Reheating the Universe After Inflation

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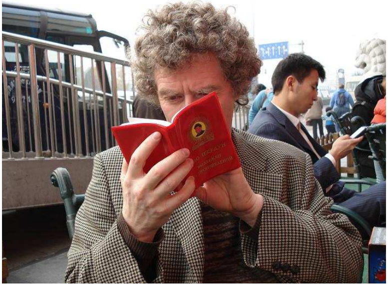
UMN

PONT - April 2011

References

Intro to (p)reheating

- Kofman, Linde & Starobinsky, "Towards the Theory of Reheating After Inflation," 1997.
- NB & Frolov, "Reheating the Universe After Inflation," to appear soon.



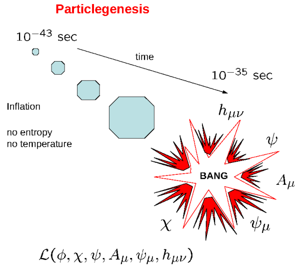
Lev Kofman:
June 17, 1957 - Nov 12, 2009.

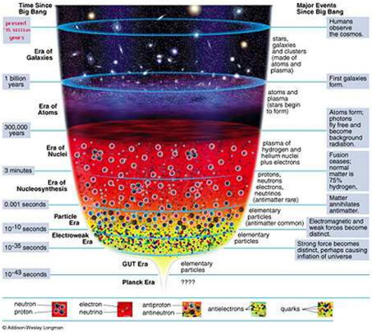
Outline

Outline

The Endpoint of Inflation

- Inflationary universe is cold, dominated by $\phi(t)$.
- $\phi(t)$ must decay to hot radiation to recover usual Big Bang.
- Reheating!



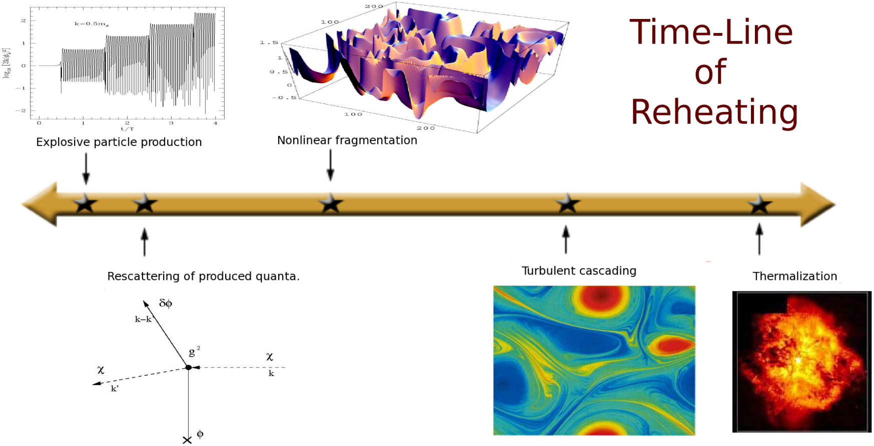


Old View of Reheating

- Instantaneous transition.
- Reheat temperature is only interesting quantity.

The Modern View

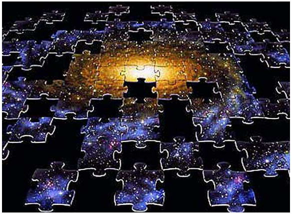
- Physics of the reheating phase is extremely rich.
- Many stages of complex dynamics before eventual thermalization.

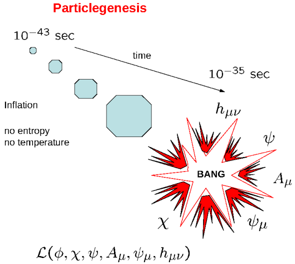


Reheating is a Key Part of Inflation

- Explains the end of inflation, beginning of thermal history.
- The origin of all elementary particles.

Important to understand dynamics of the transition...





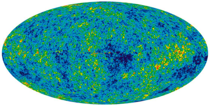
Why Study Reheating?

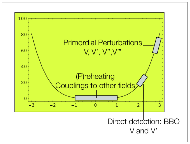
1. The matching problem.
2. Rich dynamics.
3. Constraints on model building.
4. Observable remnants.

