Cosmological imprints of string axions in plateau

Yuko Urakawa (Nagoya university, IAR)

J.Soda & Y.U.(1710.00305)

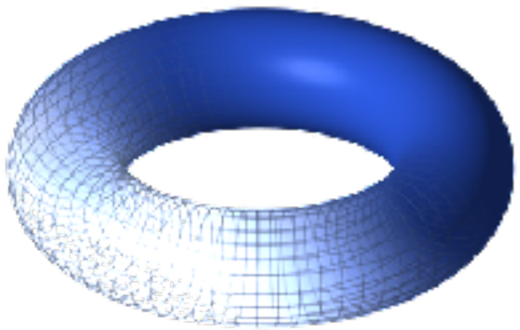
N. Kitajima, J.Soda,& Y.U.(in progress)

String axiverse

10D string theory/supergravity

+ 6D compactification

Moduli fields ~ Geometrical DOFs



4D low energy EFT + String axions ….

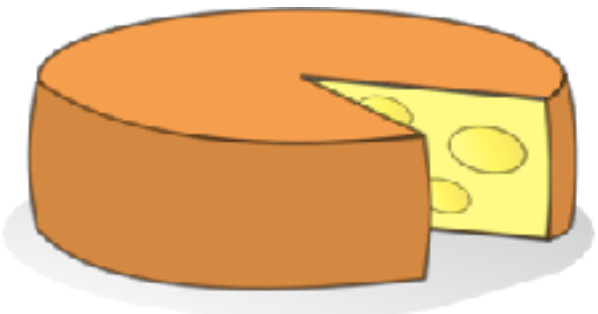
wide mass ranges → Probe of exDim

Arvanitaki et al. (10)

ex. Large Volume Scenario

Conlon et al. (05)

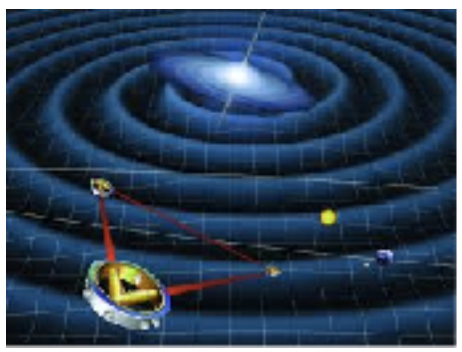
Predicts light mass axions

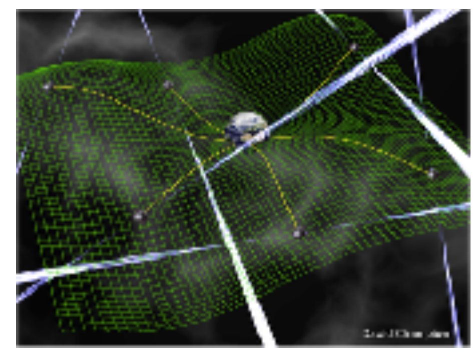


Outline

Targets

i) New window in string axiverse from GWs





ii) In particular, for Axion =DM, imprints on LSS

Keywords

- Parametric resonance instability
- Turbulence

String axions in plateau

Scalar potential $$V(a) = \Lambda^4 \left(1 - \cos \frac{a}{f}\right)$$

under the dilute instanton gas approximation

In string theory constructions, potential tends to be flatten out.

having V"<0

ex. Monodromy, ….

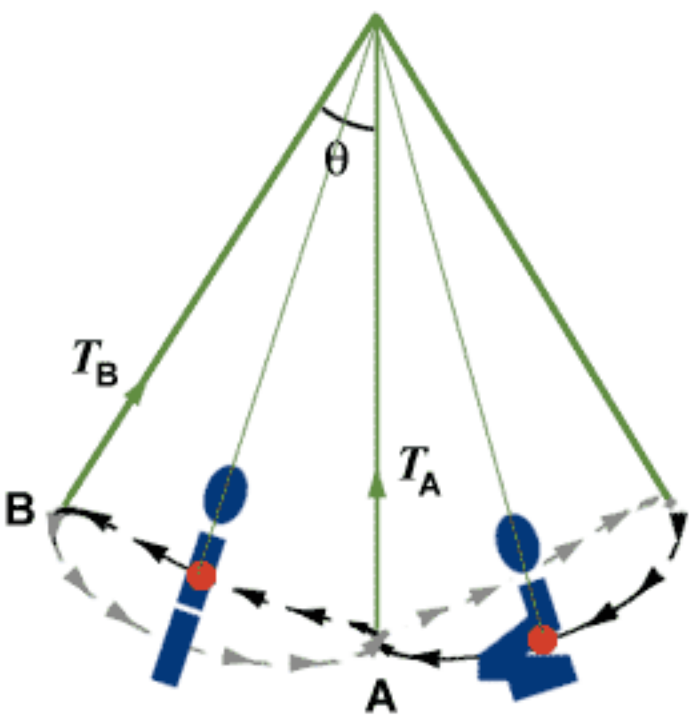
Dubovski et al. (10), Nomura, Watari&Yamazaki(17)

Axions w/flatten region *Soda & Y.U.(17)*

→ Parametric resonance instability

New window in cosmological axion search

Parametric resonance



Repeat: Up & Down in half period

→ Periodic ext. force (vs centrifugal force)

