Spillway Preheating

an efficient particle production mechanism

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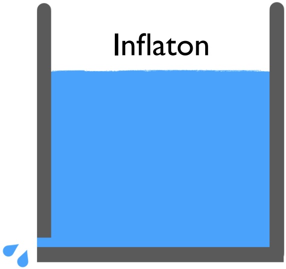
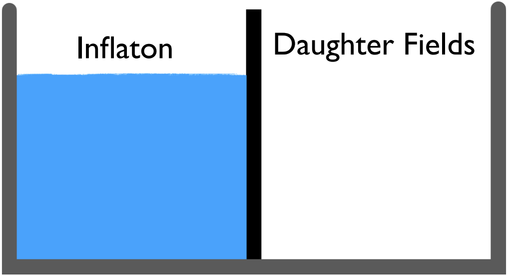
From Inflaton-dominated to Radiation-dominated

- couple inflaton to other fields $\Rightarrow$ slow perturbative decay



From Inflaton-dominated to Radiation-dominated

- couple inflaton to other fields ⇒ slow perturbative decay
- Instability driven by inflaton oscillation ⇒ resonant production of daughter fields: “preheating”



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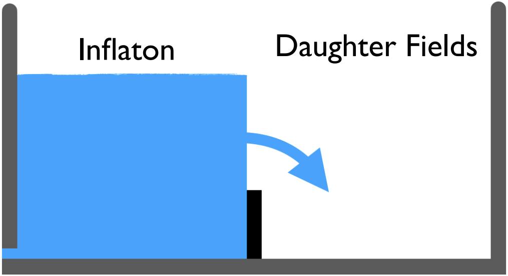
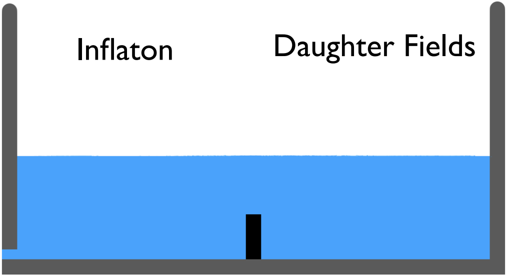
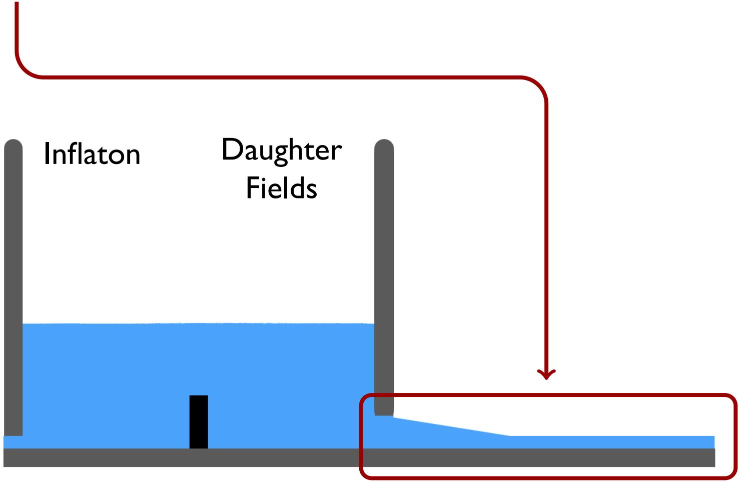


From Inflaton-dominated to Radiation-dominated

- couple inflaton to other fields $\Rightarrow$ slow perturbative decay
- Instability driven by inflaton oscillation $\Rightarrow$ resonant production of daughter fields: "preheating"
- But backreaction shuts off the instability and stops further transfer of energy.
  Existing preheating models leave between $\sim 1\%$ to $\sim 50\%$ of residual inflaton energy density $\equiv \rho_\phi/\rho_{\text{tot}}$ at end of preheating



"Spillway" Preheating



"Spillway" alleviates backreaction, allows more energy transfer

Achieves $\sim 0.01\%$ of residual inflaton energy density

Parametric scaling shows potential for further improvement

Outline

- Field content and interactions
- Numerical simulations showing efficient energy transfer
- Parametric scaling of energy transfer efficiency
- Validity of our numerical study

Our Model

$$V = \frac{1}{2}m^2\phi^2 + \frac{M^2}{\Phi_0}\phi\chi^2 + \frac{\lambda}{4}\chi^4 + y\chi\bar{\psi}\psi$$

Minimum of the potential
is quadratic during reheating

$$\lambda \geq \lambda_{\text{min}} = \frac{M^4}{2m^2\Phi_0^2}$$

to stabilize potential

Our Model

M: mass scale of χ

$$V = \frac{1}{2}m^2\phi^2 + \frac{M^2}{\Phi_0}\phi\chi^2 + \frac{\lambda}{4}\chi^4 + y\chi\bar{\psi}\psi$$

