Oscillon of Ultra-Light Axion-like Particle

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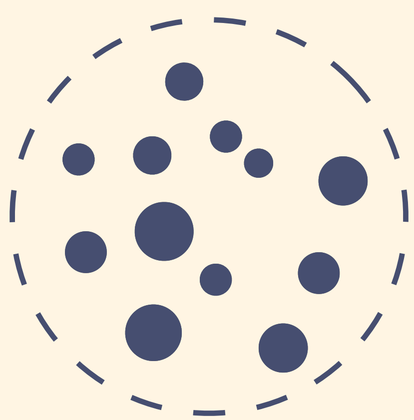
Abstract

- We focused on a local high energy clump, oscillon, of Ultra-Light Axion-like Particle (ULAP).
- We confirmed that in a ULAP potential
  - oscillon is really produced,
  - produced oscillon is very long-lived $\gtrsim 10^6$ years.



oscillon formation

$\xrightarrow{\text{survive}}$ (**ULAP constraints ?** **structure formation ?**)

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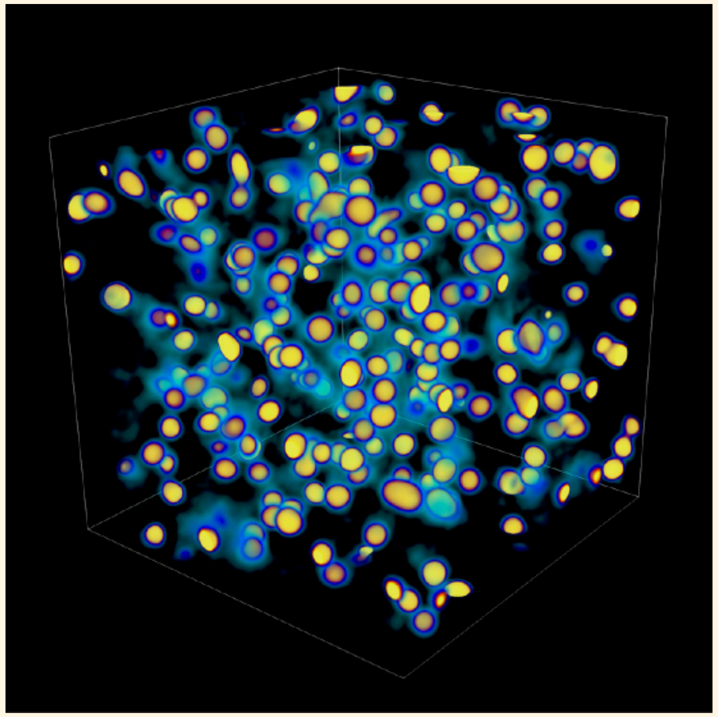
Oscillon: Introduction

- Oscillon is a pseudo soliton of a oscillating real scalar field localized by the self-interaction.
- Oscillon is defined as the minimum energy state for a given adiabatic invariant I *[S, Kasuya, et al. 2003]*

$$I \equiv \frac{1}{\omega}\int d^3x\overline{\dot{\phi}^2}. \quad \begin{pmatrix} \omega : \text{oscillating frequency} \\ \text{overline} : \text{time average} \end{pmatrix}$$



- Oscillon is meta-stable because the adiabatic invariance is only approximate.
- The lifetime of oscillon depends on its potential.

Oscillon: Formation Conditions

- With Lagrangian multiplier, we can get the oscillon profile.

$$E_\lambda = \overline{E} + \lambda \left(I - \frac{1}{\omega} \int dx^3 \overline{\dot{\phi}^2} \right),$$
$$= \frac{1}{2} \int d^3x \left[\frac{1}{2} (\nabla \Phi)^2 + V(\Phi) - \frac{1}{2} \omega^2 \Phi^2 \right] + \omega I\,.$$

where $\phi \simeq \Phi(x) \cos \omega t$ and $V(\Phi) = 2\overline{V(\phi)}$.