(1) The Matching Problem

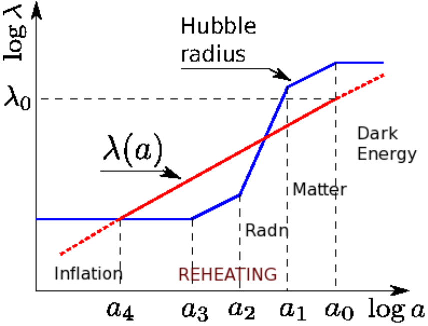
- Connect observation $P(k)$ to theory $V(\phi)$, $V'(\phi)$, $V''(\phi)$.
- Connect physical scale today ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$) to horizon crossing.
- Depends on post-inflationary expansion history.
- Uncertainty from ΔN_{reh}, ω_{reh}: relevant for precision cosmology![a]

[a] See: Martin & Ringeval; Adshead, Easther, Peiris, Pritchard, Loeb; Mielczarek.





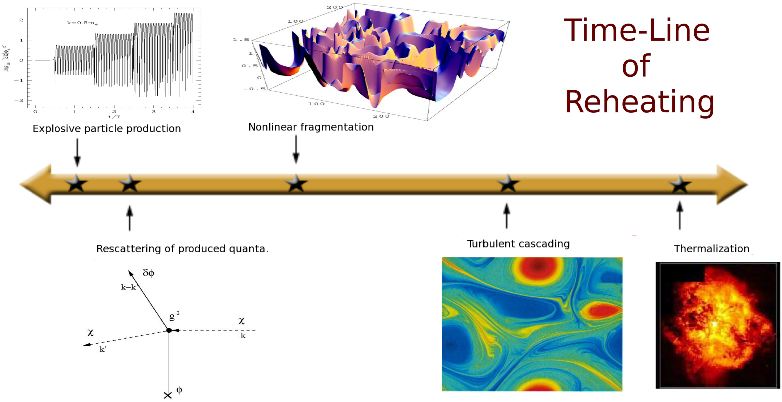
Img: Easther



Img: Mielczarek

(2) Rich Dynamics

- Preheating involves QFT under extreme conditions.
  - high energy, violent instabilities, strongly nonlinear, $\cdots$
- Rich playground to study nonequilibrium QFT.



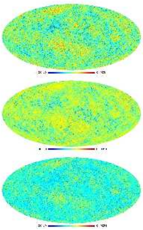
(3) Constraints on Model Building

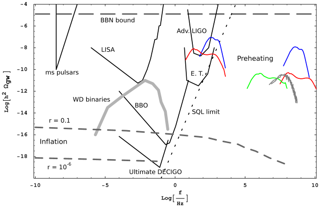
- Successful reheating not guaranteed.
  - incomplete decay
  - energy dumping into hidden sectors
- Nontrivial constraint on microscopic model-building.

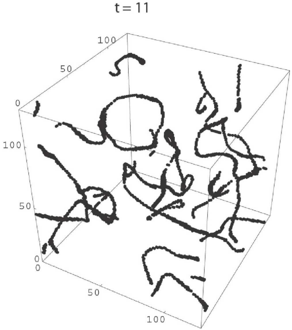
(4) Observable Remnants (???)

- Nongaussianities.[a]
- Stochastic GW bkg.[b]
- Relic topological defects, $\cdots$

[a] Enqvist et al (2004); NB & Cline (2006); Chamber & Rajantie (2008); Bond, Frolov, Huang & Kofman (2009).
[b] Khlebnikov & Tkachev; Easther, Giblin & Lim; Dufaux, Bergman, Felder, Kofman & Uzan; Garcia-Bellido & Figueroa.

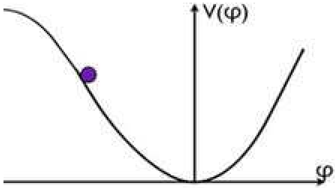


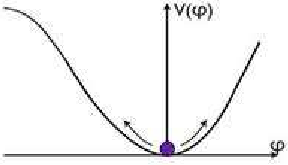




Outline

Post-Inflationary Phase of Oscillations





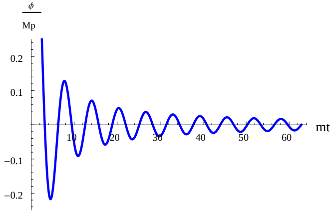
Near the minimum:

$$V(\phi) \cong \frac{1}{2} m^2 \phi^2$$

During oscillatory phase:

$$\phi(t) \cong \frac{\phi_0}{a^{3/2}(t)} \sin[mt]$$

$$a(t) \cong t^{2/3}, \quad P \cong 0$$

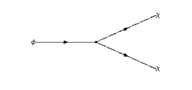


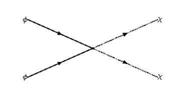
Oscillations behave like pressureless dust.