Φ_0: initial oscillation amplitude

after inflation, ϕ oscillates; time-dependent χ mass

Our Model

$$\Gamma_\chi = \frac{y^2}{8\pi} m_\chi(\phi)$$

$$V = \frac{1}{2}m^2\phi^2 + \frac{M^2}{\Phi_0}\phi\chi^2 + \frac{\lambda}{4}\chi^4 + y\chi\bar{\psi}\psi$$

"water tank" "spillway"

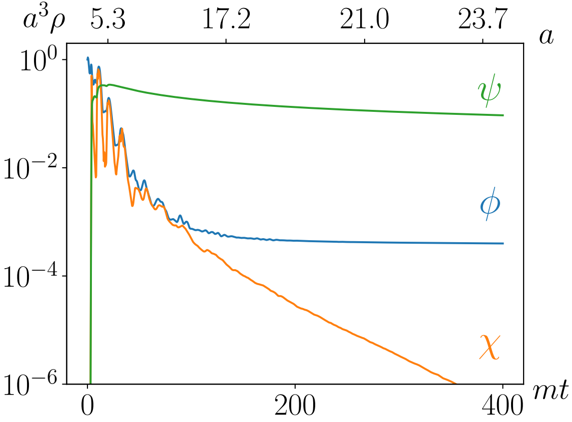
"tachyonic resonance/preheating"

(Dufaux, Felder, Kofman, Peloso, Podolsky '06)

resonant production of χ when $q \equiv \frac{M^2}{m^2}\frac{\Phi}{\Phi_0} > 1$

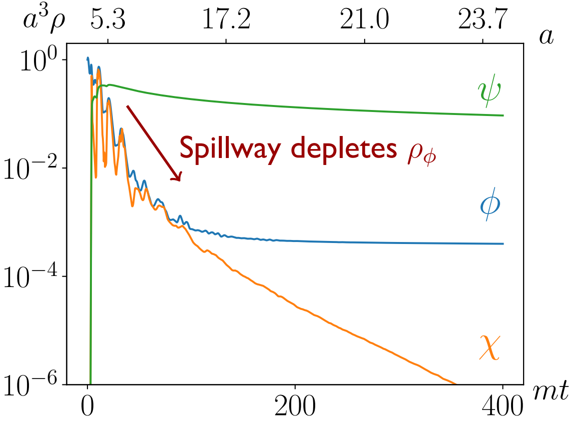
Spillway Improves Depletion of ρ_ϕ

Simulation with modified LatticeEasy (Felder, Tkachev ’00)
fermion modeled by a perfect fluid, method follows (Repond, Rubio ’16)

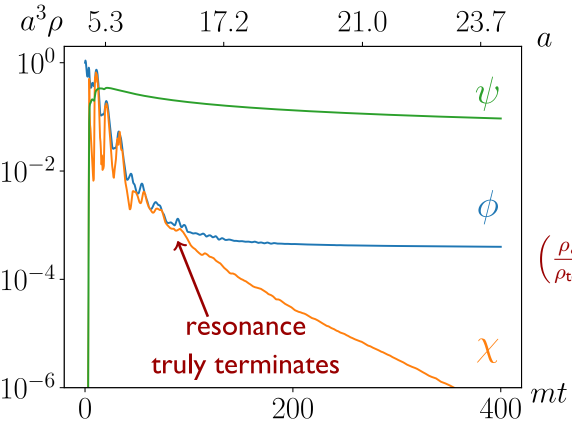


$$m = 10^{-6} M_{\mathsf{pl}},\ \Phi_0 = M_{\mathsf{pl}},\ q_0 \equiv \frac{M^2}{m^2} = 200,\ \frac{y^2}{8\pi} = 0.15$$

