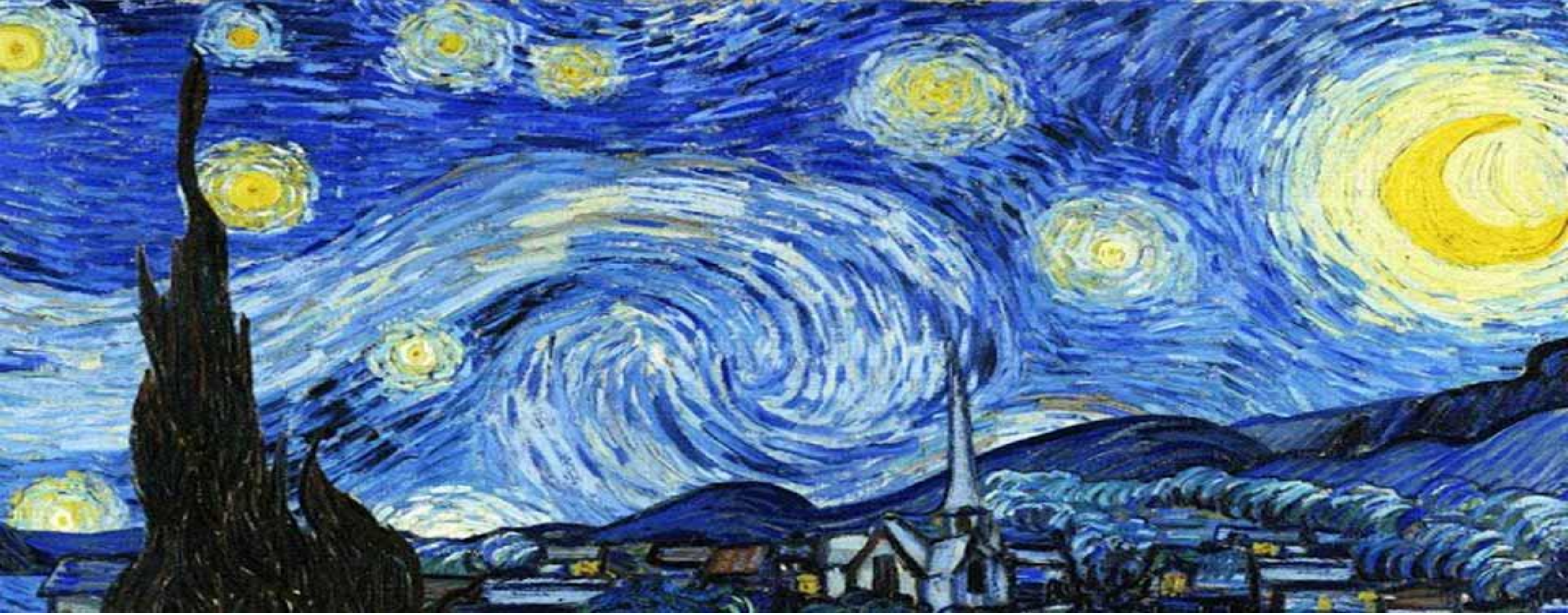

An Effective Field Theory approach to Reheating

arXiv: 1701.01455

Collider and Dark Matter Physics 2017
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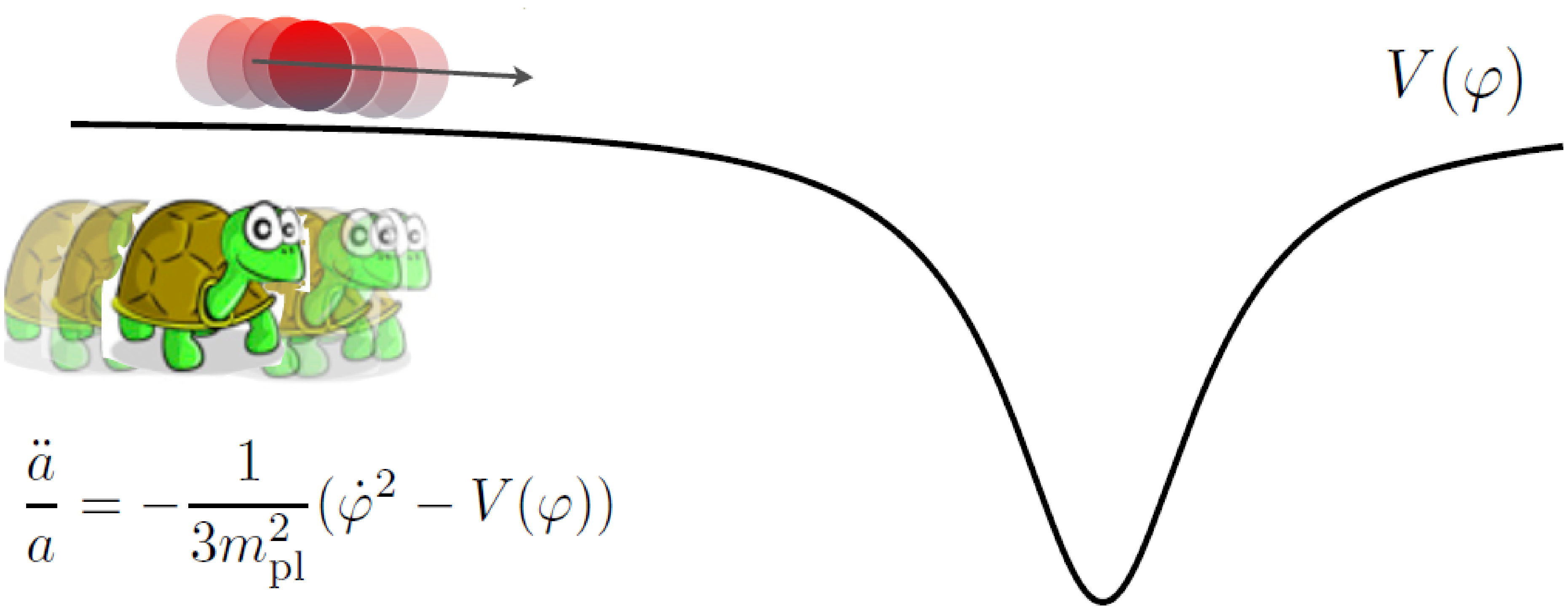
Inflation