Coupling the Inflaton to Matter

Want to see the oscillating condensate decay. Pedagogical toy model:

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{2}(\partial\chi)^2 - \frac{g^2}{2}\phi^2\chi^2 - \frac{1}{2}\sigma\phi\chi^2 - \frac{\lambda}{4}\chi^4$$





Equation of Motion

$$\frac{d^2}{dt^2}\chi_k(t) + \omega_k^2(t)\,\chi_k(t) = 0$$
$$\omega_k^2(t) = k^2 + g^2\phi_0^2\sin^2[mt] + v\phi_0\sin[mt]$$

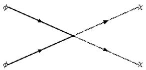
Problem of quantization of χ in time-dep bkg $\phi(t)$.

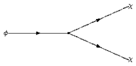
Bogoliubov computation for $n_k^{\chi} \ll 1$ (NB, Braden & Kofman):

$$\frac{d}{dt}\rho_\phi + \left[\underbrace{3H}_{\sim t^{-1}} + \underbrace{\langle \sigma v \rangle n_\phi}_{\sim t_{\rm ann}^{-1}} + \underbrace{\Gamma}_{\sim t_{\rm dec}^{-1}} \right] \rho_\phi = \underbrace{c g^2 v \rho_\phi^{3/2} \sin\left[\psi(t)\right]}_{\text{interference}}$$

- Boltzmann equation describing transfer of energy from $\phi(t)$ to $\delta\chi_k(t)$ via $\phi\phi \rightarrow \chi\chi$ and $\phi \rightarrow \chi\chi$.
- Rate and x-section agree with Feynman diagram:

$$\langle \sigma v \rangle = \frac{g^4}{32\pi\, m^2}\,, \qquad \Gamma = \frac{\sigma^2}{32\pi\, m}$$

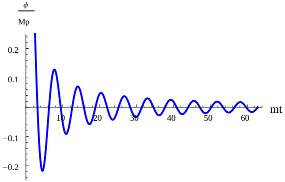




Boltzmann equation:

$$\frac{d}{dt}\rho_\phi + \left[3H + \langle\sigma v\rangle n_\phi + \Gamma\right]\rho_\phi = \underbrace{c g^2 v \rho_\phi^{3/2} \sin\left[\psi(t)\right]}_{\text{interference}}$$

- Quantum interference b/w decay channels.
- Decay of coherent oscillations, not particles.
- Avg to zero for $\Delta t \gg m^{-1}$.



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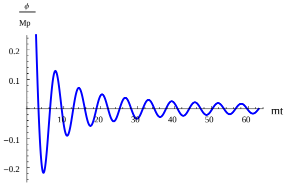
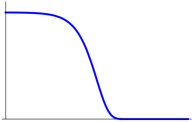


NOTE

First principles derivation, different from ad hoc dissipation:

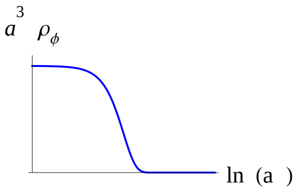
$$\ddot{\phi} + 3H\dot{\phi} + \Gamma\dot{\phi} + V' = 0$$



Reheating Temperature

- $H \gtrsim \Gamma$: $\rho_\phi \sim a^{-3}$ (dilution)
- $H \lesssim \Gamma$: $\rho_\phi \sim e^{-\Gamma t}$ (decay)
- Temp at decay ($\rho_r = 3H^2 M_p^2 = \pi^2 g_\star T_r^4/30$):

$$\mathbf{T_r \sim \sqrt{\Gamma M_p}}$$



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Failure to Decay ($\Gamma = 0$)

- Incomplete decay for pure $\phi^2\chi^2$.
- Problem: $t_{\rm ann}^{-1} \sim \langle \sigma v \rangle n_\phi \sim a^{-3} \to 0$, hubble always wins.
- Finite density of ϕ freezes in.
- Typically leaves cold, lifeless universe.

