# Inflaton Fragmentation during Preheating : Formation & Decay of Oscillons

**NEHOP 2024 @ Edinburgh**


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(With **Ed Copeland, R Mahbub, Md Shafi** & **S Basak**)


**$20^{\text{th}}$ June 2024**

# Introductory Lecture Notes [arXiv:2403.10606]

## Cosmic Inflation: Background dynamics, Quantum fluctuations and Reheating

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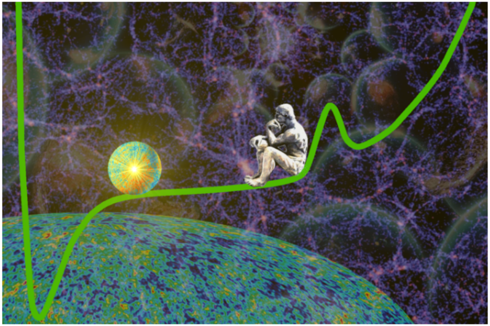
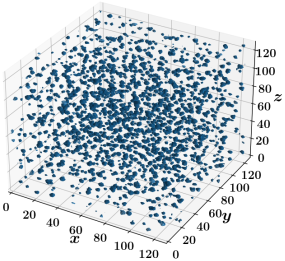
arXiv:2403.10606v1 [gr-qc] 15 Mar 2024



# PBH Formation Mechanisms

1. Collapse of large (iso-)curvature fluctuations
2. Topological Defects
3. First-order phase transitions
4. **Scalar field fragmentation**

$$mt = 600,\ \frac{\delta\tilde{\rho}_{\tilde{\varphi}}}{\tilde{\rho}} = 4$$




**Inflaton Fragmentation during preheating**

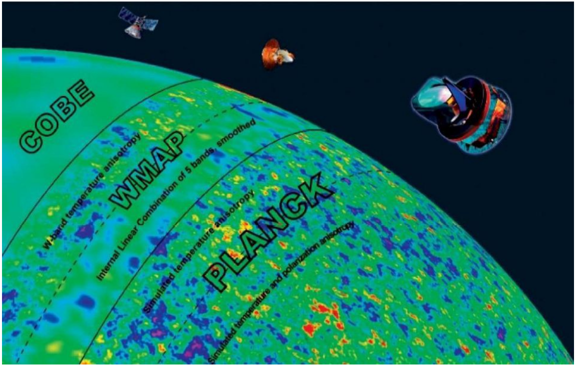
(**CAVEAT: Not as Generic as often loosely claimed!**)

Talks by **V. Takhistov** (Monday), **P. Serpico** (Tuesday)

# Best Probes of the Early Universe

**Cosmic Microwave Background (CMB) Radiation**

**+ BBN + LSS + BAO**



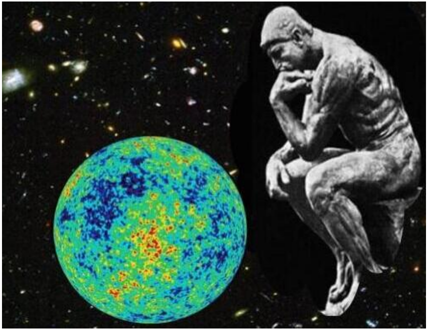

1. **What is the origin of the constituents of the plasma?**
2. **What is the origin of the fluctuations in the plasma?**

# Part-I: Primordial Fluctuations

# (Quantum) Initial conditions for structure

**Initial** $\boldsymbol{\zeta(\vec{x})} \longrightarrow$ **CMB** $\longrightarrow$ **LSS** (gravitational instability)

**Properties of initial fluctuations:**



1. **Adiabatic** $\zeta(\vec{x})$
2. Almost **scale-invariant**

$$\boxed{\mathcal{P}_\zeta = A_S \left(\frac{k}{k_*}\right)^{n_S - 1}} \; k_* = 0.05\,\mathrm{Mpc}^{-1}$$

$$A_S \simeq 2 \times 10^{-9}\,, \;\; n_S - 1 \simeq -0.035$$

3. Nearly **Gaussian** $(\sigma \simeq 10^{-4})$

$$\boxed{P[\zeta] = \mathcal{B} \exp\left[\frac{-\zeta^2}{2\sigma^2}\left(1 + f_{\mathrm{NL}}\,\zeta + ...\right)\right]}$$

$\rightarrow$ **LSS, CMB $\Rightarrow$ Large-scale primordial fluctuations**

$\rightarrow$ **Origin $\Rightarrow$ Quantum fluctuations during Inflation**

# Cosmic Inflation

$$\boxed{\textbf{System} = \textbf{Gravity}\ (g_{\mu\nu}) + \textbf{Scalar Field}\ (\varphi)}$$

$$S[g_{\mu\nu}, \boldsymbol{\varphi}] = \int \mathrm{d}^4x\, \sqrt{-g}\, \left( \frac{m_p^2}{2}\, R - \frac{1}{2}\, \partial_\mu \boldsymbol{\varphi}\, \partial_\nu \boldsymbol{\varphi}\, g^{\mu\nu} - \boldsymbol{V}(\boldsymbol{\varphi}) + \ldots \right)$$

**(1) Background Evolution/Dynamics** $\phi(t)$ **: qdS Expansion**

$$\ddot{a} > 0\ ,; \qquad \boldsymbol{a_{\mathrm{end}} = a_i\, e^{\Delta N}}\ , \qquad \boldsymbol{\Delta N > 60}$$

(Makes the universe isotropic, uniform and flat)

**(2) Linear Perturbations: Two light fields** $(\boldsymbol{m \ll H})$

$$\mathrm{d}s^2\ =\ -\beta^2(t)\, \mathrm{d}t^2\ +\ a^2(t)\, \left[ \left( e^{2\boldsymbol{\Psi}(t,\vec{x})}\, \delta_{ij} + 2\, \boldsymbol{h_{ij}}(t,\vec{x}) \right) \mathrm{d}x^i \mathrm{d}x^j \right]$$