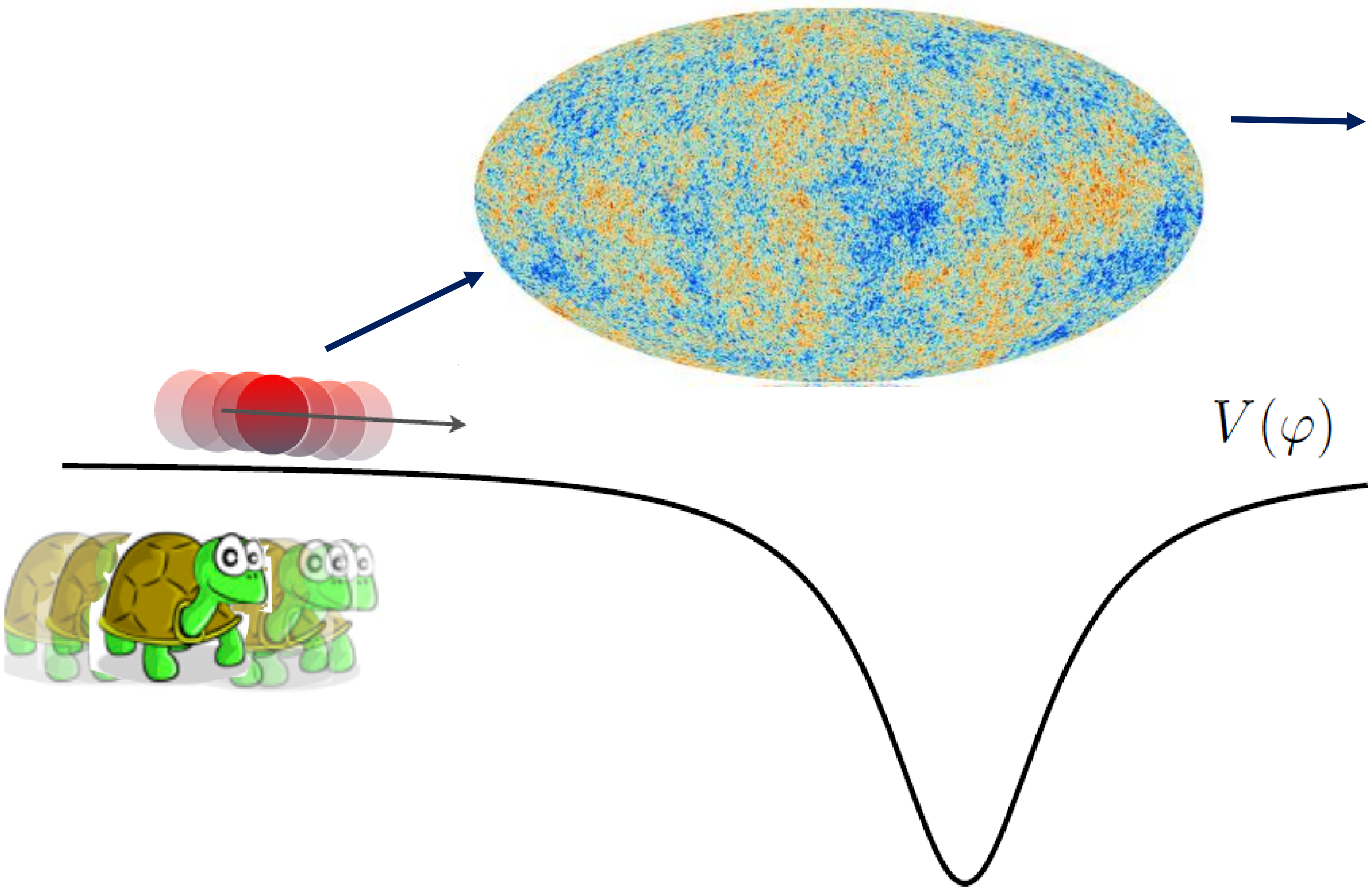


$$\frac{\ddot{a}}{a} = -\frac{1}{3m_{\mathrm{pl}}^2}\left(\dot{\varphi}^2 - V(\varphi)\right)$$

$$\dot{\varphi}^2 \ll V(\varphi) \Longrightarrow \ddot{a} > 0$$

Image: Courtesy of M. Amin

Inflation



Sets initial conditions for CMB temperature fluctuations:

$$\Delta_s^2 = A_* \left(\frac{k}{k_*}\right)^{n_s - 1}$$

- Gaussian and almost scale invariant fluctuations

$$|n_s - 1| \ll 1$$

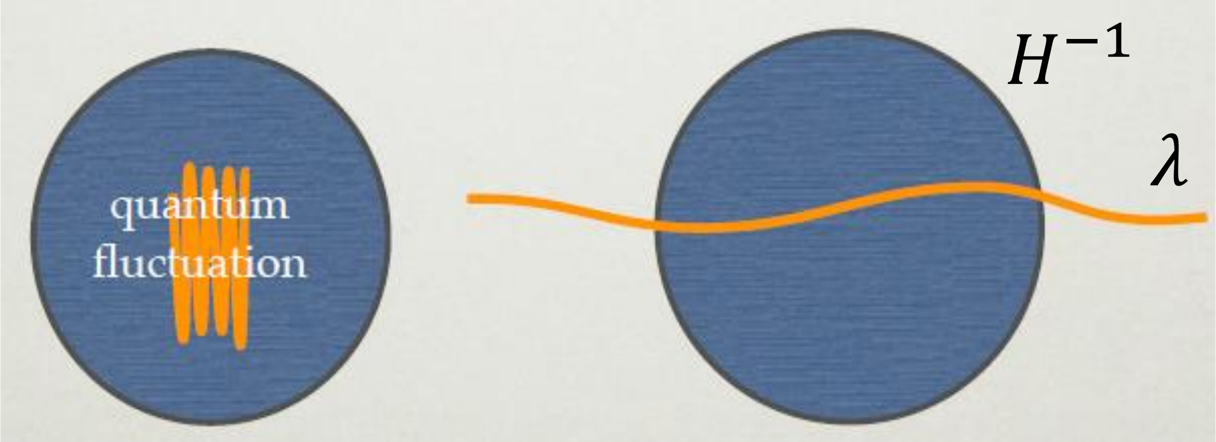
Inflation

- Also provides a causal mechanism for seemingly a-causal temperature correlations:

  e.g. provides a simple solution to the horizon problem of the hot Big Bang cosmology