Spillway Improves Depletion of ρ_ϕ

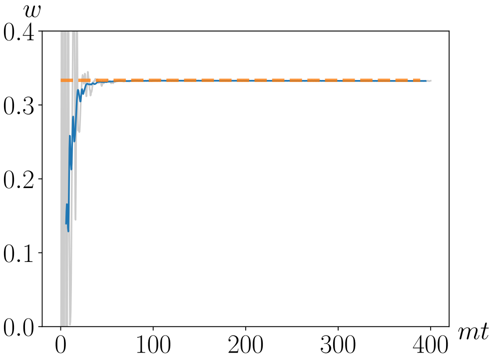


Spillway Improves Depletion of ρ_ϕ



$\left(\frac{\rho_\phi}{\rho_{\text{tot}}}\right)_{\text{min}} \approx 10^{-2}$

Improved energy transfer = more radiation-like equation of state



Depletion Efficiency Scales with q_0

In the linear regime, tachyonic resonance happens when

$$q \equiv \frac{M^2}{m^2}\frac{\Phi}{\Phi_0} > 1$$

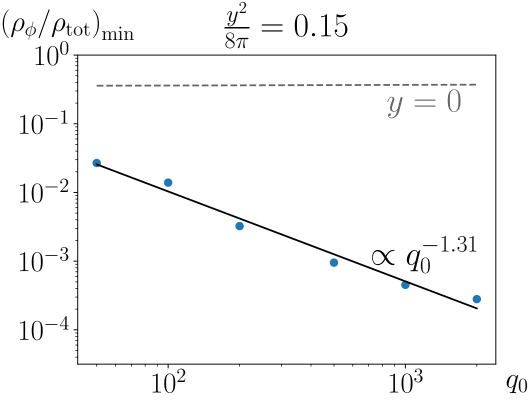
$$\frac{M^2}{m^2} \equiv q_0$$

model parameter

$$\frac{\Phi}{\Phi_0} = \sqrt{\frac{m^2\Phi^2}{m^2\Phi_0^2}} \approx \sqrt{\frac{\rho_\phi}{\rho_{\text{tot}}}}$$

$$\Rightarrow \left(\frac{\rho_\phi}{\rho_{\text{tot}}}\right)_{\text{min}} \propto q_0^{-2}$$

Numerical Study Confirms Scaling Law



Similar scaling law was found for $\frac{y^2}{8\pi} = 0.01, 0.05, 0.10$

Validity of the Numerical Study

For the numerical study to hold,

- The scalar fields need to have large occupation numbers to justify use of classical equations of motion
- Fermion backreaction on the scalar potential needs to be negligible
- ϕ perturbative decay cannot be significant during the time scale of our simulations

To satisfy all the constraints, need to couple N_f fermions to χ, where $N_f \gtrsim 1/\lambda$, and $y^2 \lesssim N_f \lambda$.

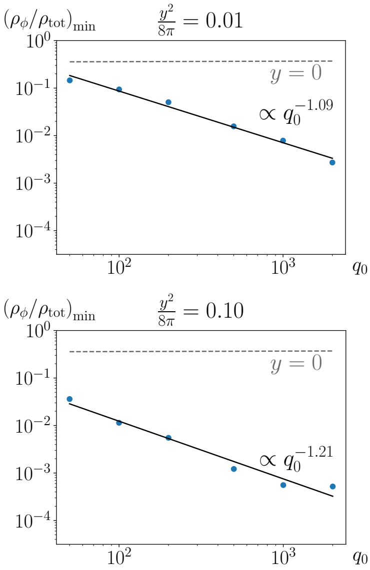
Conclusion

- Energy transfer in existing models of preheating are bottlenecked by backreaction from daughter fields
- Spillway preheating alleviates this backreaction. We were able to realize transfer of 99.99% of inflaton energy density, more efficient than existing models.
- The residual inflaton energy density scales as q_0^{-x}, $x \sim 1$, showing potential for even better energy transfer depending on model parameters.

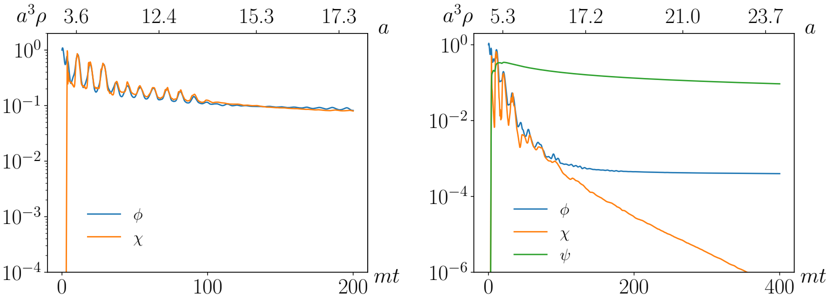
○ Effects on cosmological observables, such as inflationary observables and gravitational waves?

○ Applications outside reheating?

