

Adiabatic Invariance of I-balls/Oscillons

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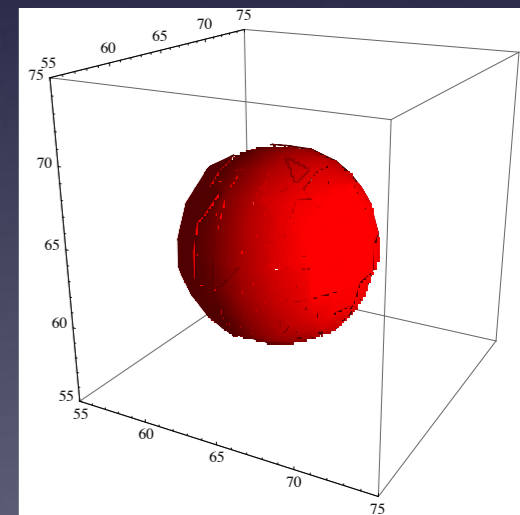
Naoyuki Takeda: Keio University (JPN)

Collaboration with

Masahiro Kawasaki: ICRR

Fuminobu Takahashi: Tohoku University

CosPA2016(Sydney Univ), 1/12/2016



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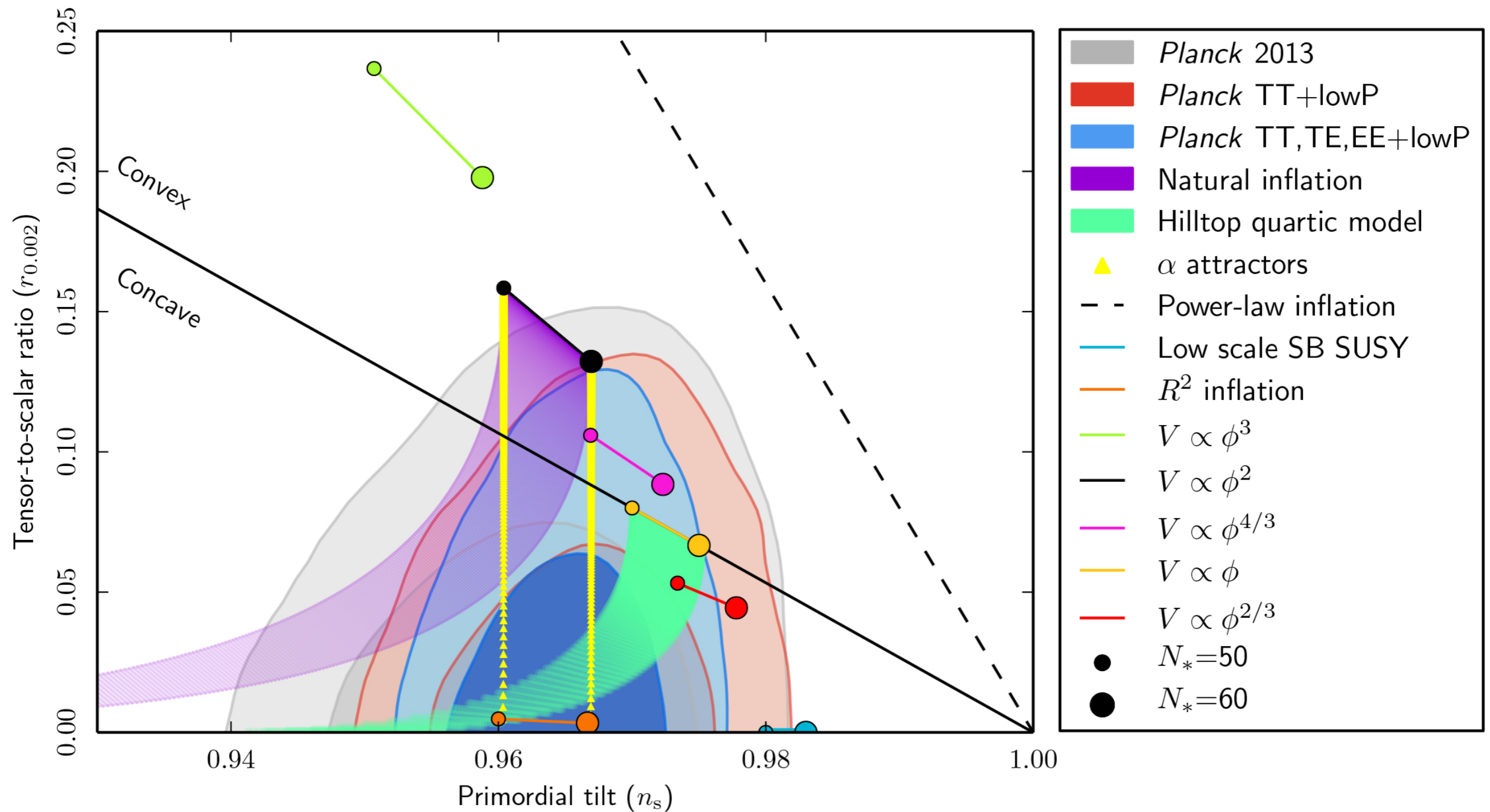
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Introduction: Inflation