$$\lambda \propto a(t), \qquad d_H = H(t)^{-1}$$

λ / d_H is increasing



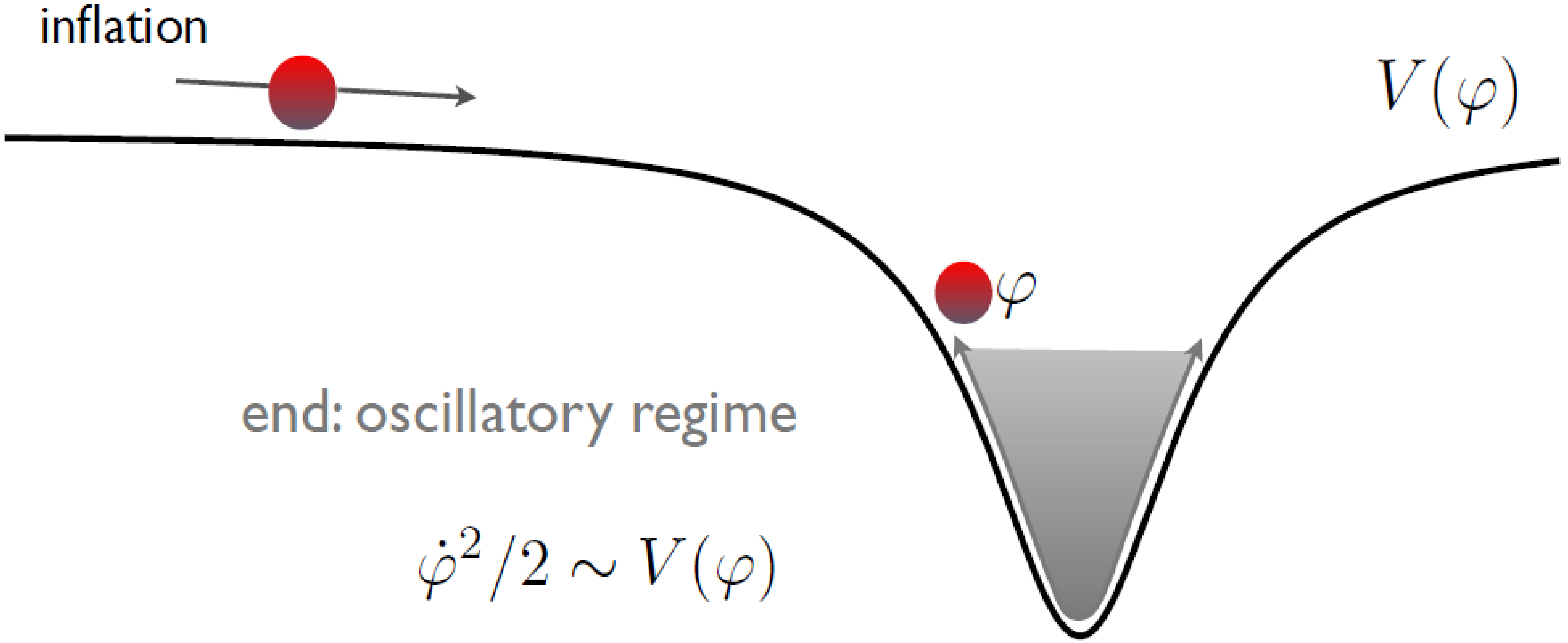
To fully enjoy the successes of the inflationary paradigm we need to understand how it ends and smoothly transitions to the Hot Big Bang

we need $\ddot{a}(t) > 0$ for 60 e-folds ➡ dilution of any matter by e^{-60} (a.k.a 0)

End of inflation

$$\frac{\ddot{a}}{a} = -\frac{1}{3m_{\mathrm{pl}}^2}(\dot{\varphi}^2 - V(\varphi)) < 0$$