$\rightarrow$ **Comoving Curvature Perturbations:** $-\boldsymbol{\zeta}(t,\vec{x}) = \boldsymbol{\Psi} + \frac{\boldsymbol{H}}{\dot{\phi}}\, \delta\varphi$

(Induce **CMB density and temperature fluctuations**)

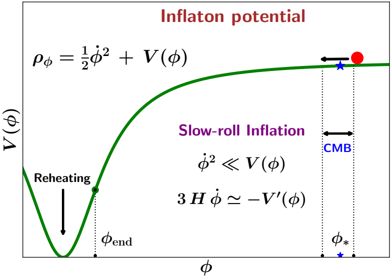
$\rightarrow$ **Transverse & traceless Tensor Perturbations:** $\boldsymbol{h_{ij}}(t,\vec{x})$

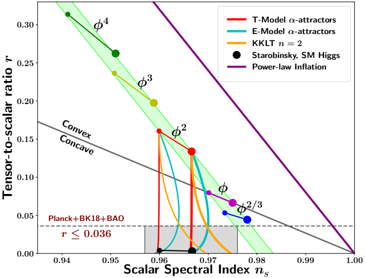
(Induce **stochastic Gravitational Waves**)

# Observational Constraints: Single field slow-roll Inflation

Scalar tilt $\boxed{n_S - 1 = -\epsilon_2 - 2\,\epsilon_1} \in [-0.043, -0.024]$ (red tilt)

Tensor-to-scalar ratio : $\boxed{r = \frac{A_T}{A_S} = 16\,\epsilon_1} \leq 0.036$ (low)




$\Rightarrow$ Single-field slow-roll paradigm of Inflation &

Asymptotically flat concave potentials!

**PLANCK Inflation (2018); **BICEP/Keck (2021); **SSM & Sahni(2022)

# What happened to other fields during inflation?

- Observations favour '**single-field slow-roll**' inflation.
- '**Cold inflationary paradigm**:'

  $\Rightarrow$ Negligible coupling to external fields $\frac{1}{2}g^2\varphi^2\chi^2$, $h\varphi\psi\bar{\psi}$

$$S[\varphi,\chi] = -\int \mathrm{d}^4x\,\sqrt{-g}\,\Big[\;\frac{1}{2}\,\partial_\mu\varphi\,\partial^\nu\varphi + V(\varphi) + \frac{1}{2}\,\partial_\mu\chi\,\partial^\nu\chi + \frac{1}{2}\,m_{0\chi}^2\,\chi^2$$
$$+\;\bar{\psi}\,(i\gamma^\mu\partial_\mu + m_{0\psi})\,\psi$$
$$+\;\cancelto{0}{\frac{1}{2}\,g^2\,\varphi^2\,\chi^2} + \cancelto{0}{h\,\psi\bar{\psi}\,\varphi} + \ldots\Big]$$

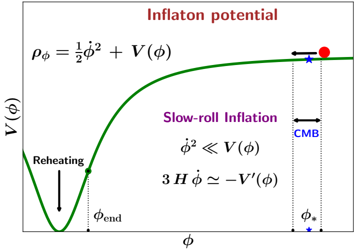
$$\boxed{\boldsymbol{g^2,\,h\;\ll\;1}}$$

$\Rightarrow$ **particle production during inflation can be neglected**.

- **Effects of the small coupling?**
  1. **Primordial Non-Gaussianity**: inflaton interactions.
  2. Decay of the inflaton field: **Reheating the universe**.

# Part-II : Post-inflationary Dynamics of the Inflaton condensate

# Post-inflationary Oscillations




Potential near minimum $\phi < \phi_e$,

$$\boxed{V(\phi) \simeq \frac{1}{2}m^2\phi^2 \pm \frac{\mu}{3}\phi^3 \pm \frac{\lambda}{4}\phi^4 + \ldots}$$

For a quadratic potential $V(\phi) \propto \phi^2$

$$\boxed{\langle w_\phi \rangle = 0 \;\Rightarrow\; \rho_\phi \propto a^{-3}}$$

$\Rightarrow$ **Inflaton behaves like Matter**

Since $m > H \quad \Rightarrow \quad T_{\rm osc} < H^{-1}$

Under **adiabatic approximation**

$$\boxed{\phi(t) = \phi_0(t)\,\cos(mt)}\;;$$

with **amplitude** $\phi_0(t) \propto \frac{1}{t}$

$\rightarrow$ *SR Inflation:* **Friction dominated**

$$\Rightarrow m^2 \equiv V_{,\phi\phi} \ll H^2$$

$\rightarrow$ *After inflation:* $m^2 \geq H^2$

$\rightarrow$ When $m^2 \gg H^2$, inflaton exhibits **Coherent Oscillations** for which

$$\Rightarrow \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \simeq \textbf{const.}$$

However, we have ignored **two important effects**:

$\rightarrow$ **External coupling:** (to other fields $\chi$, $\psi$)

$$\mathcal{I}(\varphi, \chi) = \frac{1}{2} g^2 \varphi^2 \chi^2$$

$\rightarrow$ **Asymptotically flat potentials:** **(CMB observations)**

$$V(\phi) = V_0 \left(\frac{\phi}{m_p}\right)^{2n} - |U(\lambda;\, \phi)|$$

have '**attractive self-interaction**'

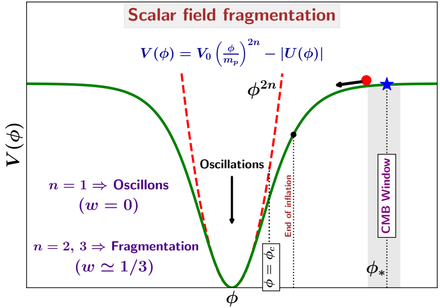
$\Rightarrow$ **Self – resonance** (due to $\boldsymbol{\lambda}$)

$\Rightarrow$ Rapid Growth of $\boldsymbol{\delta\varphi}$

$\Rightarrow$ **Scalar field fragmentation**

$\Rightarrow$ **Cosmological Solitons :**

'**Oscillons**'




**Amin *et. al* & Lozanov *et. al* (2010-2020)

# Existence of quasi-Solitons: Oscillons

→ **Self-supported, localised, long-lived non-linear 'solitary' configurations**.