→ Enhancing the amplitude

"Parametric resonance instability"

<u>Mathieu equation</u>

$$\frac{d^2}{dx^2}\tilde{\varphi} + (A - 2q\cos 2x)\tilde{\varphi} = 0$$

resonance band $A \sim n^2$

ex. First band $\tilde{\varphi} \propto e^{\gamma x}$ $\gamma \simeq q/2$

Two enemies against PR

ex. Reheating after inflation $H < m,\ \varphi(t) \sim \varphi_* \cos mt$

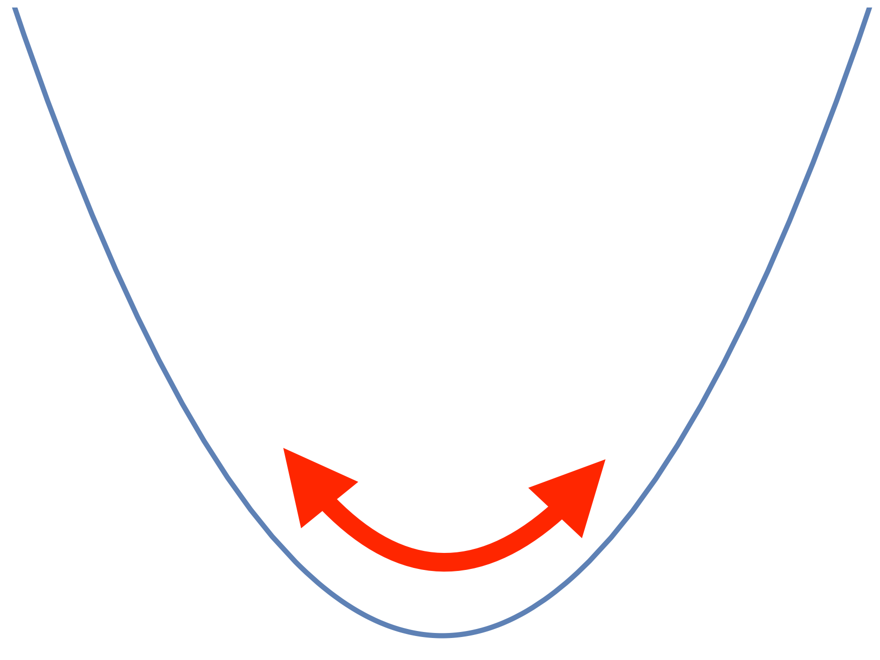
- Particle production through interaction w/SM sector
- Enhancement of inhomogeneity through self-interaction