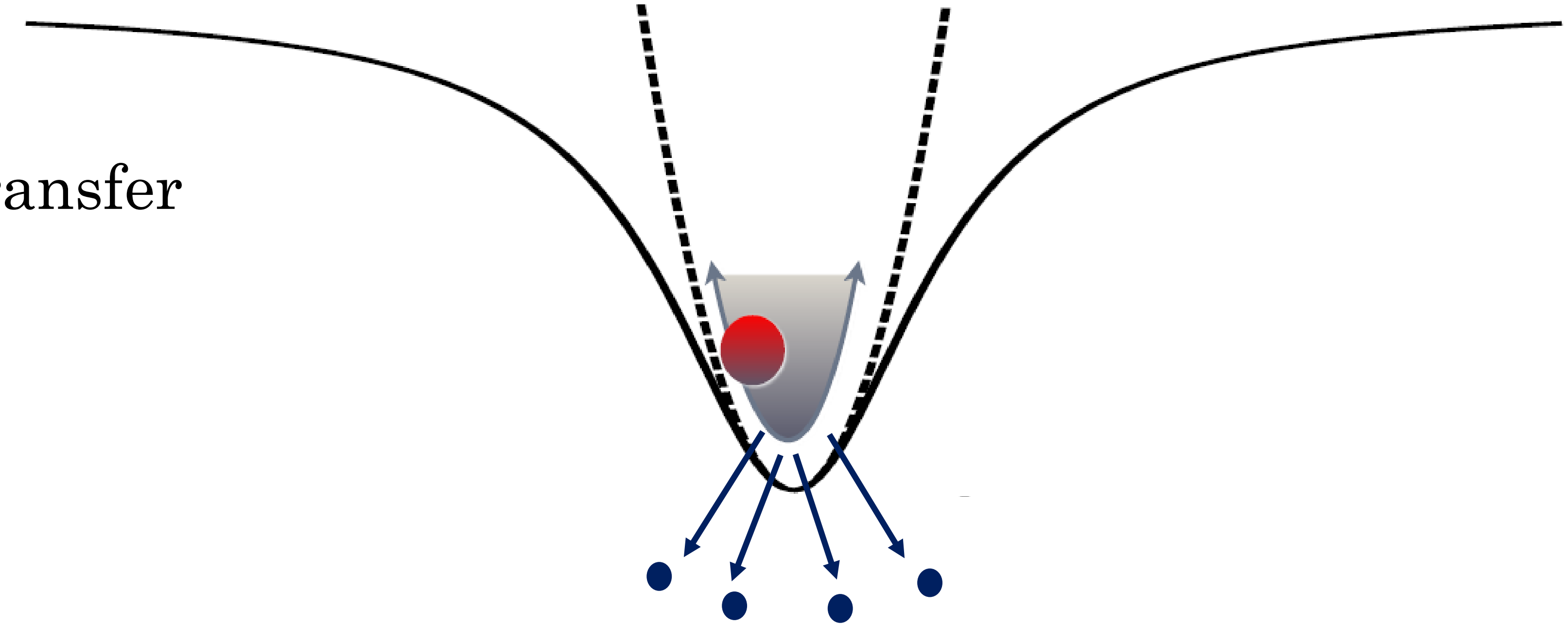
➡ Deceleratinging FLRW expansion! (Nice)



Energy Transfer: Reheating

The nature of the energy transfer process depends on:

- Shape of the potential
- Couplings to other fields



Particle production

$\chi\,,\psi$

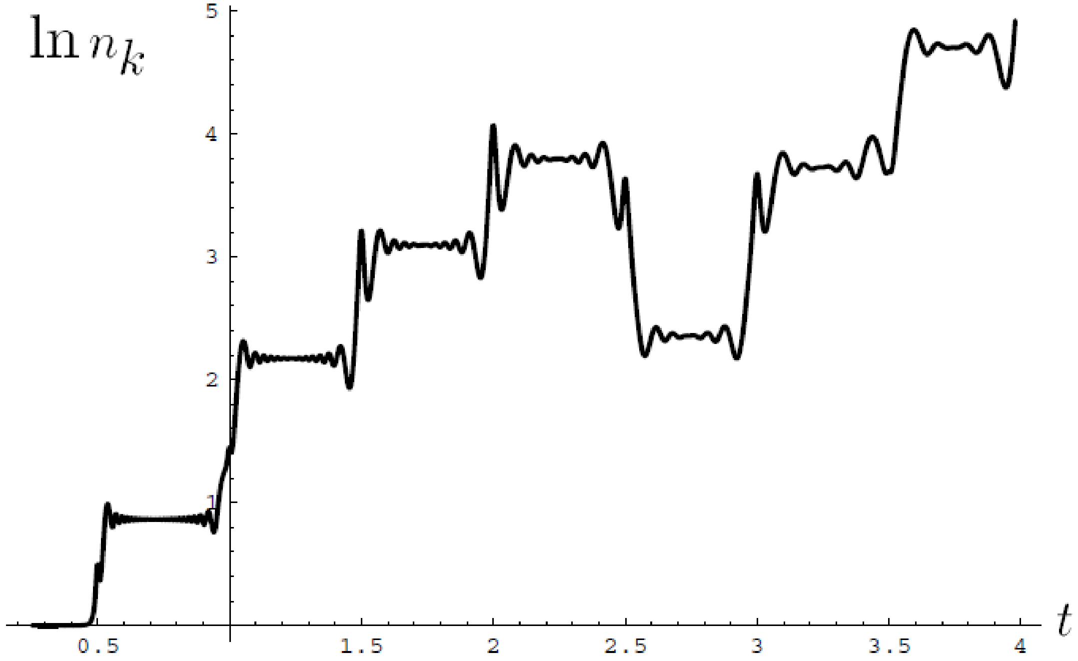
Reheating

An example:

$$V(\phi,\chi) = \frac{1}{2} m_\varphi^2 \varphi^2 + \frac{g^2}{2}\varphi^2\chi^2$$

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

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



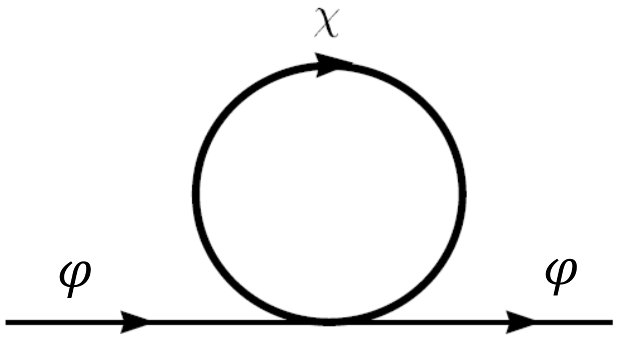
Reheating vs Inflation

Couplings we wrote down to study reheating do not appear in the picture suddenly, they should be present during inflation as well:

Conflict between reheating vs Inflation

Efficient reheating with parametric resonance requires ➡ $g \gg 10^{-5}$

Loops of daughter fields during inflation: $\Delta m_\phi^2 \sim g^2 \Lambda_{uv}^2 < m_\phi^2$ ➡ $g < 10^{-5}$



An EFT approach ?

An EFT approach:

$$\mathcal{L}_m = -\frac{1}{2} f\left(\frac{\chi}{\Lambda}\right) \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - U(\chi)$$

*Assassi et al.
*Armendariz-Picon et al.

$$\phi \to \phi + c \quad \Longrightarrow \quad f\left(\frac{\chi}{\Lambda}\right) = 1 + 2c_3 \frac{\chi}{\Lambda} + 2c_4 \left(\frac{\chi}{\Lambda}\right)^2$$

Issue to deal with: we must stabilize background χ_0

$$\ddot{\chi}_0 + 3H\dot{\chi}_0 + \partial_\chi U = \boxed{\frac{\dot{\phi}_0^2}{\Lambda^2}\chi_0 + \frac{\dot{\phi}_0^2}{\Lambda}}$$

← Source terms

An EFT approach ?