→ **Solitons are ubiquitous in nature**!

(**1834 J. S. Russell: solitary wave in a canal in 'Edinburgh'!**)

(Appearing in fluids, smoke rings, condensed matter physics, optics, HEP, topological defects and Cosmology.)

→ **Oscillons are oscillating non-topological solitons**!

→ **Analytical results** based on **small-amplitude oscillations**

$$V(\varphi) \approx \frac{1}{2}\, m^2 \varphi^2 - \frac{\lambda}{4}\, \varphi^4 + \frac{g}{6}\, \varphi^6$$

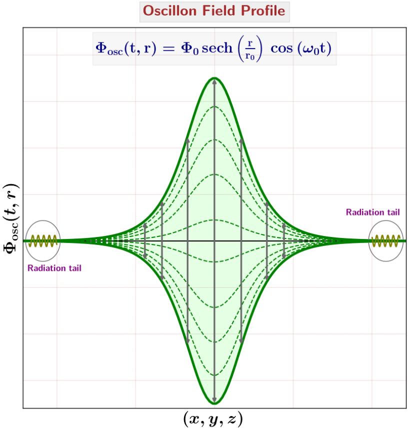
→ Supports **Oscillon-like solution** of the form

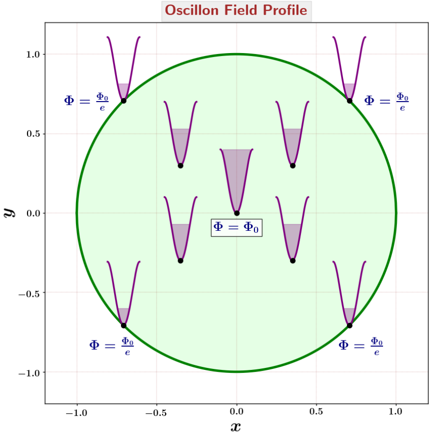
$$\boldsymbol{\varphi_{\rm osc}(t, r) \approx \Phi(r) \cos\left(\omega_0\, t\right) + \ldots}\,; \qquad \boxed{\boldsymbol{\Phi(r) \approx \Phi_0\, \mathrm{sech}\left(\frac{r}{r_0}\right)}}$$

****Rajaraman(1987), **Gleiser *et. al*; **Amin *et. al* ; **Mahbub, SSM (2023)**

## Oscillon Profile

$$\boxed{\Phi(t,r) \approx \phi_0 \ \mathrm{sech}\left(\frac{r}{r_0}\right) \cos\left(\omega_0 t\right)}$$




**Interesting compact (non-linear) field configurations !**

# Existence of Oscillons ?

1. **Oscillons exit as analytic (stationary) solutions**

   (of post-inflationary oscillations around asymptotically flat potentials)

   **(a) For symmetric plateau potentials:**

   → **small-amplitude oscillations**

$$V(\varphi) \approx \frac{1}{2}\, m^2 \boldsymbol{\varphi}^2 - \frac{\lambda}{4}\, \mu\, \boldsymbol{\varphi}^4 + \frac{g}{6}\, \lambda\, \boldsymbol{\varphi}^6$$

   → Supports **Oscillon-like solution** of the form

$$\Phi(t, r) = \phi_0\ \mathbf{sech}\left(\frac{r}{r_0}\right)\ \mathbf{cos}\left(\omega_0 t\right)$$

   **(b) For asymmetric plateau potentials?**

$$V(\varphi) \approx \frac{1}{2}\, m^2 \boldsymbol{\varphi}^2 - \frac{1}{3}\, \mu\, \boldsymbol{\varphi}^3 + \frac{1}{4}\, \lambda\, \boldsymbol{\varphi}^4$$

2. **Can they form dynamically?**

   (starting from **natural conditions at the end of inflation**)

***Copeland *et. al*(1995); *Amin *et. al*(2011); *Mahbub, SSM(2023); *Kim, McDonald**

# Self-resonance and inflaton fragmentation

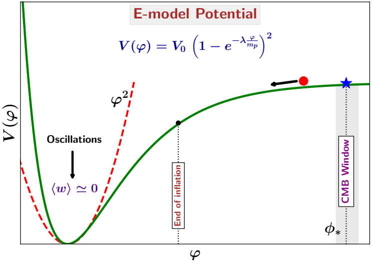
In the linear regime, Fourier mode functions satisfy

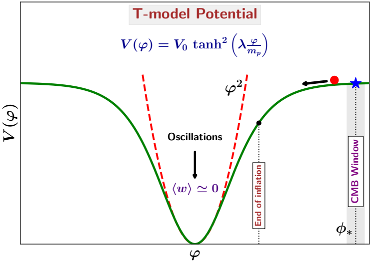
$$\boxed{\delta\ddot{\varphi}_k + 3H\delta\dot{\varphi}_k + \left[\frac{k^2}{a^2} + V_{,\phi\phi}(\phi)\right]\delta\varphi_k = 0}$$

(Equation of a **damped parametric oscillator**)