Example of reheating constraint!

Outline

Equation of Motion

$$\frac{d^2}{dt^2}X_k + \left[\frac{k^2}{a^2} + g^2\frac{\phi_0^2}{a^3}\sin^2(mt)\right]X_k = 0$$

- Previously solved perturbatively for $n_k \ll 1$.
- At $n_k \gtrsim 1$ bose stats can enhace decay prob!

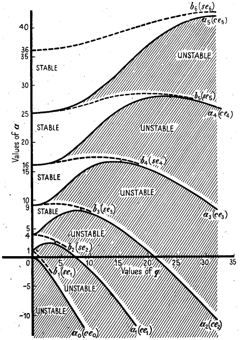
"Exact" Solution: Mathieu Equation

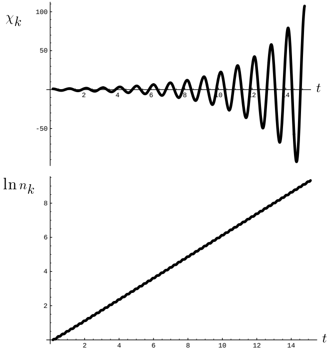
$$\frac{d^2}{dz^2}X_k + \left[A_k - 2q\cos(2z)\right]X_k = 0$$

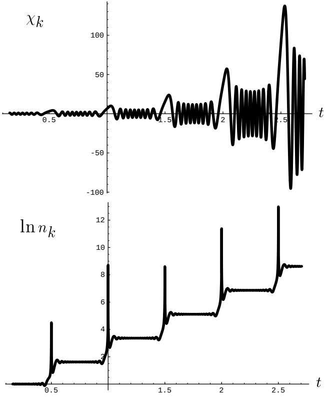
Some regions of phase space unstable:[a]

$$X_k \sim e^{\mu_k z}$$

[a] Dolgov & Kirilova; Brandenberger & Traschen; Kofman, Linde & Starobinsky







Narrow Resonance ($q \ll 1$)

Resonance b/w bkg oscillations, m, and mode, k.

Broad Resonance ($q \gg 1$)

Burst of particle prodn when $m_{\rm eff}^2(t) \propto \sin^2(mt) = 0$.

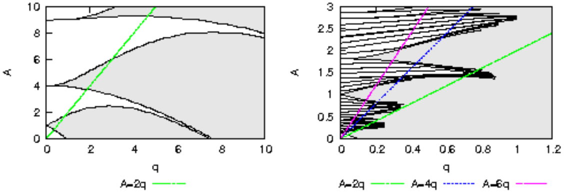
Multi-Field Inflation (NB, Braden & Kofman)

Microscopic realizations often involve many rolling scalars:

$$\mathcal{L} = \sum_i \left[-\frac{1}{2}(\partial\phi_i)^2 - \frac{m_i^2}{2}\phi_i^2 - \frac{g_i^2}{2}\phi_i^2\chi^2 - \frac{\sigma_i}{2}\phi_i\chi^2 \right]$$

Quasi-periodic Mathieu equation:

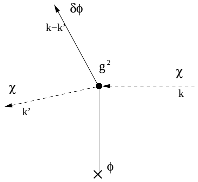
$$X'' + \left[A - 2\sum_i q_i \cos(2\omega_i z) \right] X = 0$$



- Expontential growth of fluctuations: $\chi_k(t) \sim e^{\mu_k mt}$
- Corresponds to explosive particle prodn:

$$n_k(t) \sim \frac{\rho_k(t)}{\omega_k} \sim e^{2\mu_k mt}$$

- Dynamics quickly goes nonlinear.



Rescattering of produced quanta.[a]

[a] NB, Huang, Kofman & Pogosian.