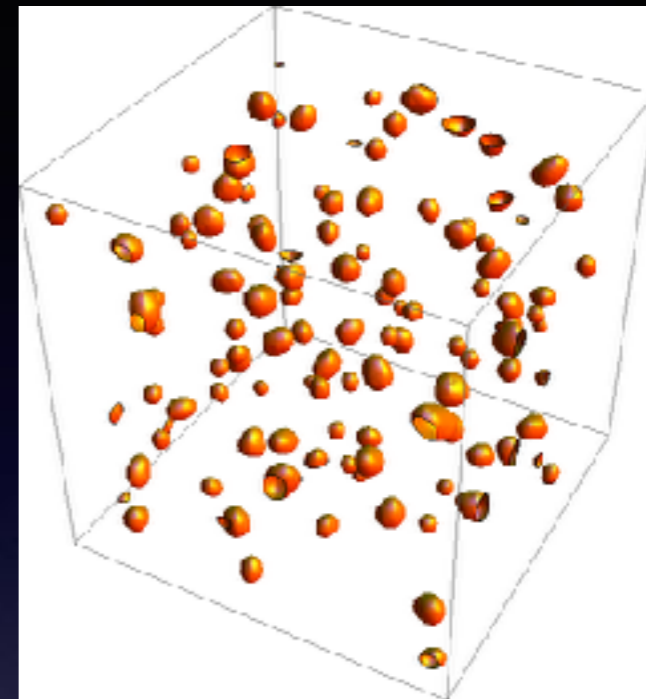
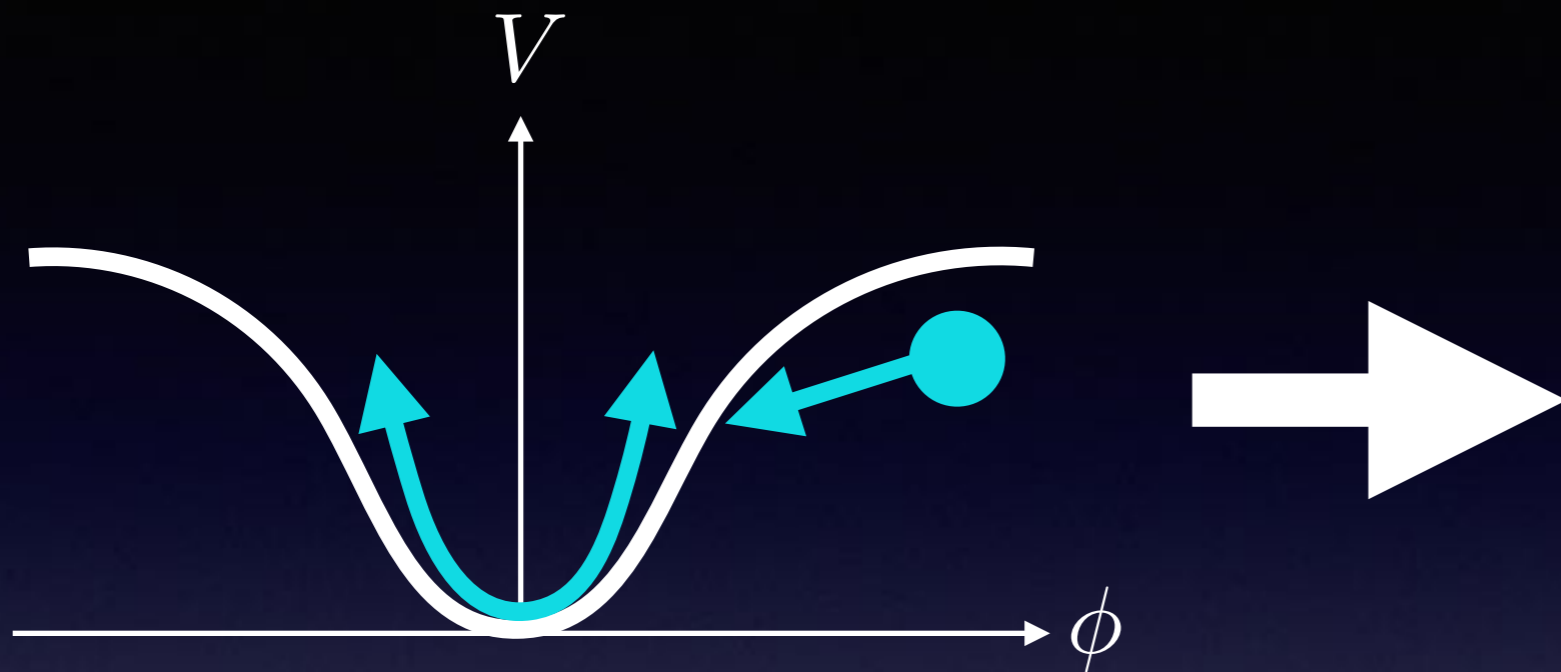
Planck(2015)