Cosmic expansion disturbs PR

i) φ_* damps due to Hubble friction

Growth rate $\gamma \propto \varphi_*^n \quad (n>0)$

ii) Redshift away from resonance bands



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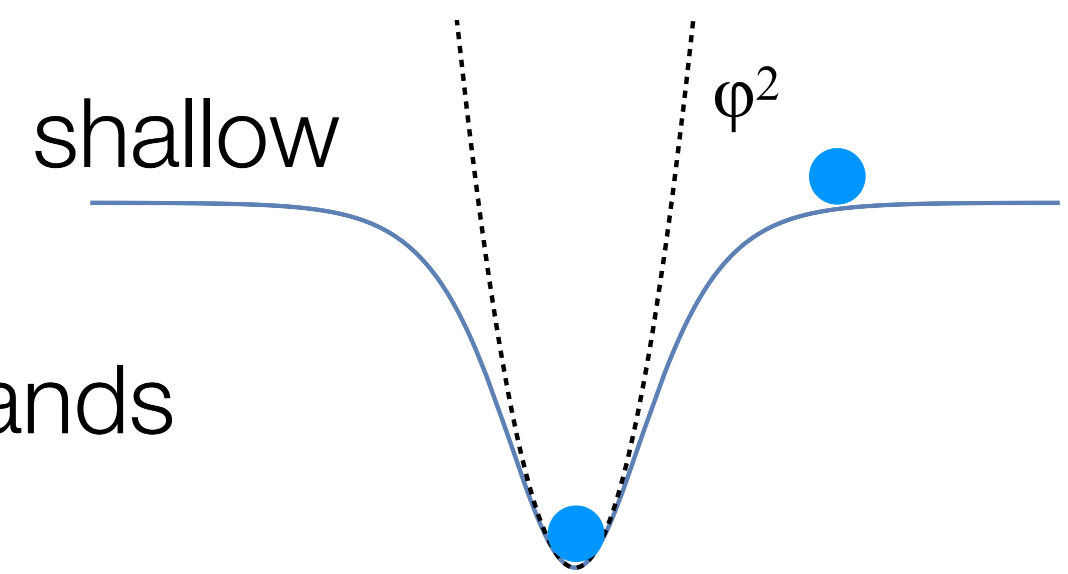
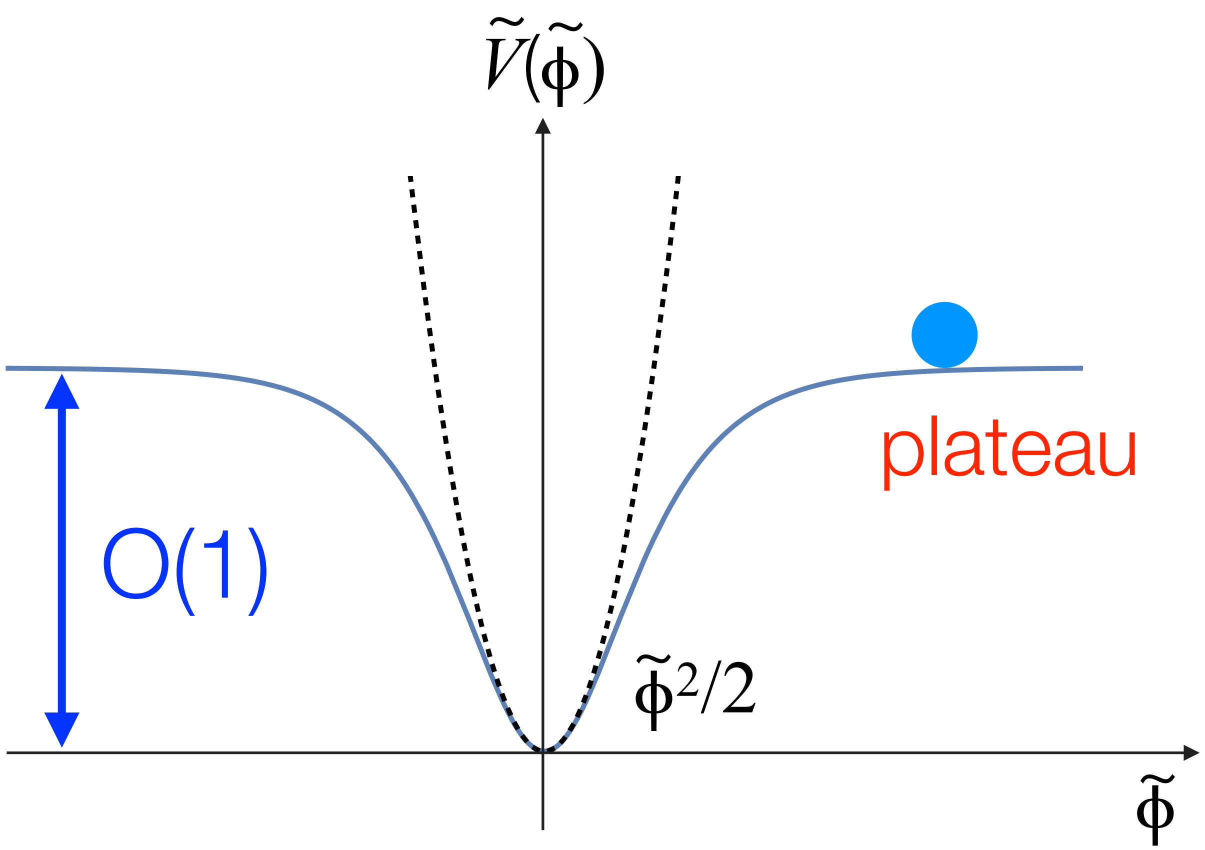


They can be overwhelmed if plateau exists!!

Setup of problem

Soda & Y.U.(17)

Given that there is a string axion (w/mass m) whose potential has a plateau region, …