- Differentiating E_λ by Φ, Φ must satisfy

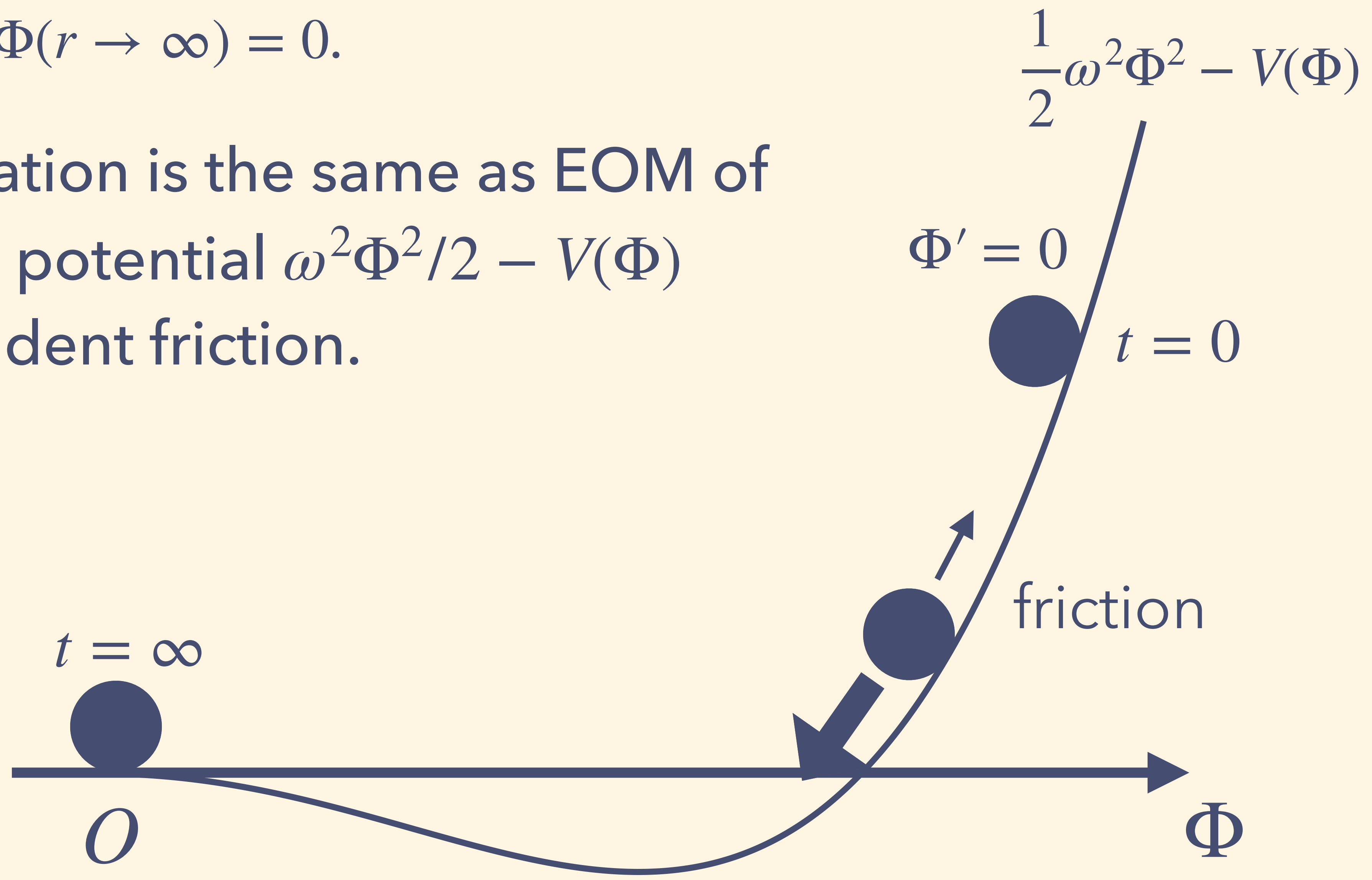
$$\frac{d^2\Phi}{dr^2} + \frac{2}{r} \frac{d\Phi}{dr} + \frac{d}{d\Phi} \left(\frac{1}{2} \omega^2 \Phi^2 - V(\Phi) \right) = 0,$$

with boundary conditions $\Phi'(r \to 0) = \Phi(r \to \infty) = 0$.

Oscillon: Formation Conditions

- Equation
$$\frac{d^2\Phi}{dr^2} + \frac{2}{r}\frac{d\Phi}{dr} + \frac{d}{d\Phi}\left(\frac{1}{2}\omega^2\Phi^2 - V(\Phi)\right) = 0,$$
with $\Phi'(r \to 0) = \Phi(r \to \infty) = 0.$

- If $r \to t$, the equation is the same as EOM of Φ moving in the potential $\omega^2\Phi^2/2 - V(\Phi)$ with time dependent friction.