$\Rightarrow$ **Resonant growth** of inflaton fluctuations $\delta\varphi_k(t) \propto e^{\mu_k m t}$

$$V(\phi) = \frac{1}{2}m^2\phi^2 - |U(\lambda;\,\phi)| \quad \text{(E-Model \& T-Model)}$$




**Lozanov, Amin(2017); **Shafi, Copeland, Mahbub, SSM, Basak (2024)

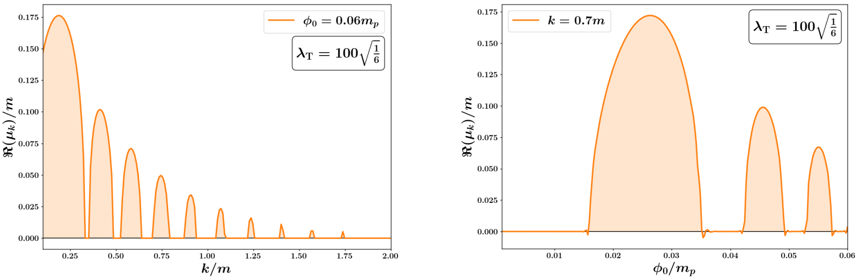
# Linear Parametric Self-resonance

**Equation of a linear parametric oscillator**

$$\boxed{\frac{\mathrm{d}^2\delta\varphi_k}{\mathrm{d}T^2} + \Omega^2_\varphi(k,T)\,\delta\varphi_k = 0}\;; \quad \Omega^2_\varphi \text{ is oscillatory in T}$$

**Floquet Theorem** $\boxed{\delta\varphi_k(T) = \mathcal{M}_k^{(+)}(T)e^{\mu_k T} + \mathcal{M}_k^{(-)}(T)e^{-\mu_k T}}$

$\Rightarrow$ **Exponentially growing** for $\mathbf{Re}(\mu_k) \neq 0$ (**in resonance bands**)




**SSM Lecture Notes (2024)

**Non-thermal particle production**

# Part-III : Non-linear Dynamics
# & Lattice Simulations

# Non-linear dynamics: $\mathcal{C}$osmo$\mathcal{L}$attice

Fully non-linear (dimensionless version of) field equations

$$\ddot{\tilde{\varphi}} + 3\tilde{H}\dot{\tilde{\varphi}} - \frac{\widetilde{\nabla}^2}{a^2}\tilde{\varphi} + \widetilde{V}_{,\tilde{\varphi}} = 0$$

$$\tilde{H} \equiv \frac{\dot{a}}{a} = \frac{1}{3m_p^2}\left\langle \widetilde{K}_{\tilde{\varphi}} + \widetilde{G}_{\tilde{\varphi}} + \widetilde{V}(\tilde{\varphi}) \right\rangle$$

Where $\tilde{t} = m\,t$ ; $\tilde{x} = m\,x$ ; $\tilde{\varphi}, \tilde{\chi} = \frac{1}{\beta}\,\frac{\varphi, \chi}{m_p}$ ; $\tilde{F} = \frac{F}{\beta^2 m^2 m_p^2}$

$$\widetilde{K}_{\tilde{\varphi}} = \frac{1}{2}\left(\frac{\partial\tilde{\varphi}}{\partial\tilde{t}}\right)^2 ; \quad \widetilde{G}_{\tilde{\varphi}} = \frac{1}{2a^2(\tilde{t})}\left[\left(\frac{\partial\tilde{\varphi}}{\partial\tilde{x}}\right)^2 + \left(\frac{\partial\tilde{\varphi}}{\partial\tilde{y}}\right)^2 + \left(\frac{\partial\tilde{\varphi}}{\partial\tilde{z}}\right)^2\right]$$

$$\tilde{\rho}_{\tilde{\varphi}} = \widetilde{K}_{\tilde{\varphi}} + \widetilde{G}_{\tilde{\varphi}} + \widetilde{V}(\tilde{\varphi}); \quad \tilde{p}_{\tilde{\varphi}} = \widetilde{K}_{\tilde{\varphi}} - \frac{1}{3}\widetilde{G}_{\tilde{\varphi}} - \widetilde{V}(\tilde{\varphi})$$

**Lattice specifications:**

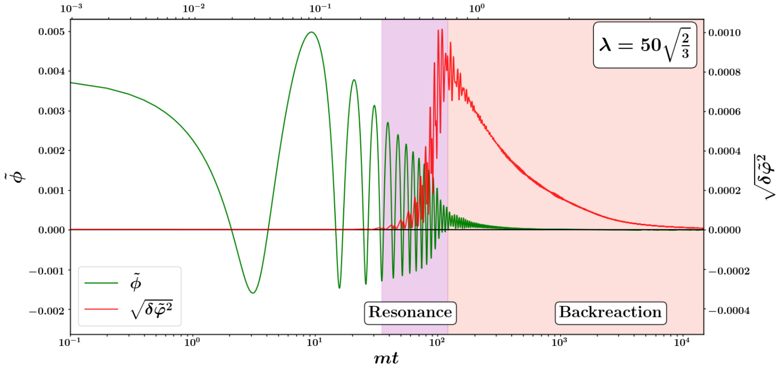
$$\boxed{N = 128^3 ; \quad 0.05\, m^{-1} \leq k \leq 5\, m^{-1}}$$