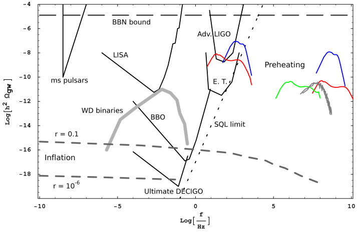
Lattice Field Theory Approach

1. LATTICEASY: Gary Felder
2. DEFROST: Andrei Frolov
3. HLATTICE: Zhiqi Huang
4. PSECTRE: Easter, Finkel & Roth

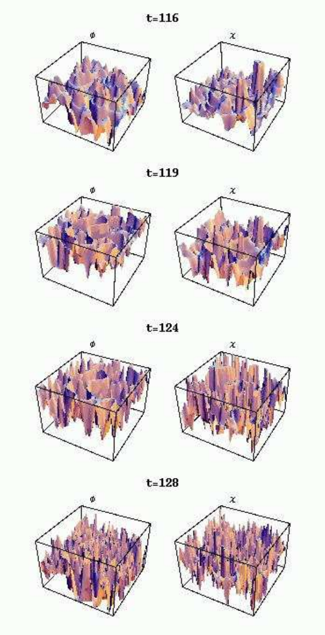
Nonlinear Regime

- Highly inhomogeneous.
- Formation, collision of lumpy structures.
- Dominates emission of GW.[a]

[a] Khlebnikov & Tkachev; Easther, Giblin & Lim; Dufaux, Bergman, Felder, Kofman & Uzan; Garcia-Bellido & Figueroa.



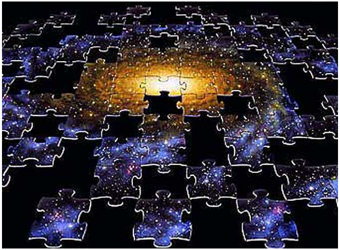
Dufaux et al.



Kofman & Felder, 2006

Some General Lessons

- (P)reheating dynamics very sensitive to model, couplings.
- So far only decay of condensate, not actual heating of the SM...



Towards Realistic Particle Physics

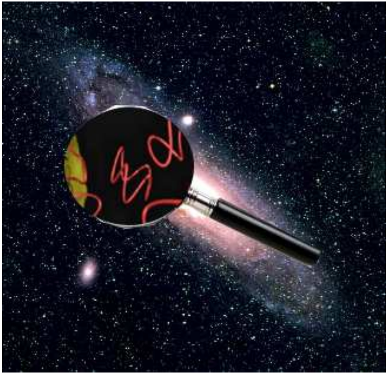
- Motivation to go beyond ad hoc approach to couplings.
- How does reheating look in a complete particle physics theory of inflation + SM?
- String theory?

Outline

Stringy Inflation

- Lots of progress obtaining inflation in "realistic" stabilized vacua.[a]
- Opportunity to address UV sensitivies in coherent framework.

[a] KKLT, KKLMMT, D3/D7, racetrack, N-flation, monodromy, LVC, modular inflation, etc



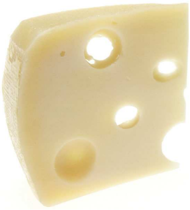
How can String Theory Inform Reheating?

- Top-down identification of couplings.
- How robust are conclusions from simple ad hoc models?
- Successful reheating?
- New stringy phenomena?

Modular Inflation

- Representative example: encodes many interesting features.[a]
- Based on well-studied IIB vacua.

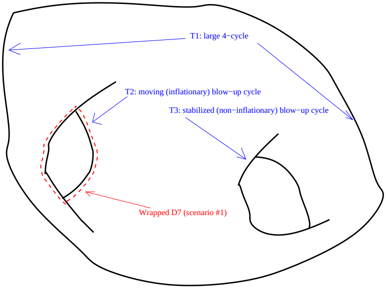
[a] Conlon & Quevedo; Bond et al; NB et al; ...



Large Volume CY

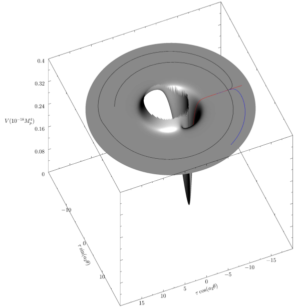
- Swiss-cheese structure.
- Stabilized moduli.[a]
- "Realistic" MSSM pheno.

[a] Balasubramanian, Berglund, Conlon, Quevedo, ...



The Inflaton: $T = \tau + i\theta$

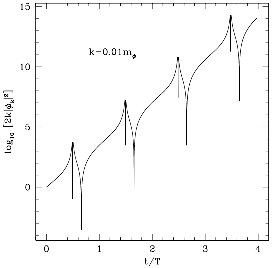
Hole size modulus and axion partner.