Oscillon: Formation Conditions

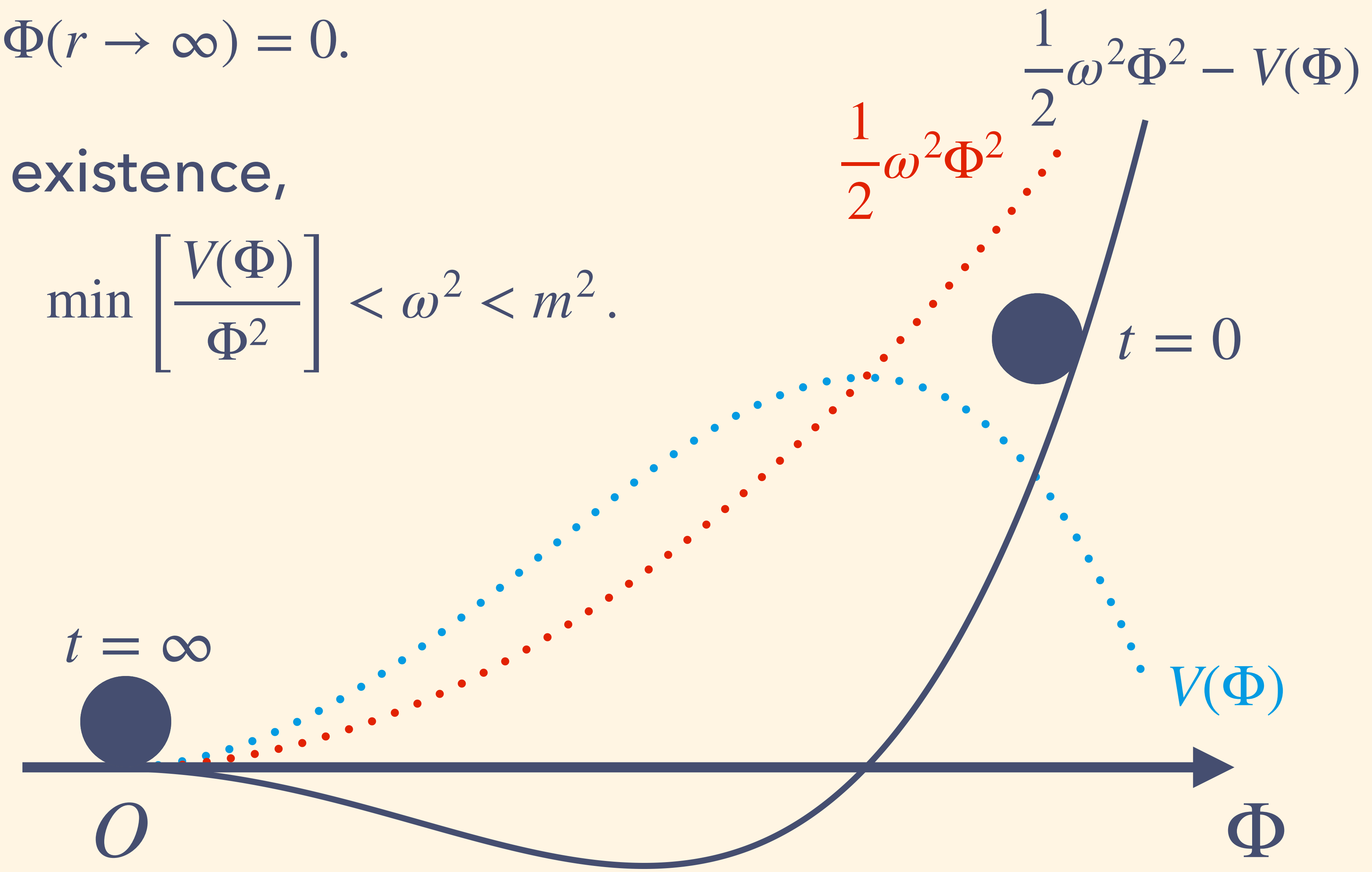
- Equation

$$\frac{d^2\Phi}{dr^2} + \frac{2}{r}\frac{d\Phi}{dr} + \frac{d}{d\Phi}\left(\frac{1}{2}\omega^2\Phi^2 - V(\Phi)\right) = 0.$$

with $\Phi'(r \to 0) = \Phi(r \to \infty) = 0.$

- For the solution existence,

$$\min\left[\frac{V(\Phi)}{\Phi^2}\right] < \omega^2 < m^2 .$$



Oscillon: Formation Conditions

- Two conditions for the oscillon formation

1. The potential must be shallower than the quadratic.

$$\min\left[\frac{V(\Phi)}{\Phi^2}\right] < \omega^2 < m^2 \,.$$

2. Fluctuations must be large as $\delta\phi/\phi \sim \mathcal{O}(1)$.

   → Initial large fluctuations or the fluctuation enhancement mechanism (i.e. resonance) is necessary.

- Above two conditions are not sufficient just necessary, so we must perform lattice simulation to confirm the oscillon formation.