****Figueroa *et. al* (2020, 2021); **Mahbub, SSM (2023)**

# Self-resonance and Inflaton Fragmentation

**Strong self-resonance ⇒ Inflaton fragmentation**

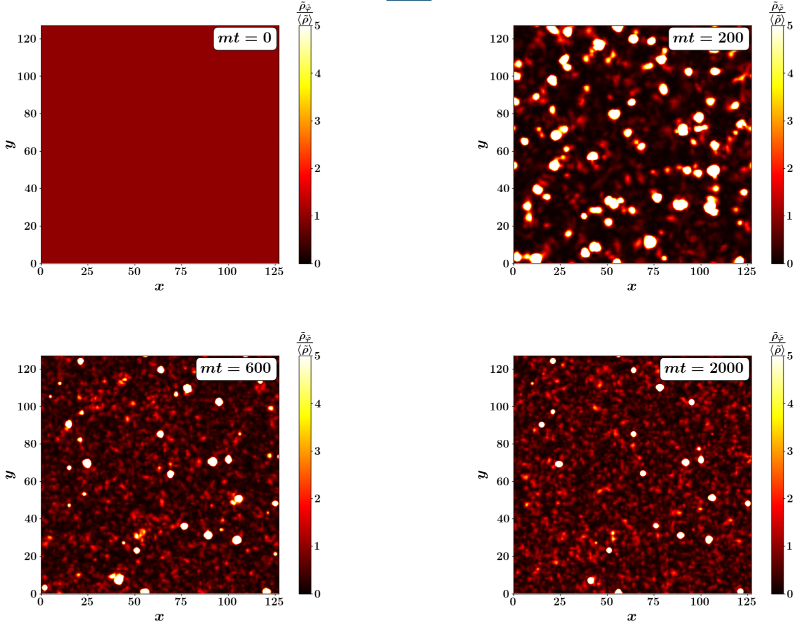
**(Asymmetric E-Model potential)**




**Inflation condensate** **Inflation fluctuations**

**Mahbub, SSM (2023); **Shafi, Copeland, Mahbub, SSM, Basak (2024)

# Oscillon formation in real time (Asymmetric)

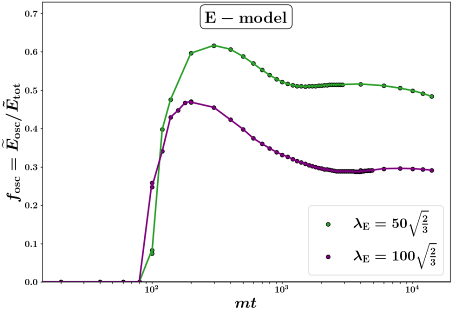


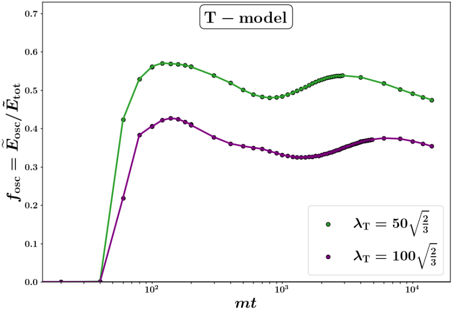
# Fractional Energy Density of Oscillons

**Energy/Mass fraction**

$$\boxed{f_{\rm osc} \equiv \frac{E_{\rm osc}}{E_{\rm tot}} = \frac{\int_{\delta\rho_\varphi \gtrsim 4\bar{\rho}_\varphi} \mathrm{d}^3\boldsymbol{x}\,\rho_\varphi(\boldsymbol{x},t)}{\int \mathrm{d}^3\boldsymbol{x}\,\rho_\varphi(\boldsymbol{x},t)}}$$

(**Fractional energy density of oscillons**)




$\gtrsim 40\%$ **of the total density** $\Rightarrow$ **Significant!**

****Mahbub, SSM (2023)**

## Conclusions (so far)

1. Oscillons form **for both Symmetric and Asymmetric plateau potentials**.
2. **Oscillons do form** after inflation in absence of external coupling starting from **generic initial conditions**.

## Important Questions

1. What is the **lifetime of oscillons**? How do they **decay?**
2. We have **ignored external coupling;** $g \to 0$

   **What happens if $g \neq 0$ ? Do oscillons form?**

**Our latest work!**

****Hertzberg (2010); **Zhang, Amin, Copeland, Saffin, Lozanov (2020)**

# (P)reheating via Oscillon decay

Prepared for submission to JCAP

## Formation and decay of oscillons after inflation in the presence of an external coupling, Part-I: Lattice simulations

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( **To appear on arXiv 2406.00108**)

# Part-IV : Oscillon Formation in presence of an External Coupling

# Dynamics of Inflaton Decay (Preheating)

$\boxed{\textbf{System :}\ \text{Inflaton}\ \varphi \ \longrightarrow\ \text{massless offspring}\ \chi}\ ;\quad \boldsymbol{m \gg m_{0\chi}}$

Described by the **action**

$$\boxed{\boldsymbol{S[\varphi,\chi] = -\int \mathrm{d}^4x\,\sqrt{-g}\left[\frac{1}{2}\,\partial_\mu\varphi\partial^\nu\varphi + V(\varphi) + \frac{1}{2}\,\partial_\mu\chi\partial^\nu\chi + \mathcal{I}(\varphi,\chi)\right]}}$$

With interaction $\boldsymbol{\mathcal{I}(\phi,\,\chi) = \frac{1}{2}g^2\varphi^2\chi^2}$

The corresponding **field equations** are

$$\ddot{\varphi} - \frac{\nabla^2}{a^2}\varphi + 3H\dot{\varphi} + V_{,\varphi} + \mathcal{I}_{,\varphi} = 0$$

$$\ddot{\chi} - \frac{\nabla^2}{a^2}\chi + 3H\dot{\chi} + \mathcal{I}_{,\chi} = 0$$

with **Hubble parameter**

$$\boxed{H^2 \;=\; \frac{1}{3\,m_p^2}\;\left[\frac{1}{2}\,\dot{\varphi}^2 + \frac{1}{2}\,\frac{\vec{\nabla}\varphi}{a}.\frac{\vec{\nabla}\varphi}{a} + V(\varphi) + \frac{1}{2}\,\dot{\chi}^2 + \frac{1}{2}\,\frac{\vec{\nabla}\chi}{a}.\frac{\vec{\nabla}\chi}{a} + \mathcal{I}(\varphi,\,\chi)\right]}\,.$$