- Inflaton potential is flatter than quadratic

Introduction: I-ball/Oscillons

- Oscillating real scalar field forms I-balls/Oscillons



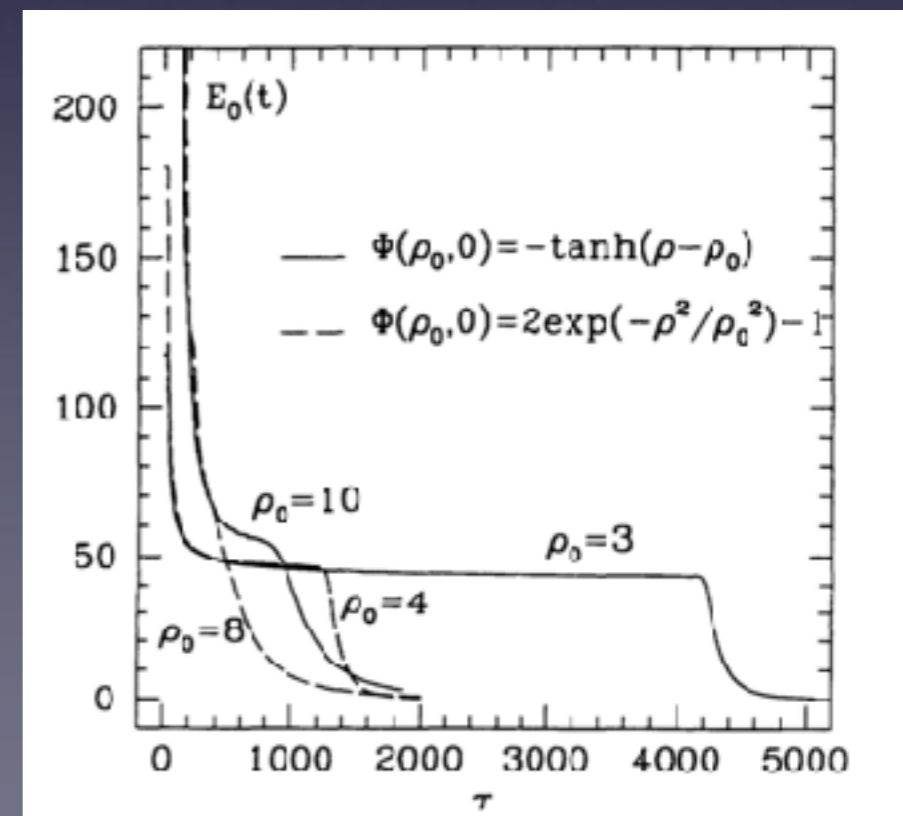
Amin et al' 12

flatter than $m^2\phi^2$

ex): $\lambda(\phi^2 - \Lambda^2)$, $\frac{m^2}{2}\phi^2 - \lambda\phi^4 + g\frac{\phi^6}{M^2}$, $\Lambda^4 \left(1 + \frac{\phi^2}{M^2}\right)^{1/n}$

Gleiser(94)

- Long life time and sudden decay
- Effect on the dynamics of ϕ
 - decay rate, equation of state etc.
- Try to understand the stability focusing on a conserved charge:
adiabatic invariance