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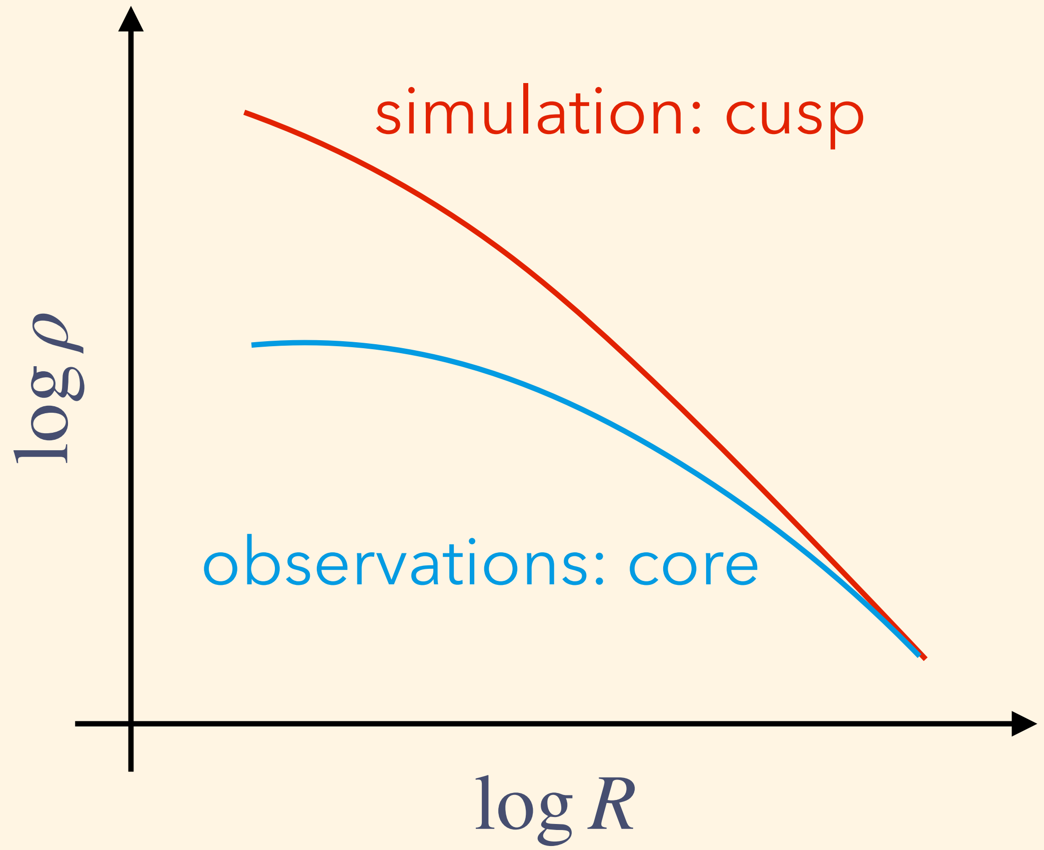
ULAP: Introduction

- Ultra-Light Axion-like Particle (ULAP) is
  - Ultra-light: typically $m \sim 10^{-22}\ \mathrm{eV}$
  - Axion-like: coherently oscillating around the universe
- Motivated as the solution to the core-cusp problem. *[W. Hu, et al. 2000, L. Amendola, et al. 2006]*
- Core-cusp problem:
  The tension of the density profile at the galactic center between ΛCDM model and observations.
  - ΛCDM: cusp (by simulation)
  - Observations: core

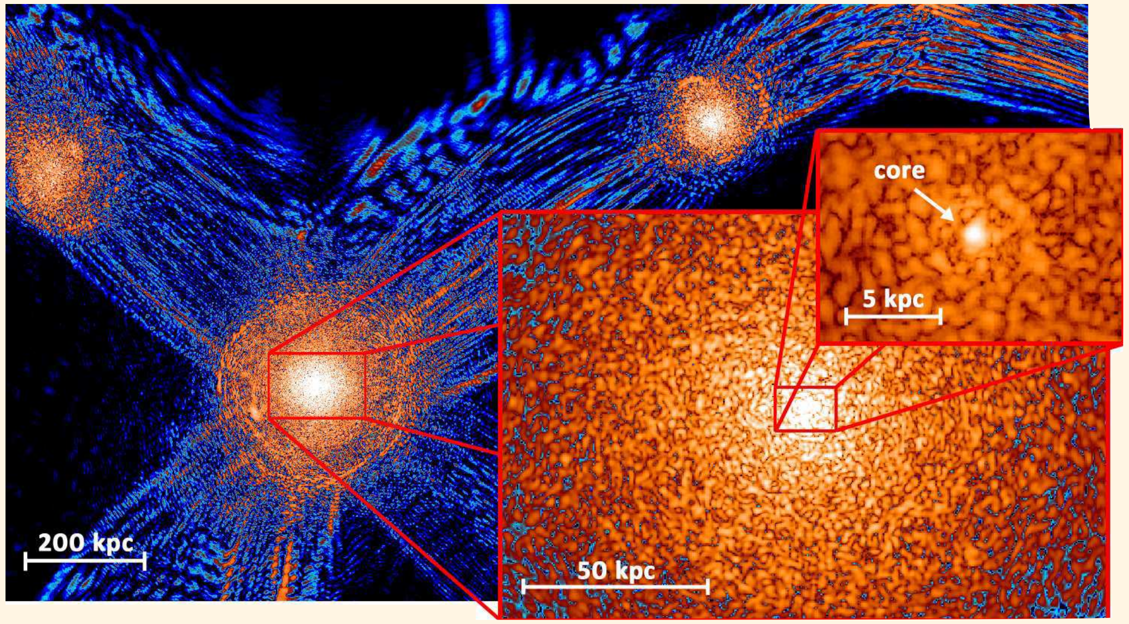


ULAP: Solution to Core-Cusp Problem

- The attractive solution is ULAP. *[W. Hu, et al. 2000, L. Amendola, et al. 2006]*
- De Broglie length of ULAP is almost the same size as the galactic core,

$$\lambda = \frac{h}{mv} \simeq \left(\frac{10^{-22}\ \mathrm{eV}}{m}\right)\left(\frac{10^{-3}}{v}\right)\ \mathrm{kpc}\,.$$

- Quantum pressure smears out the central structure of galaxies.