# Preheating via Self & External Resonance

$\rightarrow$ For inflaton decay, $|\phi(t)| \gg \delta\varphi(t,\vec{x}),\ \chi(t,\vec{x})$

$$\begin{aligned} \varphi(t,\vec{x}) &= \phi(t) + \boldsymbol{\delta\varphi}(t,\vec{x}) \\ \chi(t,\vec{x}) &= \cancelto{0}{\bar{\chi}(t)} + \boldsymbol{\delta\chi}(t,\vec{x}) \quad (\boldsymbol{\chi} \ \ \textbf{field is in vacuum state}) \end{aligned}$$

$\rightarrow$ At the end of inflation, $\rho_\phi \gg \rho_\chi,\ \rho_{\delta\varphi}$ (**Condensate dominated**)

$\rightarrow$ Resulting **equations of dynamics in the linear regime**

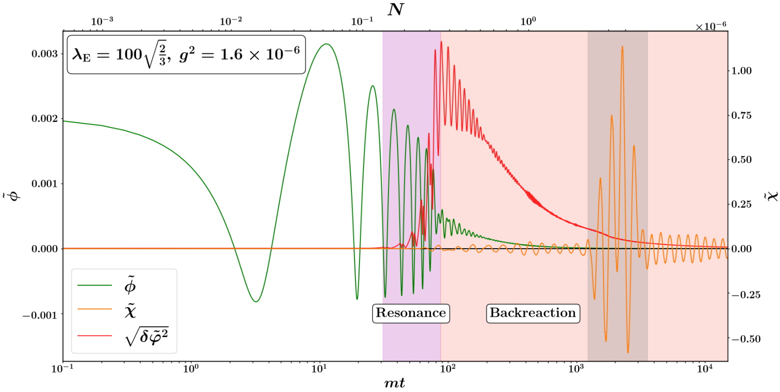
$$\begin{aligned} \ddot{\phi} + 3H\dot{\phi} + V_{,\phi}(\phi) &= 0 \\ \boldsymbol{\ddot{\delta\varphi}_k + 3H\dot{\delta\varphi}_k + \left[\frac{k^2}{a^2} + V_{,\phi\phi}(\phi)\right]\delta\varphi_k} &= 0 \quad \textbf{Self – resonance} \\ \boldsymbol{\ddot{\chi}_k + 3H\dot{\chi}_k + \left[\frac{k^2}{a^2} + g^2\,\phi^2\right]\chi_k} &= 0 \quad \textbf{External – resonance} \end{aligned}$$

and the **Hubble parameter** $H^2 \simeq \frac{1}{3\,m_p^2}\left[\frac{1}{2}\,\dot{\phi}^2 + V(\phi)\right]$

****SSM Lecture Notes (2024)**

# Self-resonance and Oscillon decay for $g \neq 0$

**Self-resonance $\rightarrow$ Oscillons $\rightarrow$ $\chi$ production**



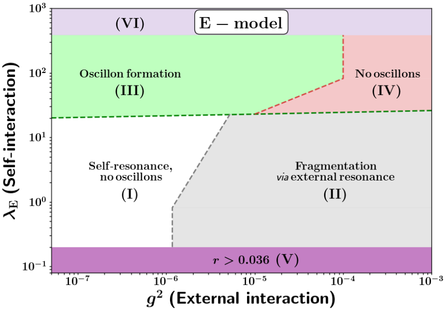

**Asymmetric E-model potential**

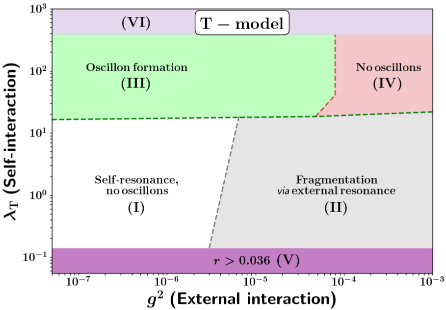
**Mahbub, SSM (2023); **Shafi, Copeland, Mahbub, SSM, Basak (2024)

# Parameter space of Oscillon formation $\{\lambda,\, g^2\}$

**External Coupling** $\boxed{\mathcal{I}(\varphi,\chi) = \frac{1}{2}\, g^2\, \varphi^2\, \chi^2}$

$$V_{\rm E}(\varphi) = V_{0\rm E}\ \left(1 - e^{-\boldsymbol{\lambda}_{\rm E}\,\frac{\varphi}{m_p}}\right)^2 \qquad\qquad V_{\rm T}(\varphi) = V_{0\rm T}\ \tanh^2\left(\boldsymbol{\lambda}_{\rm T}\,\frac{\varphi}{m_p}\right)$$



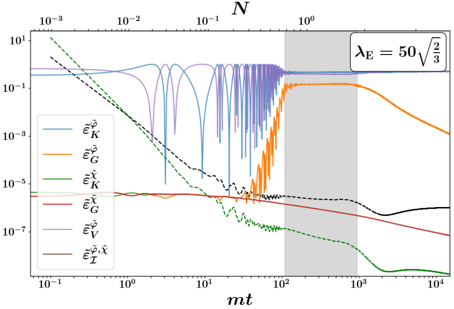




(**E-Model** $\quad \boldsymbol{\lambda}_{\rm E}\ \textit{vs}\ \boldsymbol{g^2}$) (**T-Model** $\quad \boldsymbol{\lambda}_{\rm T}\ \textit{vs}\ \boldsymbol{g^2}$)