scalar potential

$$V(\phi) = (mf)^2\,\tilde{V}(\tilde{\phi}) \qquad \tilde{\phi} \equiv \phi/f$$

i) $\tilde{V}(\tilde{\phi}) \to \tilde{\phi}^2/2 \qquad \tilde{\phi} \to 0$

ii) $\tilde{V}(\phi)/\tilde{\phi}^2 \to 0 \qquad \tilde{\phi} \to \infty$

+ Z_2 symmetry

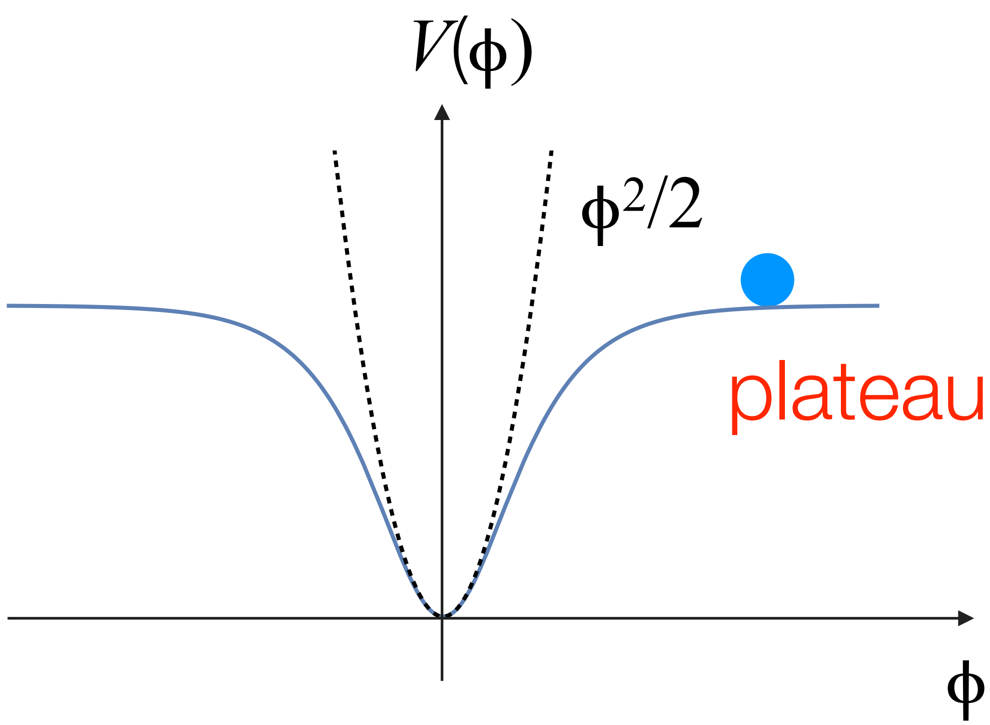
Bottom-line story

1. Axion slowly rolls in plateau

2. Onset of oscillation $H_{osc}/m < 1$

3. Exponential growth due to PR

if $H_{osc}/m << 1$ No disturbance due to cosmic exp.



4. Rescattering → PR becomes inefficient *eg. Kofman, Linde, Starobinsky*

5. Momentum transfer due to turbulence → GW emission

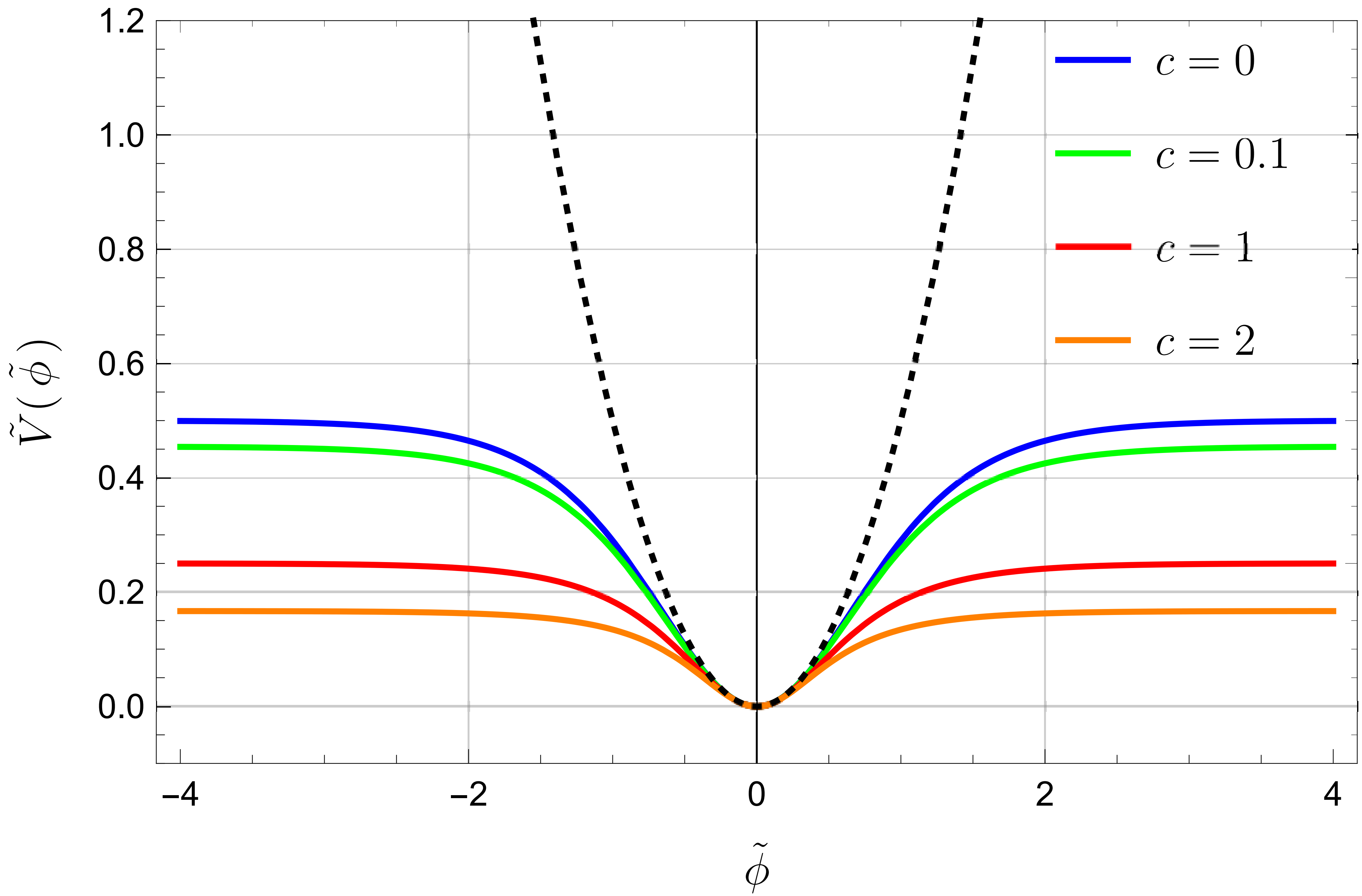
Micha & Tkachev (02,04)

6. Oscillon/I-ball formation

Kasuya+(03),Amin + (10, 12, 17), Zhou(13), Antusch +(17), Kawasaki+(17), ⋯.