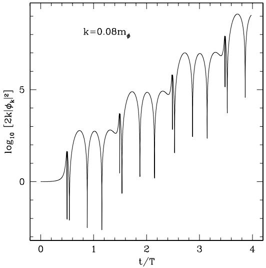


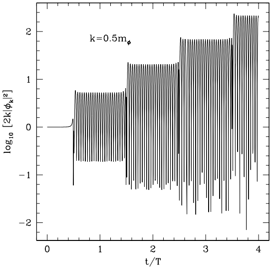
Effective SUGRA:

$$\mathcal{L} = -\frac{1}{2} G_{ab} \partial\phi^a \partial\phi^b - V(\phi^c)$$

- G_{ab} non-trivial
- Sharp potential minimum.
- Strong preheating instability.





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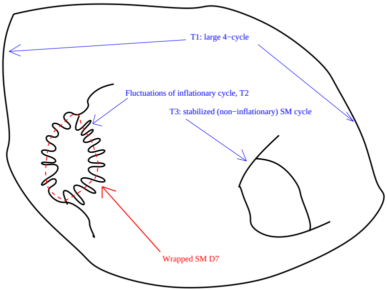


Reheating the SM

- Can identify location of SM in CY.
- Follow energy transfer into visible sector.

Moduli Couplings to SM

$$\mathcal{L}_{\rm int} = -\lambda\,\phi\,F^2 - h\,\phi\,\bar{\psi}\psi + \cdots$$

All couplings and T_r calculable in terms of microscopic data.

Beyond Effective Field Theory

Warped Brane Inflation

Very complicated chain of decays and cascading of energy.[a]

Not field theoretical, requires input from string theory!

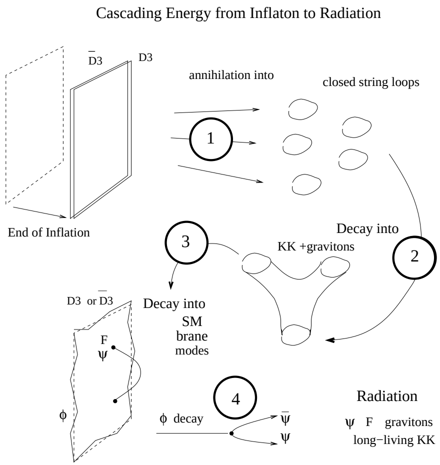
[a] NB, Burgess & Cline (2004); Kofman & Yi (2005); Dufaux et al. (2008); · · ·

Tachyon Condensation

Novel DBI effects: caustics[a], overproduction of cosmic strings.[b]

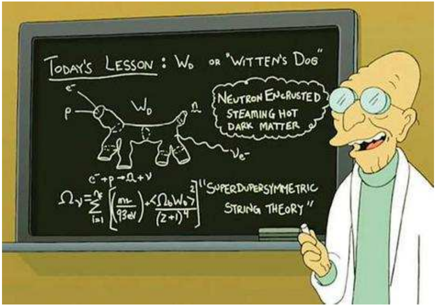
[a] Kofman & Felder, NB

[b] NB, Berdsen, Cline & Stoica



Stringy Reheating

- Still in infancy.
- Very few models investigated.



Try to Abstract General Lessons:

1. Realistic dynamics usually very complicated.
2. Instabilities reasonably generic, in some cases VERY strong.
3. Can follow transfer of energy to SM
4. New instrinsically stringy effects possible.[a]

[a] NB, Burgess & Cline; NB, Huang & Kofman.

Outline

Conclusions

- Reheating is a key part of the inflationary story.
  - Necessary to recover hot BB, explains the origin of all particles in the universe.
- Multi-stage process: explosive particle production, rescattering, fragmentation, turbulence, thermalization.
- Rich dynamics of interacting QFT far from equilibrium.
- Can study stages of ϕ decay in “realistic” particle framework.
  - Complex instabilities.
  - New stringy processes.
  - Transfer of energy to SM.
- Possible observable signatures: NG, GW, defects, ...
  - Also features/NG from similar processes DURING inflation. More promising?[1]

[1] See Sorbo's talk. Also: NB, Huang, Kofman & Pogosian (2009), NB & Huang (2009), NB (2010), NB & Peloso (2011), NB, Namba & Peloso (2011).