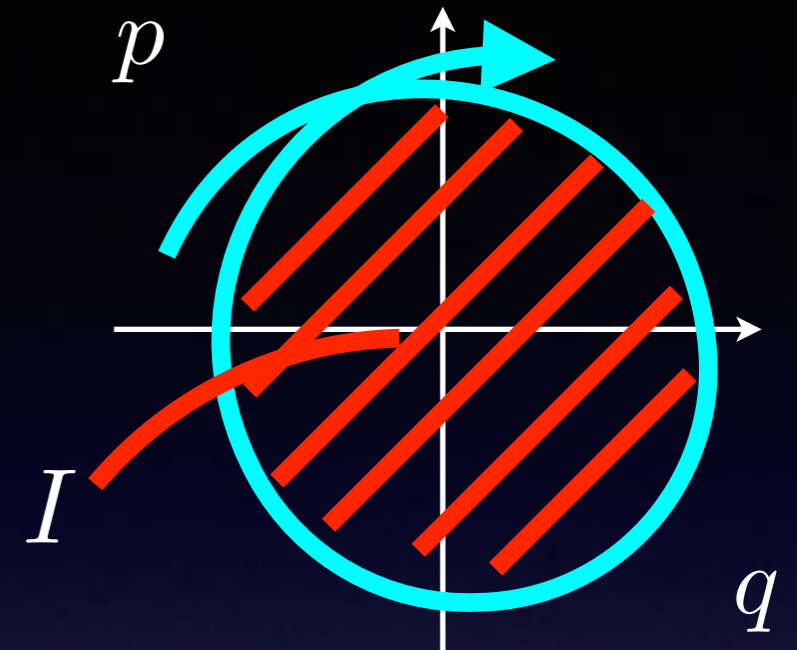


Intro: Adiabatic Invariance (Classical mechanics)

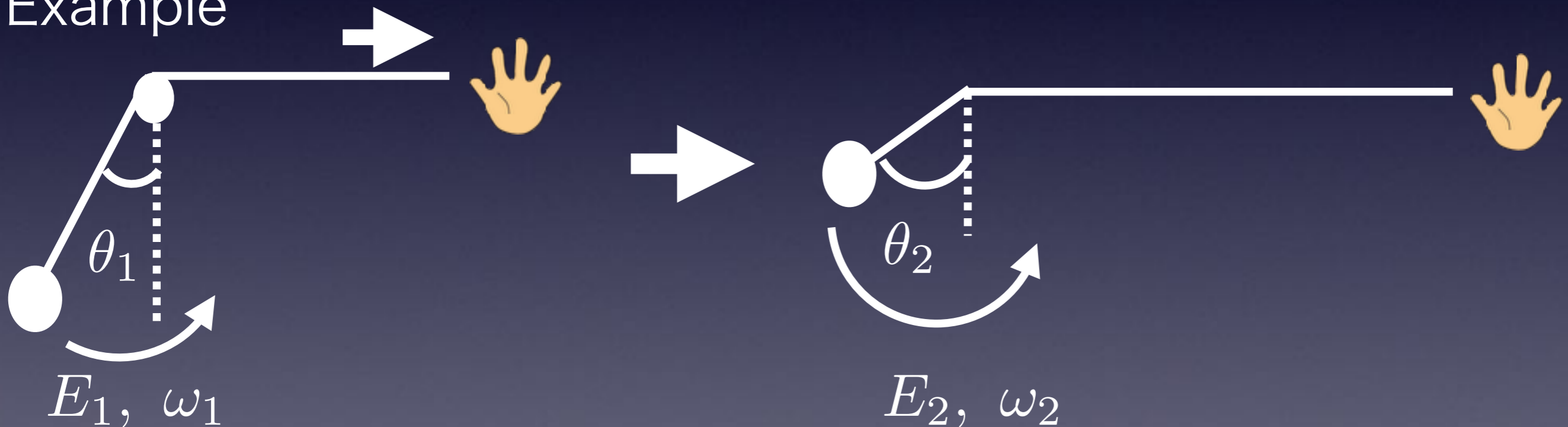
Classical mechanics

- Phase space surrounded by quasi-periodic oscillation is conserved.

$$I_{cl} = \oint dq \cdot p = \frac{\overline{\dot{q}^2}}{\omega}$$



Example



- ω, E change: $\omega_1 < \omega_2$, $\theta_1 < \theta_2$, $E_1 < E_2$

Adiabatic invariance is conserved: $E/\omega = \text{const}$

Work: Adiabatic Invariance (Scalar field)

■ Adiabatic Charge

$$I = \int d^3x \oint d\phi \cdot \pi = \int d^3x \overline{\frac{\dot{\phi}^2}{\omega}} \quad \omega: \text{frequency}$$