[Schive, et al. 2014]

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ULAP Oscillon: Potential

- Often assumed the simple cosine potential

$$V(\phi) = m^2F^2\left(1 - \cos\frac{\phi}{F}\right).$$

- However, in the cosine potential, the resonance is too weak for the oscillon formation, and resultant oscillon is short-lived. *[B. Piette, et al. 1998, A. Vaquero, et al. 2018]*

- Then, we pick up the monodromy type potential with $p > -1$. *[Y. Nomura, et al. 2017]*

$$V(\phi) = \frac{m^2F^2}{2p}\left[1 - \left(1 + \frac{\phi^2}{F^2}\right)^{-p}\right].$$

ULAP Oscillon: Formation Conditions

- Expand the potential with $\phi \ll F$,

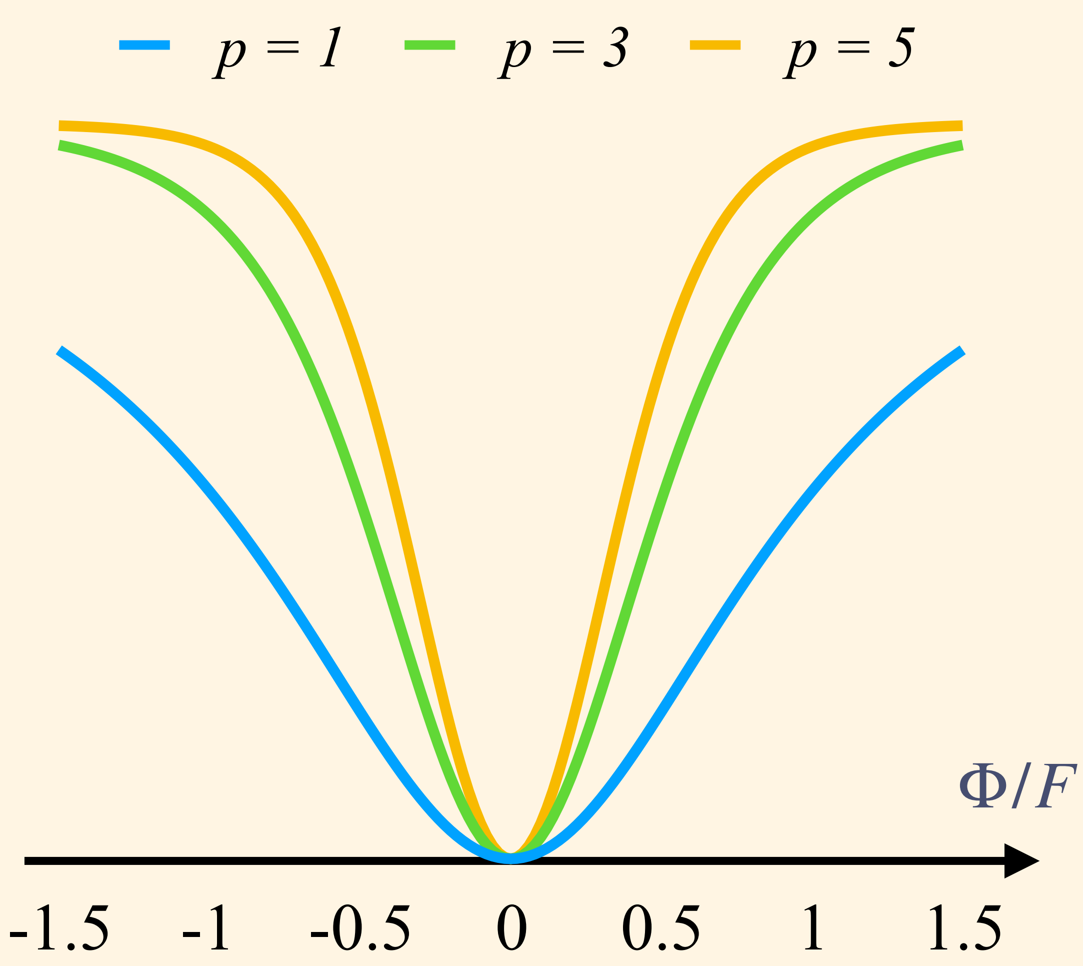
$$V(\phi) = \frac{m^2F^2}{2p}\left[1 - \left(1 + \frac{\phi^2}{F^2}\right)^{-p}\right] \simeq \frac{m^2F^2}{2}\left(\frac{\phi^2}{F^2} - \frac{p+1}{2}\frac{\phi^4}{F^4}\right).$$

- Floquet index of instability band is

$$\frac{\mu_{\max}}{m} \simeq \frac{3(p+1)}{8}\left(\frac{\Phi}{F}\right)^2,$$

$$\text{at} \quad \frac{k}{m} \simeq \sqrt{\frac{3(p+1)}{2}}\frac{\Phi}{F}.$$

- Larger p leads to the stronger instability.