Backup slides



$(\rho_\phi/\rho_{\rm tot})_{\rm min}$
$\frac{y^2}{8\pi} = 0.01$
$y = 0$
$\propto q_0^{-1.09}$
$\frac{y^2}{8\pi} = 0.05$
$\propto q_0^{-1.30}$
$\frac{y^2}{8\pi} = 0.10$
$\propto q_0^{-1.21}$
$\frac{y^2}{8\pi} = 0.15$
$\propto q_0^{-1.31}$
q_0



$$m = 10^{-6} M_{\mathsf{pl}},\ \Phi_0 = M_{\mathsf{pl}},\ q_0 \equiv \frac{M^2}{m^2} = 200$$

$\frac{y^2}{8\pi} = 0$ **(left) and** $\frac{y^2}{8\pi} = 0.15$ **(right)**

Details of Numerical Simulations

- LatticeEasy modified to use Runge-Kutta 4th order integrator
- Fermion modeled as a radiation-like homogeneous fluid with energy density ρ_ψ
- Time evolution of ρ_ψ derived by $\Delta_\mu T^{\mu 0} = 0$
- $\dot{\rho}_\psi + 4H\rho_\psi - \langle \Gamma_\chi \dot{\chi}^2 \rangle = 0$
- $\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \frac{M^2}{f}\phi\chi + \lambda\chi^3 + \Gamma_\chi\dot{\chi} = 0$
- $\Gamma_\chi = \frac{y^2}{8\pi} m_\chi(\phi) = \begin{cases} \frac{y^2}{8\pi}\sqrt{\frac{M^2}{f}\phi}, & \phi > 0 \\ \frac{y^2}{8\pi}\sqrt{\frac{2M^2}{f}|\phi|}, & \phi < 0. \end{cases}$

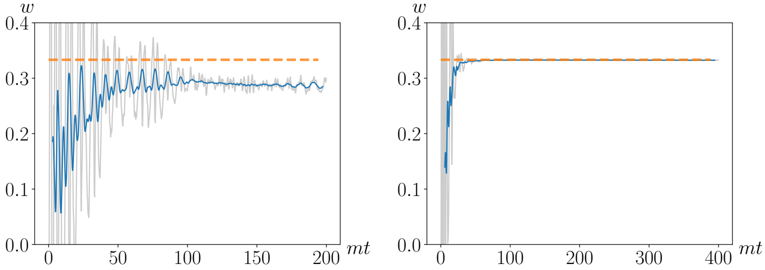
$$V = \frac{1}{2}m^2\phi^2 + \frac{M^2}{\Phi_0}\phi\chi^2 + \frac{\lambda}{4}\chi^4 + y\chi\bar{\psi}\psi \qquad (1)$$

Validity of the Numerical Study

For the numerical study to hold,

- The scalar fields need to have large occupation numbers to justify use of classical equations of motion
- Fermion backreaction on the scalar potential needs to be negligible
  - Fermion cannot have a large mass from $\langle\chi\rangle\bar{\psi}\psi$
  - Tadpole term $\chi\left\langle\bar{\psi}\psi\right\rangle$ cannot be large compared to $\phi\chi^2$ term
- ϕ perturbative decay cannot be significant during the time scale of our simulations
- Need to avoid Pauli blocking: fermions cannot have large occupations numbers

To satisfy all the constraints, need to couple N_f fermions to χ, where $N_f \gg 1$, and $y^2 \lesssim N_f\lambda$.



$$m = 10^{-6} M_{\rm pl}, \; \Phi_0 = M_{\rm pl}, \; q_0 \equiv \frac{M^2}{m^2} = 200$$

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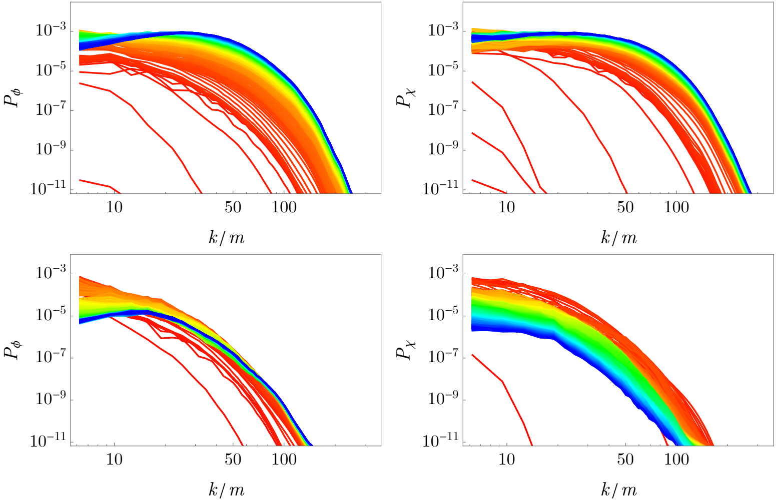

$$m = 10^{-6} M_{\mathsf{pl}},\ \Phi_0 = M_{\mathsf{pl}},\ q_0 \equiv \frac{M^2}{m^2} = 200$$

$\frac{y^2}{8\pi} = 0$ **(top) and** $\frac{y^2}{8\pi} = 0.15$ **(bottom)**