- We proved that Adiabatic Charge is conserved for scalar field theory

■ Assumption

- Field is divided into separable form

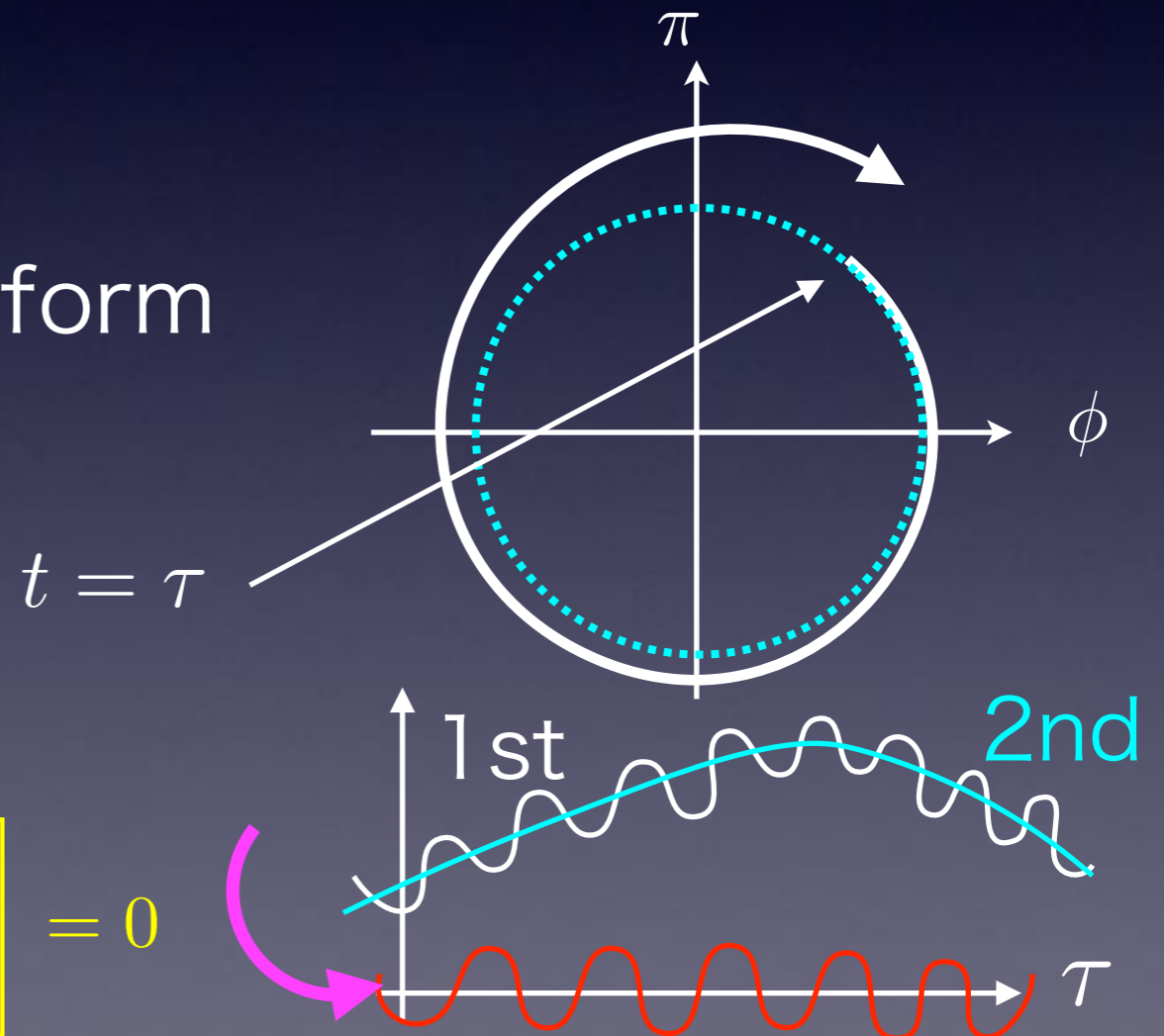
$$\phi(t, \vec{x}) = \Phi(\vec{x}) f(t)$$

■ Constant of motion

$$\tilde{\mathcal{H}} = \mathcal{H} - \frac{1}{2} \partial_i (\phi \partial^i \phi)$$

$$\rightarrow \overline{\partial_\mu J^\mu} = \int_0^T d\tau \frac{da}{d\tau} \times \left[\frac{\partial \tilde{\mathcal{H}}(\pi, \phi, a)}{\partial a} - \overline{\frac{\partial \mathcal{H}}{\partial a}} \right] = 0$$

$$J^0 \equiv \frac{2\pi}{\omega} \overline{\dot{\phi}^2}, \quad J^i \equiv -\frac{\pi}{\omega} \left(\dot{\phi} \partial_i \phi - \phi \partial_i \dot{\phi} \right) \quad a: \text{parameter of external force}$$



Work: Potential for separable form

- Separable form: $\phi(t, \vec{x}) = \Phi(\vec{x})f(t)$

► E.O.M.

$$\frac{\ddot{f}}{f} - \frac{\nabla^2 \Phi}{\Phi} = - \frac{\partial V(\Phi f)}{\partial(\Phi f)}$$