ULAP Oscillon: Simulation Setup

- Simulations are performed in radiation dominated universe $a \propto \tau$ (τ: conformal time).

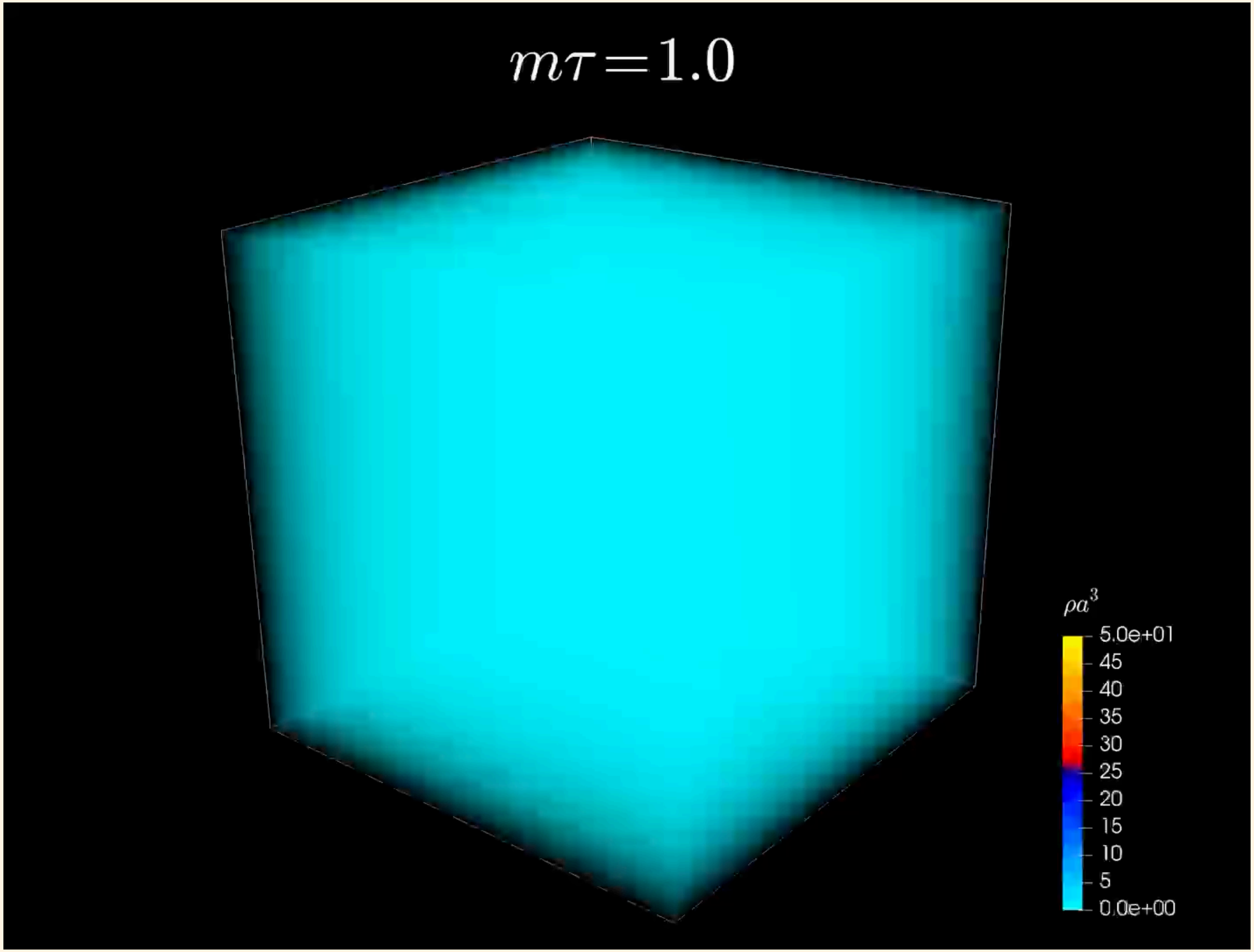
- We set the fiducial initial condition

$$\frac{\phi_i}{F} = \frac{2}{3}\pi(1+\zeta), \quad \phi_i' = 0,$$

where ζ is a random fluctuation with the size $\mathcal{O}\left(10^{-5}\right)$.

p	varying
Box size mL	8
Grid size N	256^3
Time mτ	1 - 51

ULAP Oscillon: Simulation Result ($p = 3$)



ULAP Oscillon: Simulation Result

- Oscillon is produced when $p \gtrsim 2$.
- Smaller p can also lead to the oscillon formation when the initial amplitude ϕ_i is larger because the number of oscillations in a Hubble time increases.

$$m/H \sim m/m_{\rm eff} \sim \left(1 + \phi_i^2/F^2\right)^{(p+2)/2} .$$

- Therefore, ULAP oscillon is produced in almost all region of p if we set the appropriate (larger) initial amplitude.