Exercise: α-attractor

$$V(\phi) = \frac{(m_a f)^2}{2} \frac{(\tanh \frac{\phi}{f})^2}{1 + c(\tanh \frac{\phi}{f})^2}$$



Solving KG eq. in cosmological spacetimes

Klein-Gordon eq. $\Box\phi - V_\phi = 0$

eg. Homogeneous mode

$$\frac{d^2\tilde{\phi}}{dx^2} + \frac{3p}{x}\frac{d\tilde{\phi}}{dx} + p^2\frac{d\tilde{V}}{d\tilde{\phi}} = 0$$

Dimensionless form

$\tilde{\phi} = \phi/f$ $\quad x = m/H = mt/p$ $\quad a \propto t^p$

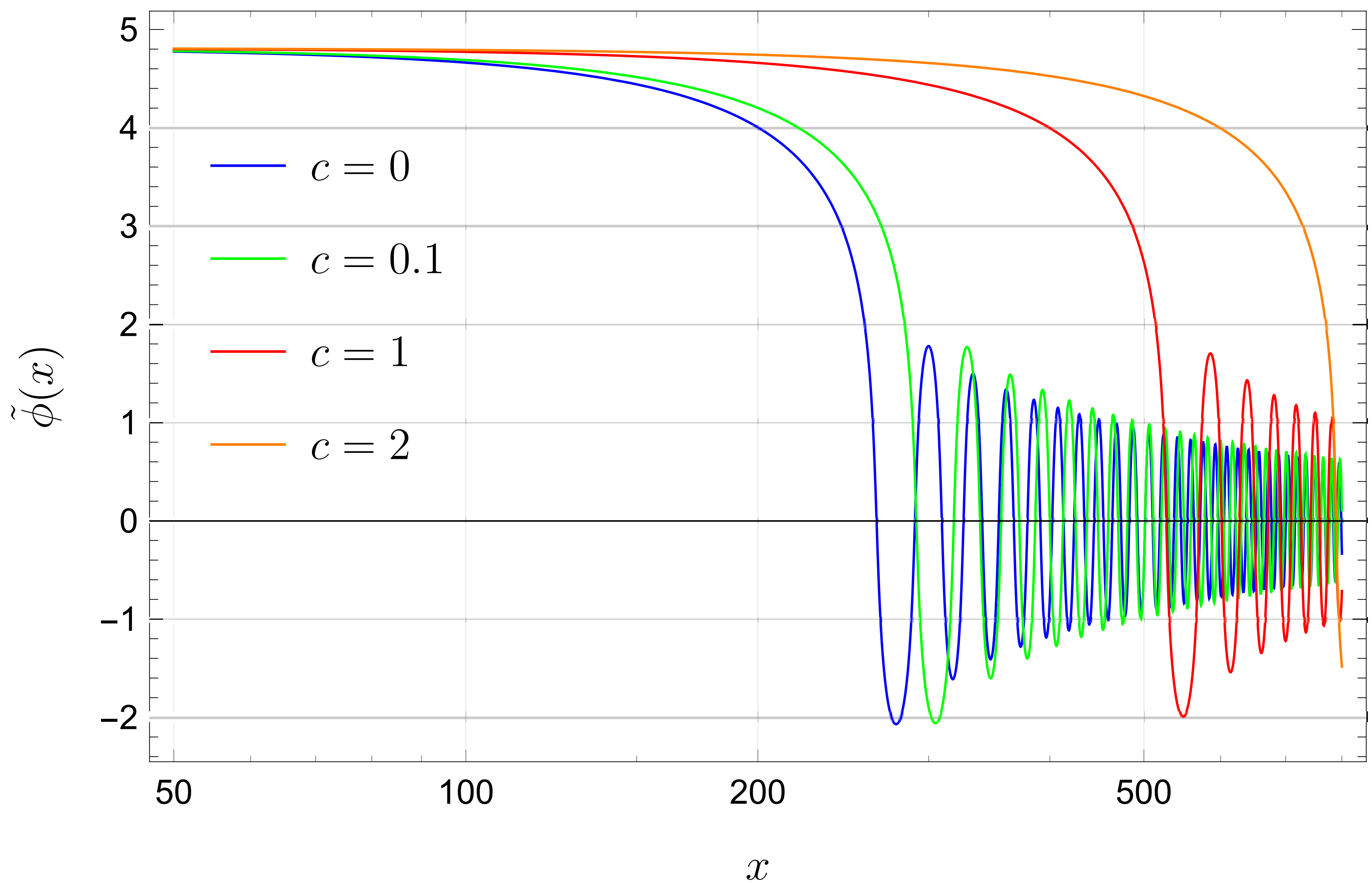
(IC) $\tilde{\phi}(x_i)$, $d\tilde{\phi}/dx(x_i)$ $\longrightarrow$ x_{osc}=O(1) - O(10^4)

- $m \rightarrow H_{osc} = m/x_{osc}$

- $f \rightarrow$ Abundance

Background evolution

$\tilde{\varphi}_i$=5 RD Soda & Y.U.(17)



$x = m/H$

Onset of oscillation is not $m \sim H$, but delayed!