- Φ and f need to evolve independently

- $\frac{\partial V(\Phi f)}{\partial(\Phi f)} = A(\Phi) + B(f)$

- V is the function of ϕ

- $\frac{\partial V(\Phi f)}{\partial(\Phi f)} = C(\Phi f)$

► C satisfies def. of logarithmic function

$$\underline{C(\Phi f) = C(\Phi) + C(f) - A(1) - B(1)}$$

$$\rightarrow C(\phi) = \ln(\phi)$$

$$\rightarrow \boxed{V = \frac{m^2}{2} \phi^2 \left[1 - K \ln \frac{\phi^2}{2M^2} \right]}$$

Kawasaki, Takahashi, Takeda '15

m, M : mass parameter, $0 < K < 1$

Work: I-ball solution

I-ball solution

- Lagrange multiplier with fixed I

$$\bar{E}_{\tilde{\omega}} = \bar{E} + \tilde{\omega} \left[I - \int d^3x \frac{\dot{\phi}^2}{\omega} \right]$$

- potential

$$V = \frac{m^2}{2} \phi^2 \left[1 - K \ln \frac{\phi^2}{2M^2} \right]$$

- Lowest energy condition: $\delta \bar{E}_{\tilde{\omega}} / \delta \Phi = 0$

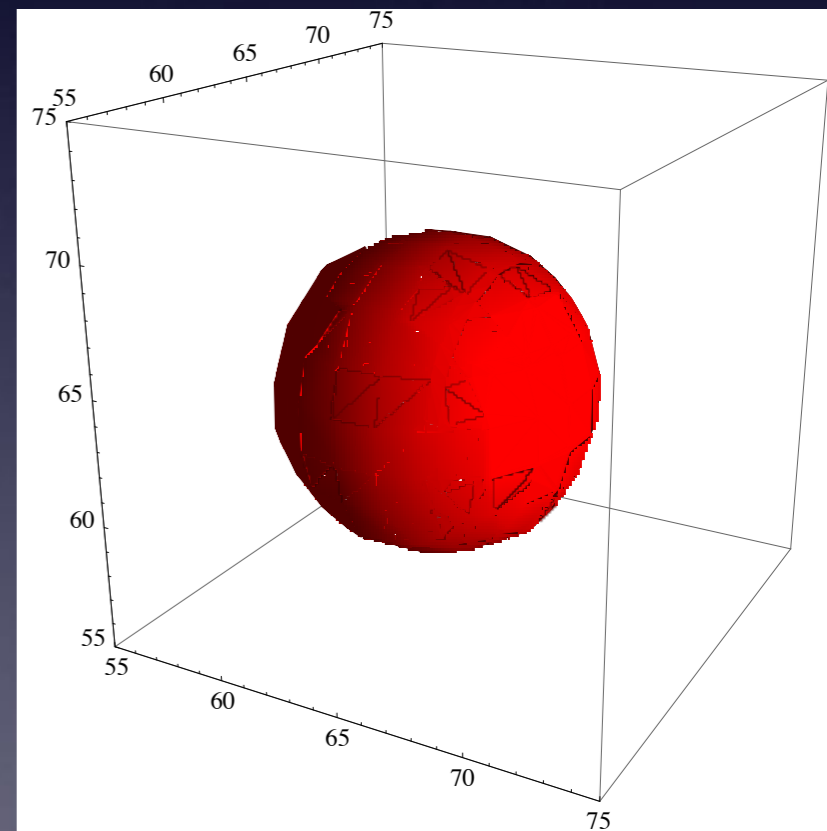
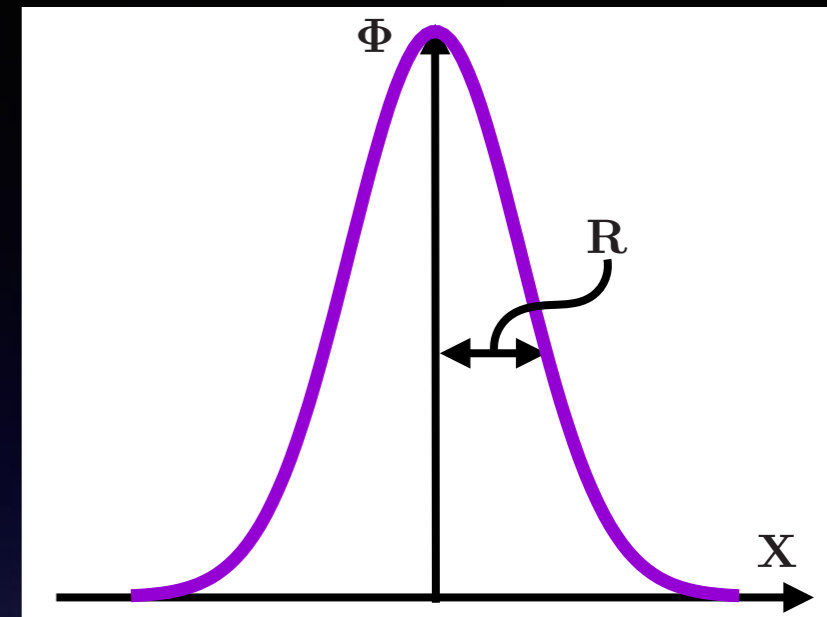
$$\Phi(r) = \Phi_c \exp(-r^2/R^2), \quad R = \sqrt{\frac{2}{K} \frac{1}{m}}$$