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ULAP Oscillon: Lifetime

- We have analytically derived the oscillon lifetime in *[M. Ibe, M. Kawasaki, W. Nakano, ES 2019]*.

- Decompose ϕ into the oscillon profile $\psi(r)$ and fluctuations around it $\xi(r)$ as

$$\phi(x) = 2\psi(r)\cos\omega t + \xi(r),$$

where $|\xi(r)| \ll |\psi(r)|$.

- $\phi(r)$ and $\psi(r)$ follow

$$\begin{cases} (\Box + m^2)\phi(r) = -V'(\phi), \\ (\Box + m^2)2\psi(r)\cos\omega t = -\overline{V'(\psi)}\cos\omega t\,. \end{cases}$$

where the overline denotes the time average.

ULAP Oscillon: Lifetime

- EOM of $\xi(r)$ becomes

$$(\Box + m^2)\xi(r) = \overline{V'(\psi)} \cos \omega t - V'(\phi) \,.$$

- Approximating $V'(\phi)$ as

$$V'(\phi) \simeq V'(2\psi \cos \omega t),$$

  we can solve the EOM of ξ.

- Decay rate $\Gamma = \dot{E}/E$ is derived from

$$\frac{dE}{dt} = 4\pi r^2 \overline{T^{0r}},$$

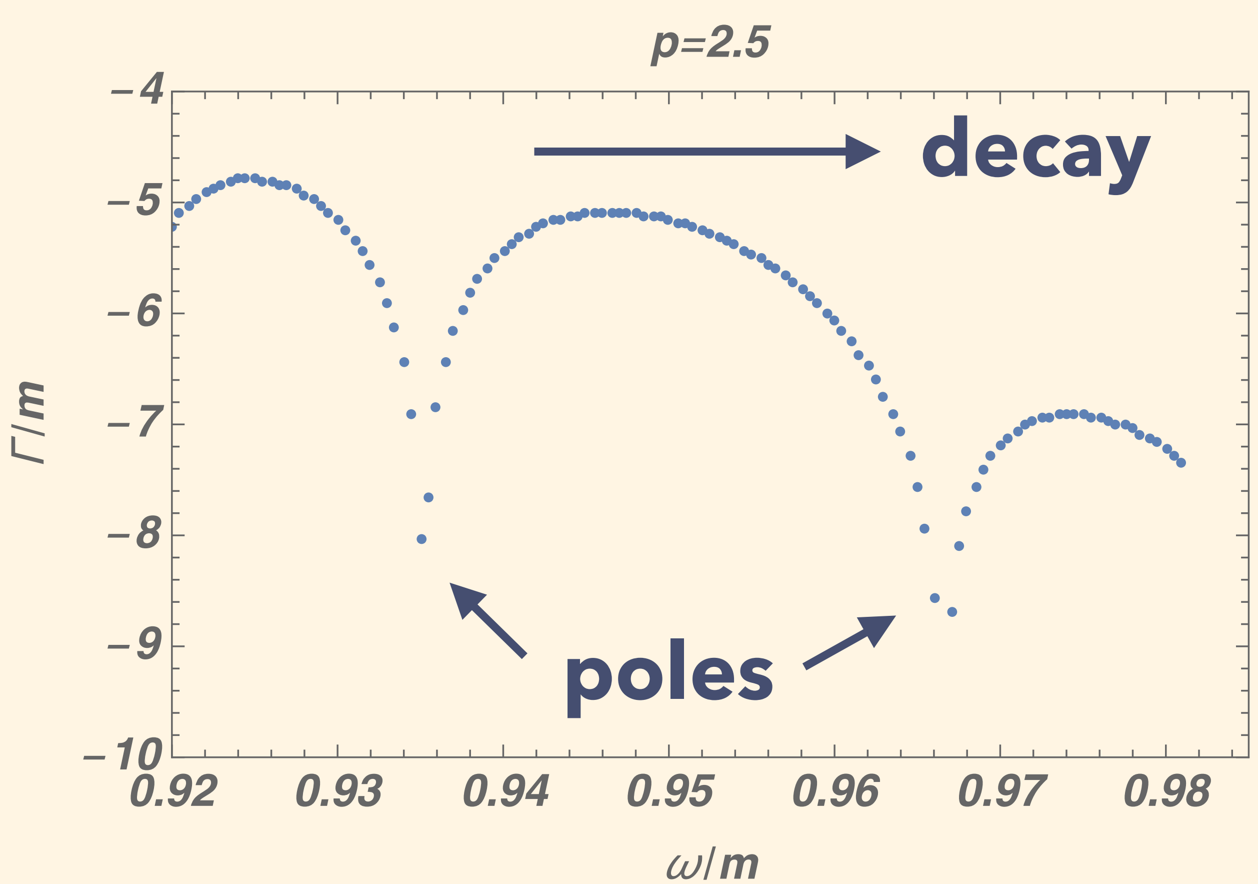
  where $T_{0r} = \partial_0 \xi \partial_r \xi$.