Linear perturbation

in Newtonian gauge

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{k^2}{a^2}\varphi + V_{\phi\phi}\varphi - 2V_\phi\Phi + \dot{\phi}\,\dot{\Phi} = 0$$

Φ: Bardeen potential

<u>2 possible instabilities</u>

i) Parametric resonance instability

Non-linear potential $V_{\phi\phi} \supset \phi^n \sim (\phi^* \cos mt)^n$

$\longrightarrow \cos(nmt)$

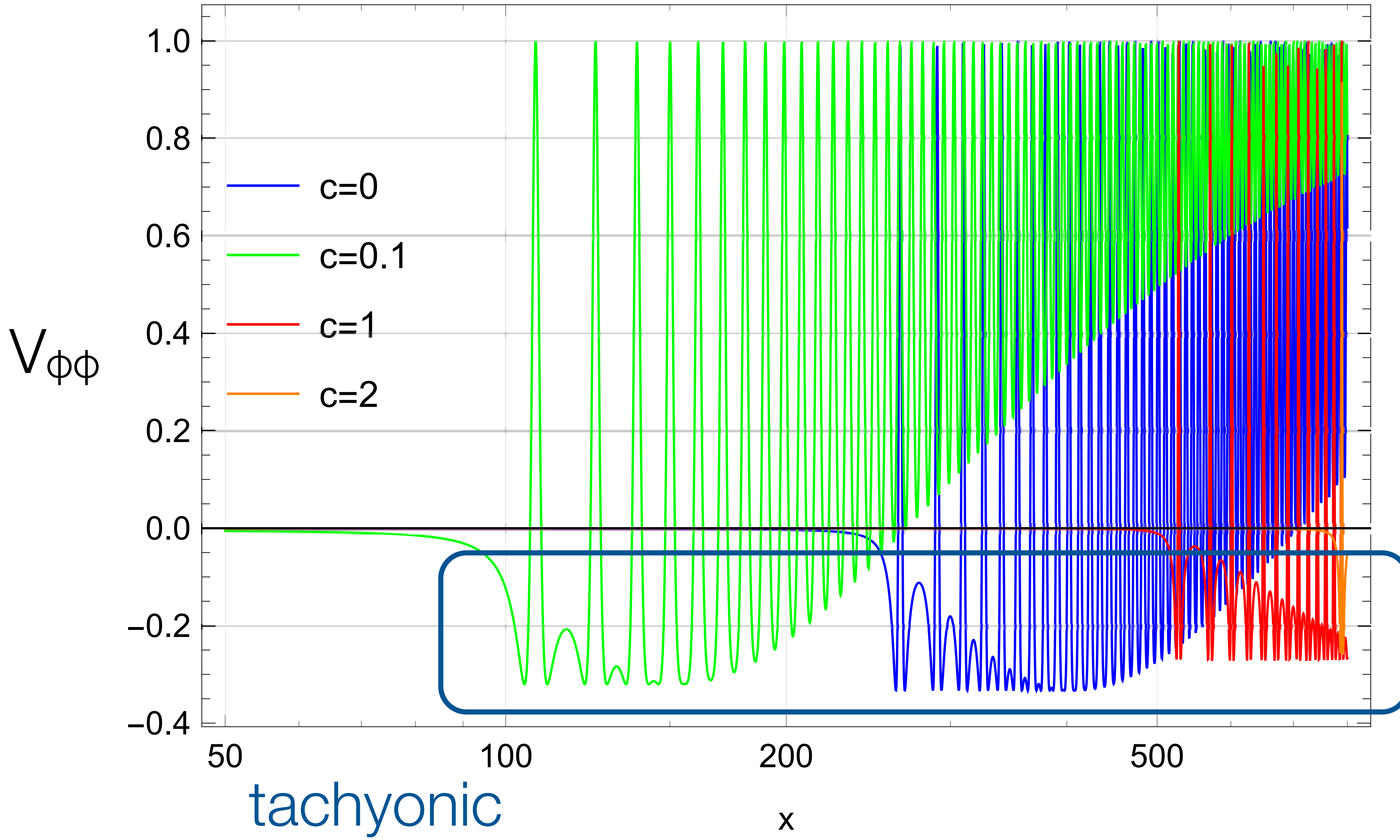
ii) Tachyonic instability

Region w/ $V_{\phi\phi} < 0$

* Backreaction of ULA on Φ was neglected.

Tachyonic instability?

Time evolution of mass term $\tilde{\varphi}_i = 5$ RD (p=1/2)