- I-ball is the lowest lowest energy state for a fixed I

- Lemma

Adiabatic charge is conserved even for $\dot{K} \neq 0$

- I-ball should deform following prediction from I



Work: Adiabatic deformation of I-ball

- Deformation

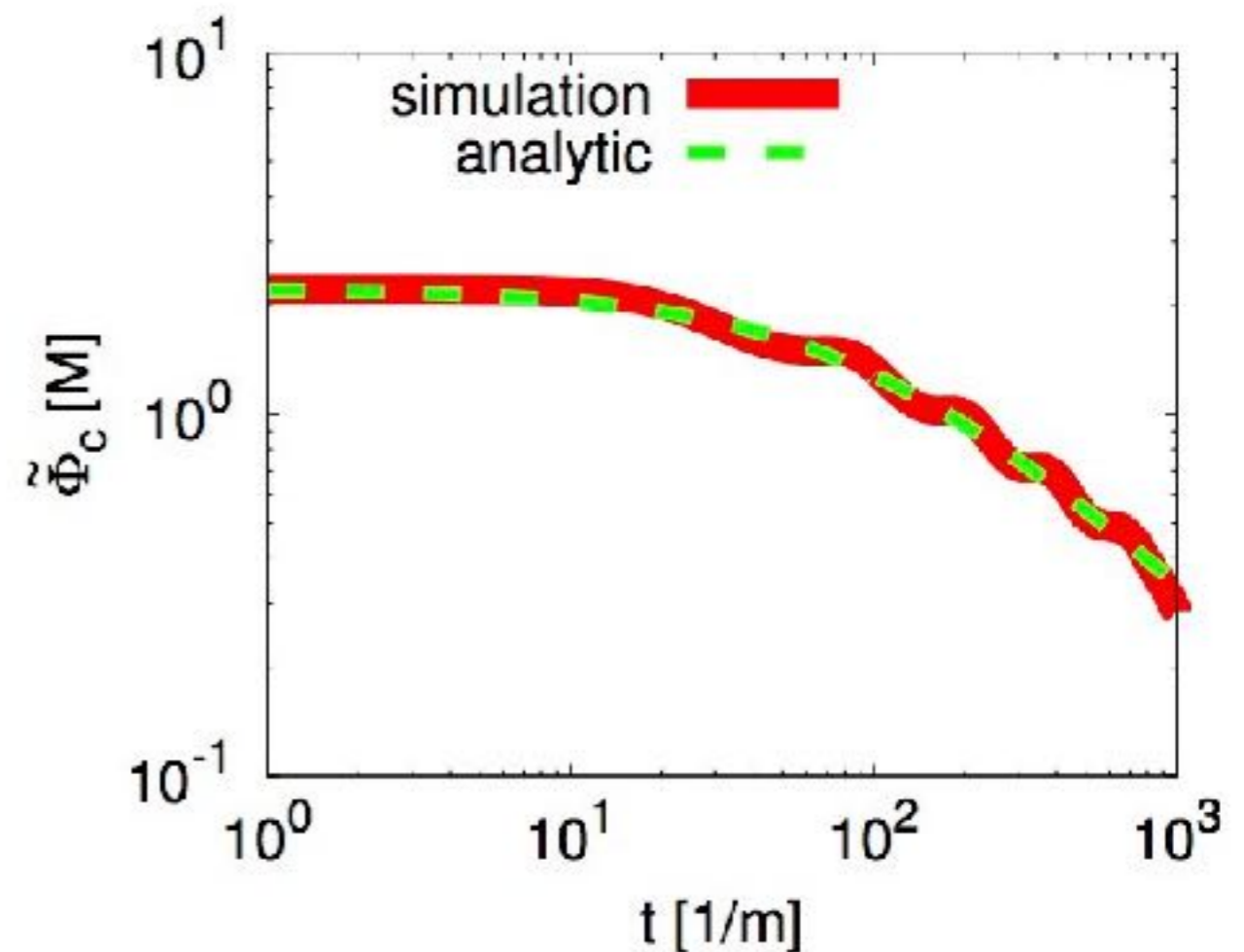
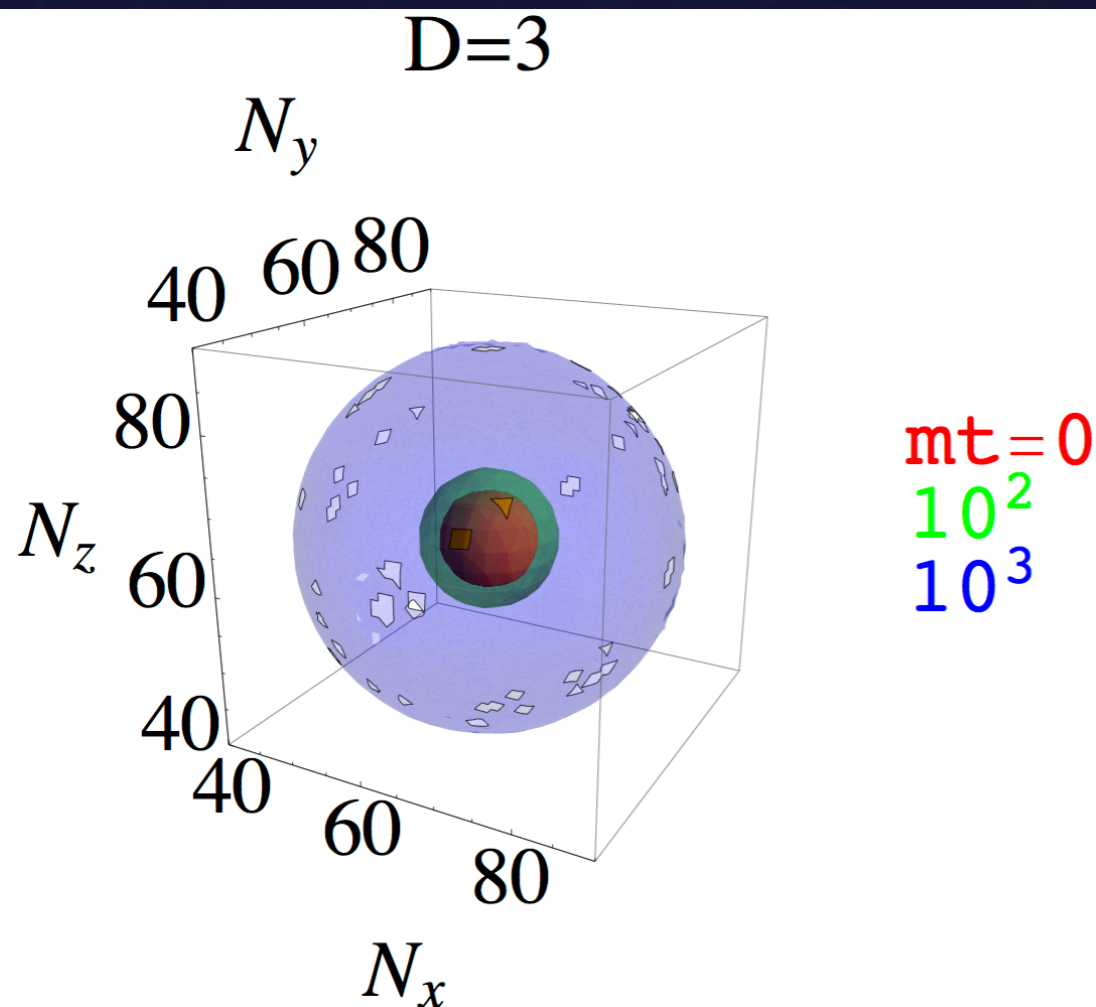
$$K(t) = \frac{K_0}{1 + \alpha m t}; \alpha, K_0: \text{dimensionless constant}$$

- Radius: $R(t) = \sqrt{2/K_0} \sqrt{1 + \alpha m t}/m$

- Field amplitude: $\Phi_c = \Phi_{c,0} (1 + \alpha m t)^{-3/4}$

- Numerical simulation

$$\alpha = 10^{-2}$$



Deformation follows the prediction of Adiabatic Charge

Conclusion

- Inflaton potential is suggested to be flatter than quadratic
 - Some scalar field with flatter potential forms I-ball
 - We focused on the **adiabatic charge** to verify the I-ball's stability.
 - We proved the conservation of the adiabatic charge for the scalar field
 - Further revealed that the I-ball deforms adiabatically following the prediction of the adiabatic charge
- **Adiabatic Charge is important for the stability of I-ball**