# Evolution of energy density components

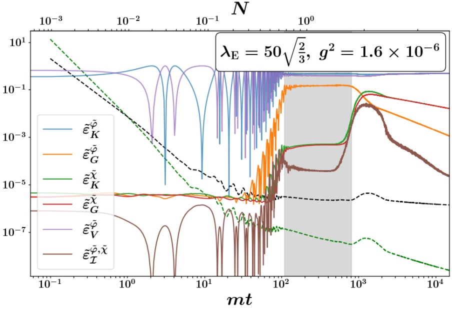
## Absence of external interaction

**Long-lived Oscillons**




## Presence of external interaction

**oscillon decay into $\chi$**

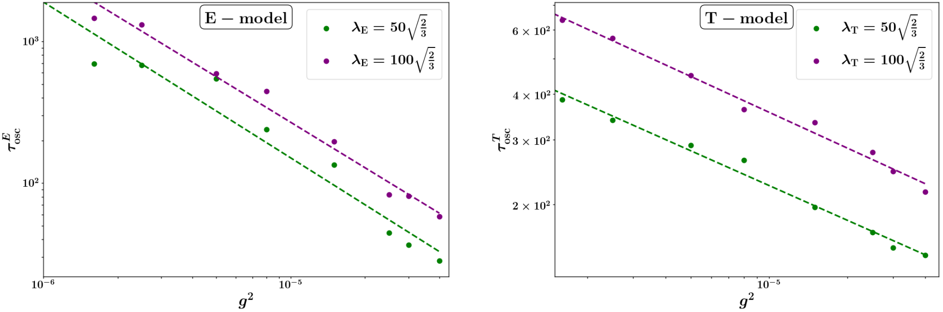



(**Production of $\chi$-particles due to oscillon decay**!)

****Shafi, Copeland, Mahbub, SSM, Basak (2024)**

# Lifetime of (a population of) Oscillons

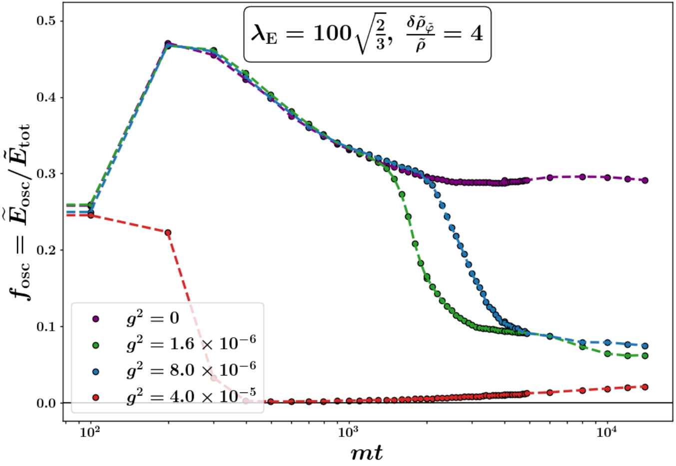
**Robust oscillons** for **Gradient term** $G_\varphi \propto a^{-3}$




**Empirically :** $\boxed{\tau^E_{osc} \propto \left(g^2\right)^{-1.1} \; ; \quad \tau^T_{osc} \propto \left(g^2\right)^{-0.3}}$

**Shafi, Copeland, Mahbub, SSM, Basak (2024)

# Energy(Mass) Fraction of Oscillons




**Reduction in $f_{\rm osc}$ due to $\chi$-production**

****Shafi, Copeland, Mahbub, SSM, Basak (2024)**

# Summary

1. **What happens if $g \neq 0$ ? Do oscillons form?**

   **YES! (Preheating via Oscillon decay into $\chi$)**

2. **Lifetime of oscillons? How does an oscillon decay?**

   **Our upcoming work (analytical)!**

**Phenomenological implications of oscillons?**

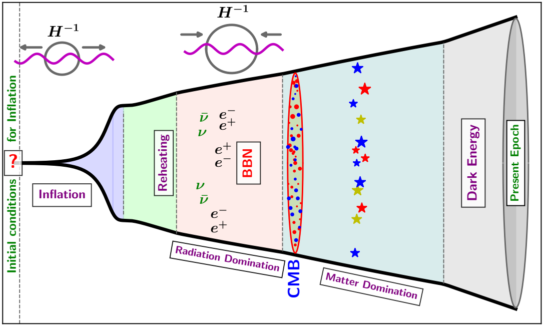
- Universal (high frequency) GWs
- Late-time Gravitational clustering and GWs
- **Primordial Black Holes (NEHOP)**
- Oscillons in scalar field (fuzzy) dark matter
- Gravitational solitons (**Oscillatons**)

**Arthur Conan Doyle conceived the idea of Sherlock Holmes in Edinburgh**

# Extra Slides

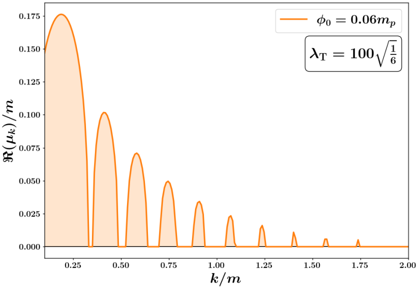
## The hot Big Bang phase:

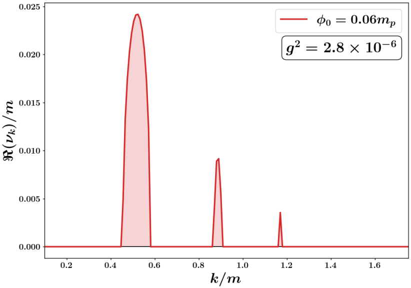
- Beginning of the Universe (×)
- End of an earlier epoch of accelerated expansion (✓)