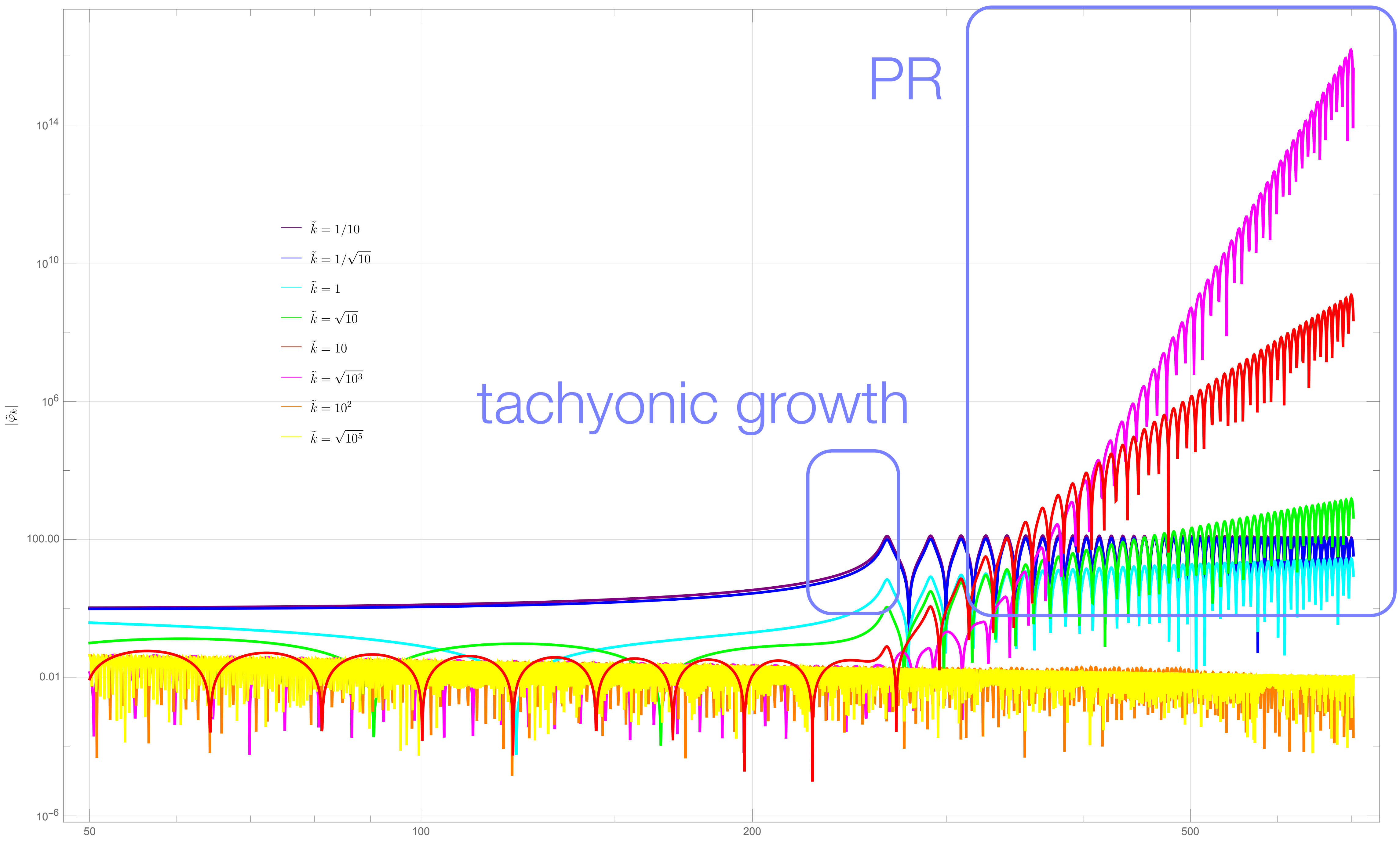
$x = m/H$

Linear perturbation

Soda & Y.U.(17)

Onset of oscillation in RD

$\tilde{k} = k/(a_i m)$



Parametric resonance instability

Neglect cosmic exp. and Φ

$$\frac{d^2}{dx^2}\tilde{\varphi} + (A - 2q\cos 2x)\tilde{\varphi} = 0$$

Band width (q/A)^n

BG axion $\tilde{\phi} = \tilde{\phi}_*$ … f

$$A \equiv \frac{1}{4}\left[\left(\frac{k}{m\, a_{osc}}\right)^2 + 1 - (2+3c)\tilde{\phi}_*^2\right] \qquad q \equiv \frac{2+3c}{8}\,\tilde{\phi}_*^2$$