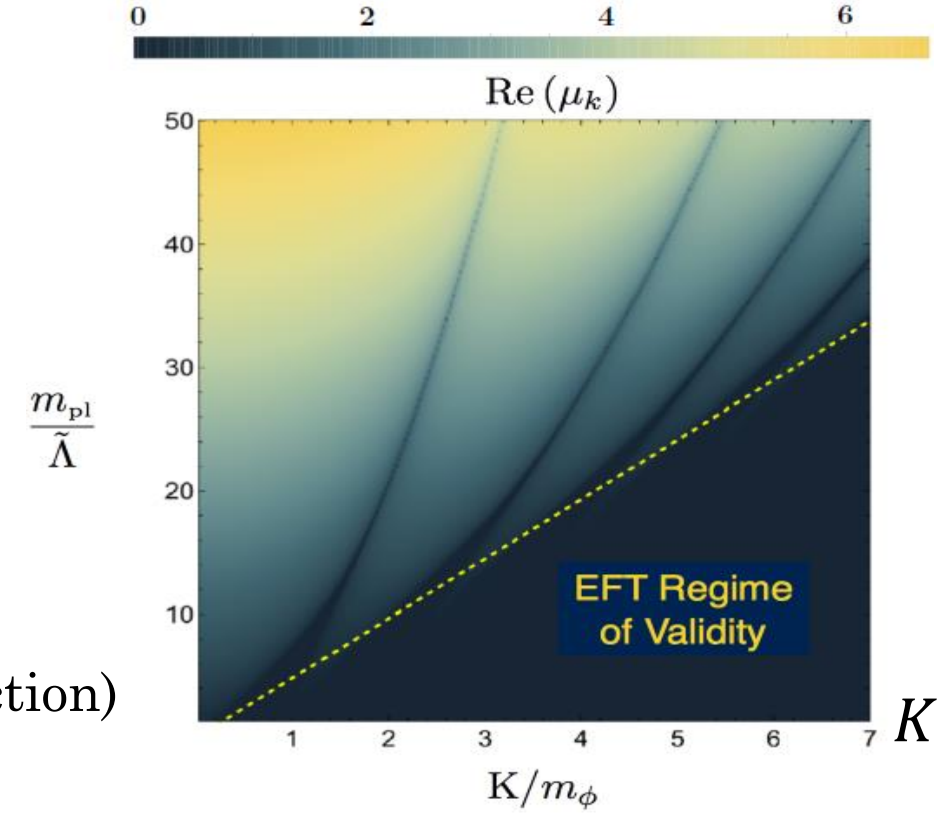
$$U_{eff} = \frac{1}{2} m_\chi^2 \chi^2 - \frac{1}{2}\frac{\dot{\phi}_0^2}{\Lambda^2}\chi^2 - \frac{\dot{\phi}_0^2}{\Lambda}\chi \quad \Rightarrow \quad \frac{\chi_0}{\Lambda} < 1 \quad \Rightarrow \quad \boxed{\frac{m_\phi}{m_\chi} < \frac{\Lambda}{M_{pl}}}$$

Fluctuations:

$$\delta\ddot{\chi}_k + \left[k^2 + m_\chi^2 - \frac{\dot{\phi}_0^2}{\Lambda^2}\right]\delta\chi_k = 0$$

$$\boxed{\delta\chi_k \sim e^{\mu_k t}}$$

Certain wave-numbers grow (Particle Production)



$$K = \sqrt{k^2 + m_\chi^2}$$

New EFT approach

Alternative Approach:

Take the background evolution as a priori $\{\ a(t), H(t), \dot{H}(t), \ldots\}$, e.g. $\ddot{a}(t) < 0$

Write down the most general EFT for fluctuations around this background.

It is customary to use symmetries as a guidance for constructing the EFT.

Observation:

Background FRW evolution ➡ time re-parametrizations are broken !

Use the left-over symmetries to build EFT ➡ $x^i \to x^i + \xi^i(x)$

New EFT approach

$$S = \int d^4x \sqrt{-g} \left[\frac{m_{\rm pl}^2}{2} R - f_1(t) - f_2(t) g^{00} + F^{(2)}(\delta g^{00}, \chi, \delta R_{\mu\nu\rho\sigma}, \delta K_{\mu\nu}; \nabla_\mu; t) \right]$$

background evolution fixes ➡ $f_1(t) = m_{pl}^2(3H^2 + \dot{H})$, $f_2(t) = -m_{pl}^2 \dot{H}$

(the only linear terms in fluctuations)

One scalar mode π is hidden in $g^{00} = -1 + \delta g^{00}$. It can be re-introduced by $t \to t + \pi$

$F^{(2)}(\dots)$ is an expansion in fluctuations and their derivatives:

δg^{00}: 0 derivative, $\delta K_{\mu\nu}$ contains a single derivative of the metric, etc..