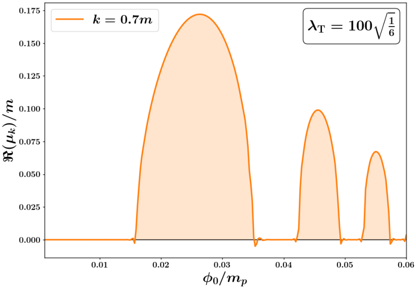


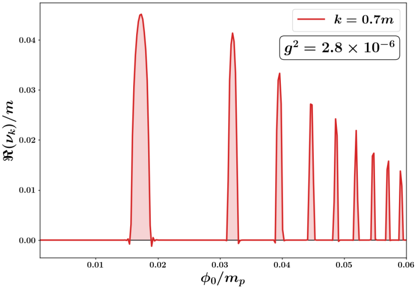

**REHEATING: Origin of all primordial matter!**

# Structure of the resonance with $\{\lambda,\, g^2\}$



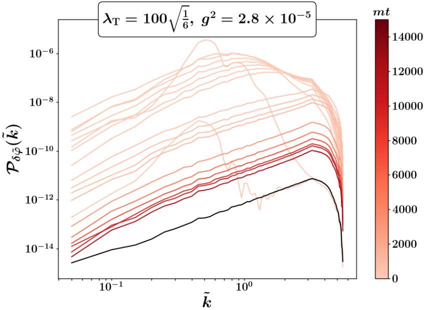



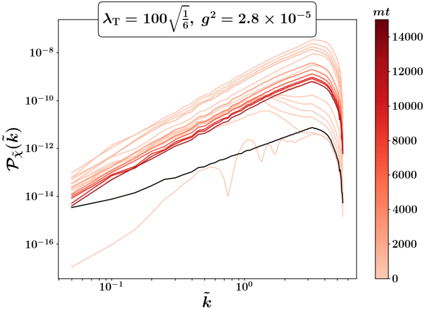



# Power spectra of fluctuations: Resonance

**Inflaton $\delta\varphi$-fluctuations**



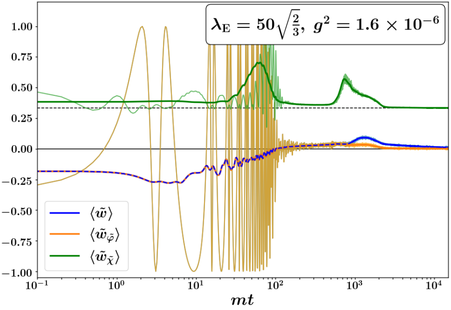

**Offspring $\chi$-fluctuations**



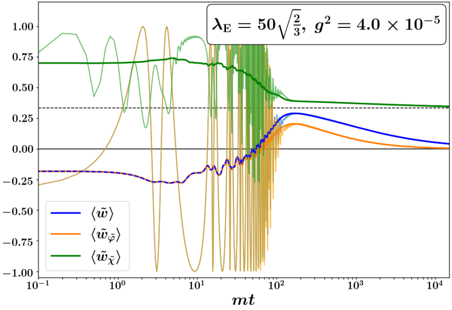

****Shafi, Copeland, Mahbub, SSM, Basak (2024)**

# Evolution of Equation of State

**Low external interaction**



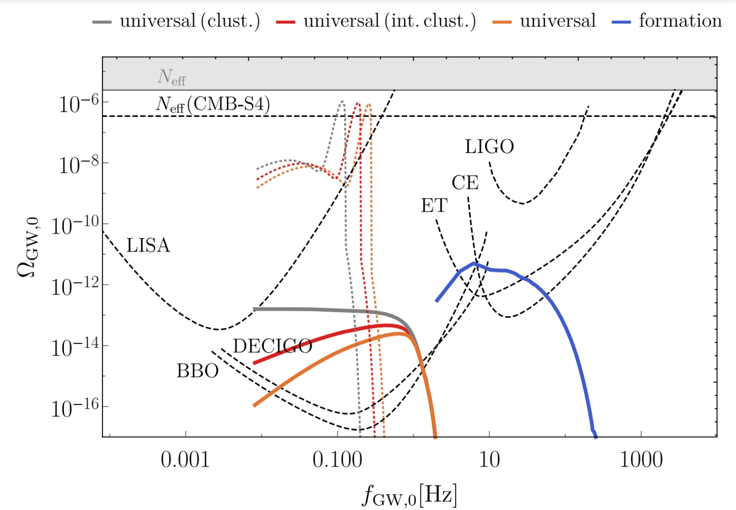

**Large external interaction**




$\langle w_\varphi \rangle \to 0$ **asymptotically**

****Shafi, Copeland, Mahbub, SSM, Basak (2024)**

# Universal Gravitational Waves




****Lozanov, Sasaki, Takhistov (2023)**

# Power-spectra: Linear Perturbation Theory

**Slow-roll** regime, $\boxed{\epsilon_1,\ \epsilon_2 \ll 1}$ **(slow terminal speed)**

with $$\boxed{\epsilon_1 = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{3m_p^2 H^2}\,; \quad \epsilon_2 = \frac{\mathrm{d}\ln\epsilon_1}{\mathrm{d}N}}$$

**Primordial power-spectrum** on **large scales** –

$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2}\left(\frac{H}{m_p}\right)^2 \frac{1}{\epsilon_1} = A_S\left(\frac{k}{k_*}\right)^{n_S - 1}$$

**Scalar spectral index**

$$\boxed{n_S - 1 = -\epsilon_2 - 2\,\epsilon_1} \ll 1$$

$$\mathcal{P}_T(k) = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2 = A_T\left(\frac{k}{k_*}\right)^{n_T}$$

**Tensor spectral index**

$$\boxed{n_T = -2\,\epsilon_1} \ll 1$$

CMB pivot scale $k_* = 0.05\ \mathrm{Mpc}^{-1}$

$\Rightarrow$ **Tiny fluctuations** that are **nearly scale-invariant**