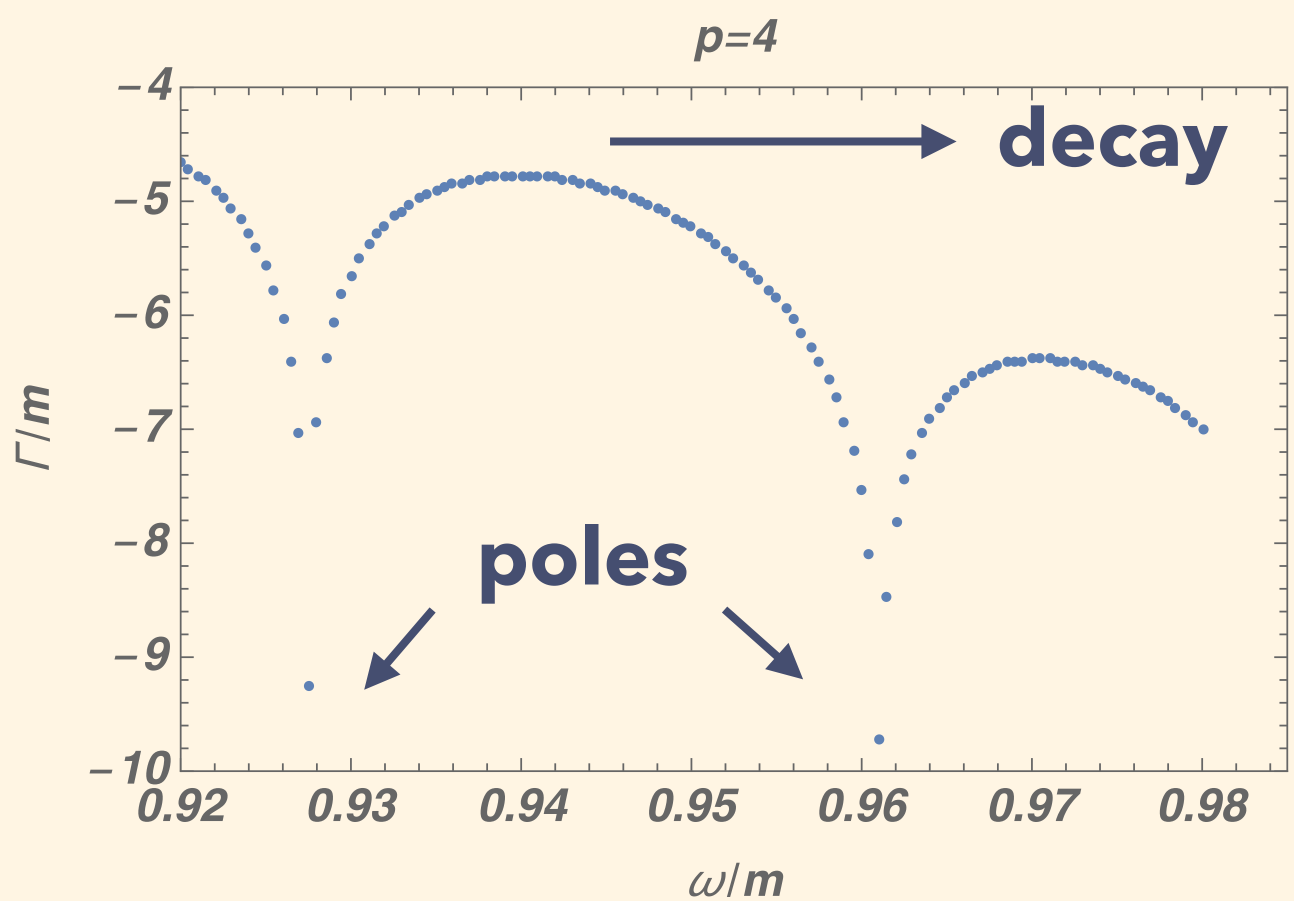
ULAP Oscillon: Lifetime

- Lifetime

$$\Gamma^{-1} \gtrsim 10^7 m^{-1} \sim 10^6 \text{ years } \left(\frac{10^{-22}\text{ eV}}{m}\right).$$

- The Lifetime will be much longer, maybe the age of the universe, because of the poles.





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Conclusion

- We investigated the oscillon formation in a ULAP potential.
- We have confirmed the oscillon formation in almost all parameter regions of p, depending on the initial amplitude.
- The produced oscillon is quite long-lived and can live up to the present universe.
- Such long-lived oscillon may affect some current ULAP constraints and structure formation.

Thank you :)