*Cheung et al.

$$S_{\rm g} = \int {\rm d}^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - m_{\rm pl}^2\left(3H^2(t)+\dot{H}(t)\right) + m_{\rm pl}^2\dot{H}(t)g^{00} + \frac{m_2^4(t)}{2!}\left(\delta g^{00}\right)^2 + \dots\right]$$

$$S_\chi = \int {\rm d}^4x\sqrt{-g}\left[-\frac{\alpha_1(t)}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi + \frac{\alpha_2(t)}{2}(\partial^0\chi)^2 - \frac{\alpha_3(t)}{2}\chi^2 + \text{censorable}\right]$$

Capturing existing models: $\alpha_1 = 1,\ \alpha_2 = 0,\ m_2 = 0$ and notice that

$m_{pl}^2(3H^2+\dot{H}) \equiv V(\varphi)$ ➡ $\alpha_3 \propto \left(m_{pl}^2(3H^2+\dot{H})\right)^p$ to capture $g^2\Lambda^{4-m-n}\,\varphi^m\chi^n$

Background parametrization:

$$H(t) = H_{\rm FRW}(t) + H_{\rm osc}(t)P(\omega t)$$

$$\omega \gg H(t)$$

$$H(t) = H_{\rm FRW}(t) - \frac{3H_{\rm FRW}(t)^2}{4m_\phi}\sin(2m_\phi t)$$

$$m_\phi \gg H(t)$$

New class of models

$$S_\chi = \int d^4x\sqrt{-g}\left[-\frac{\alpha_1(t)}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi + \frac{\alpha_2(t)}{2}(\partial^0\chi)^2 - \frac{\alpha_3(t)}{2}\chi^2 + \text{still censorable}\right]$$

$c_\chi^2 = \alpha_1/(\alpha_1+\alpha_2)$ ➡ Non-trivial sound speed, $c_\chi \neq 1$.

$$\ddot{\tilde{\chi}}_c^k + \left[c_\chi^2\frac{k^2}{a^2} + \underbrace{M^2F(\omega t)}_{\alpha_3(t)}\right]\tilde{\chi}_c^k = 0$$

$$k_*^2 \equiv \frac{M\omega}{c_\chi^2} \gtrsim \frac{k^2}{a^2}$$

broader bands compared to $c_\chi = 1$

$n_\chi(t) \sim \frac{(M\omega)^{3/2}}{c_\chi^3} e^{2\mu\omega t}$ ➡ Number of particles are enhanced due to sound speed, $c_\chi < 1$.

Gravitational Waves

$$h''_{ij} + \left(k^2 - \frac{a''}{a}\right) h_{ij} = M_{pl}^{-2} \, T_{ij}^{TT}$$

$$\Omega_{\rm gw} \sim \frac{(M\omega)^{3/2}}{c_\chi^3 \, H^4} \frac{k^3}{M_{pl}^2} \times$$ censorable

→ Scattering of produced particles leads to GW background: Also amplified via small sound speed.

$$f \approx \frac{(M\omega)^{1/2}}{a_* H_* \, c_\chi} \; 4 \times 10^{10} Hz$$

→ Oops, peak frequency also increases ☹

Conclusions/Outlook

Direct approach EFT of fluctuations: Adequate to capture all existing models in the literature.

Guided by the symmetries we have found new models with non-trivial sound speed, $c_\chi \neq 1$.

Amplifications of GW's during the linear stage of parametric resonance by $c_\chi \neq 1$

Non-linear stage is crucial in setting up the final amplitude of GW's.
Therefore it would be good to check our analytic estimates by Lattice simulations to determine if one can amplify GW's significantly.

Cheat Sheet

Preferred time slicing:

$$t \to t + \xi^0(x), \qquad \text{under which} \qquad \delta\phi(x) \to \delta\phi(x) - \dot{\phi}_0(t)\xi^o(x),$$

fix the “gauge” by $\xi^o(x) = \delta\phi(x)/\dot{\phi}_0(t)$ to set $\delta\phi(x) = 0$

$$\omega_\chi^2 \simeq c_\chi^2 \frac{k^2}{a^2} + \frac{1}{2} M^2 \omega^2 (t - t_j)^2$$

Particle production when ω_χ^2 is at its minimum

$$\frac{\mathrm{d}^2 \widetilde{\chi}_c^k}{\mathrm{d}\tau^2} + \left(\kappa^2 + \tau^2\right) \widetilde{\chi}_c^k = 0$$

1-D Scattering Problem from a parabolic potential

Cheat Sheet

$$\bar{h}_{ij}(\mathbf{k},\tau) = \frac{2}{M_{\rm pl}^2} \int d\tau' \; G_k(\tau,\tau') \; a(\tau') \; T_{ij}^{TT}(\mathbf{k},\tau')$$