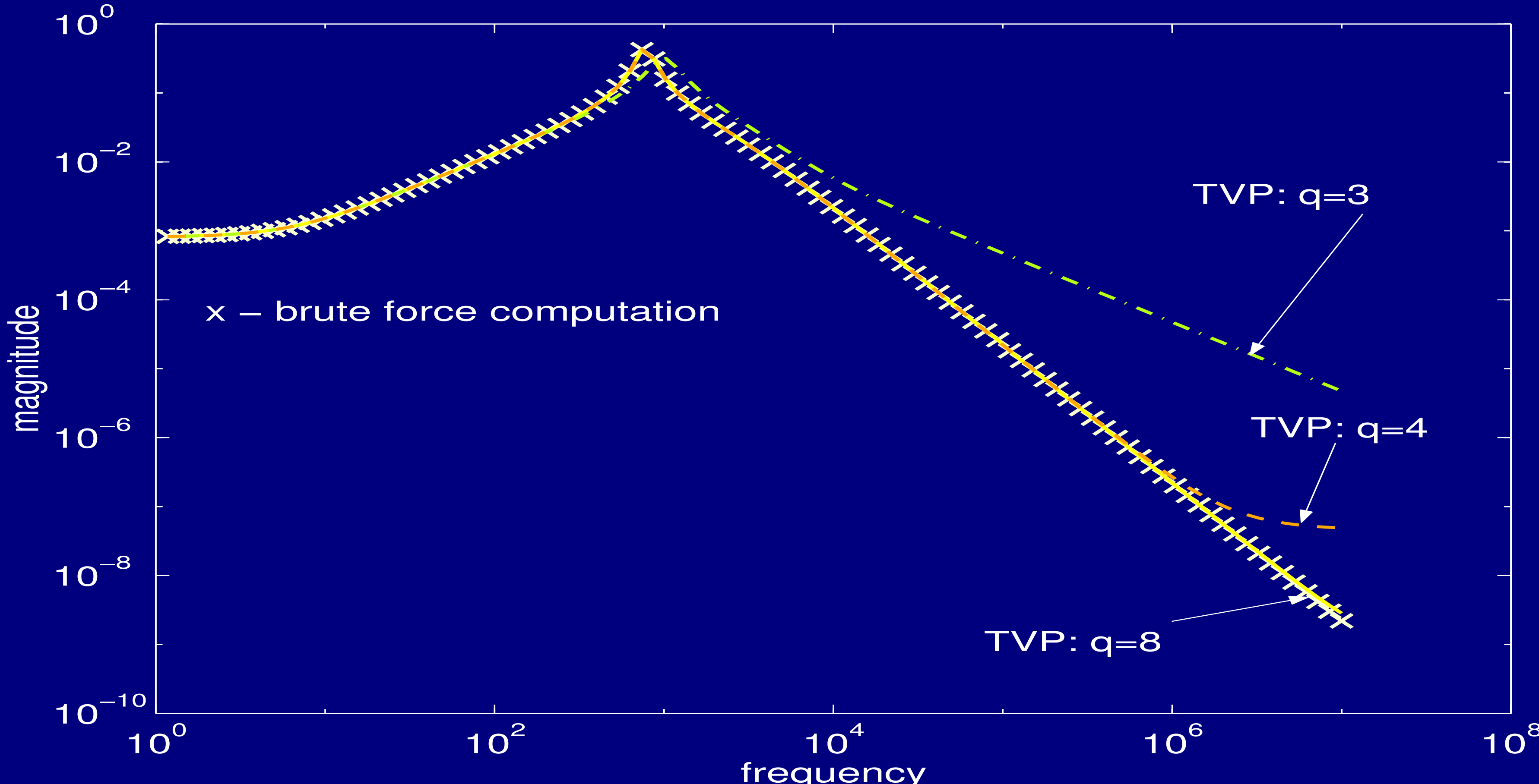

- clock: 100 kHz; PWM gain: 10
- Vref: 1.4V; RC pole ≈ 20 Hz
- Steady-state: Shooting (≈ 200 points)

# TVP: Switching Converter, gain=10




$$\frac{-0.147 \mp 1.1j}{j2\pi f - (-24.66 \mp 38.36j)} + \frac{0.0366}{j2\pi f - (-250.74)} + \text{small}$$

# Switching Converter, gain=1000




$$\frac{-0.0124 \mp 0.0455\,j}{j2\pi f - (+80.32 \mp 773.4\,j)} + \frac{0.0239}{j2\pi f - (-2854.9)} + \text{small}$$

# Conclusion

- TVP - automated macromodelling for mixers and other LTV systems
  - weak signal-path nonlinearities also incorporated
- Automated nonlinear macromodelling: coming soon (?)
  - oscillators, VCOs (phase/amplitude domain)
  - LNAs, mixers, switching filters, op-amps, comparators
  - large digital aggressor blocks: interference macromodels
  - from research idea ⇒ designer tool: open-source prototypes
- Automated MM: critical enabler for first-time-correct SoC design methodologies