<u>Mathieu equation</u>

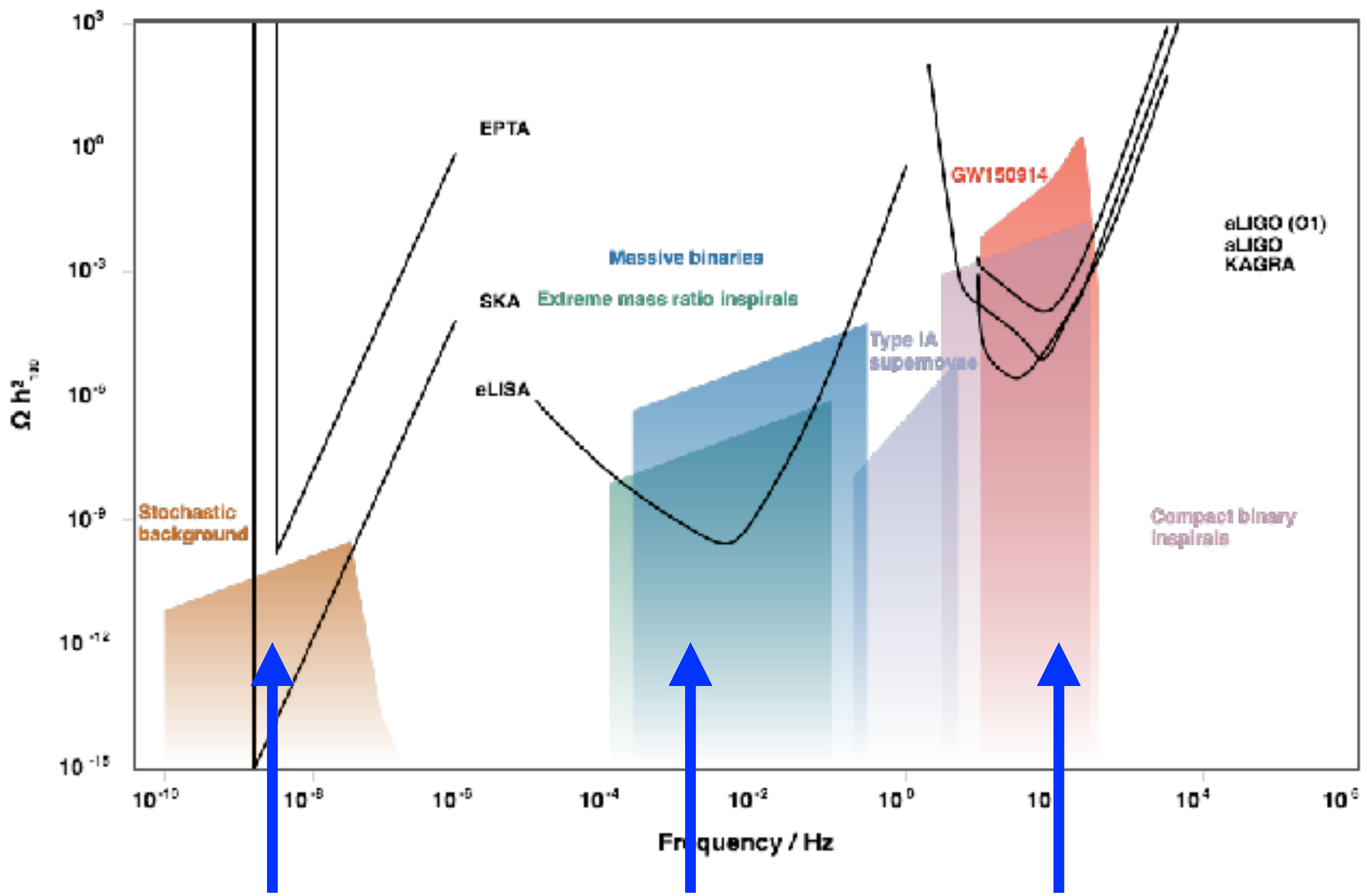
Resonance band $A \simeq n^2$

First resonance band $\tilde{\varphi} \propto e^{\gamma x}$ $\gamma \simeq \frac{q}{2} = \frac{2+3c}{16}\,\tilde{\phi}_*^2$

GWs from PR of axion

Frequency at present

$f_0 \simeq m/(1+z_*)$ z_*:Redshift at emission $z_{osc} \sim z_*$



$m \sim 10^{-16} eV$ $m \sim 10^{-6} eV$ $m \sim 10^{3} eV$

Bottom-line story of Axion's excursion

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J.S&Y.U(07)

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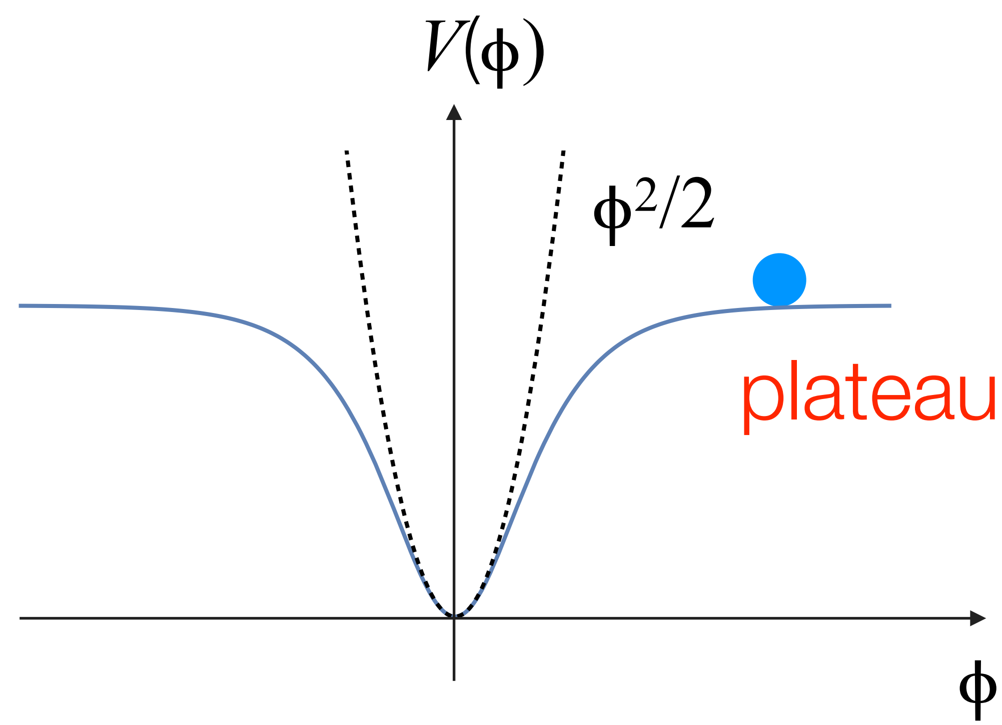


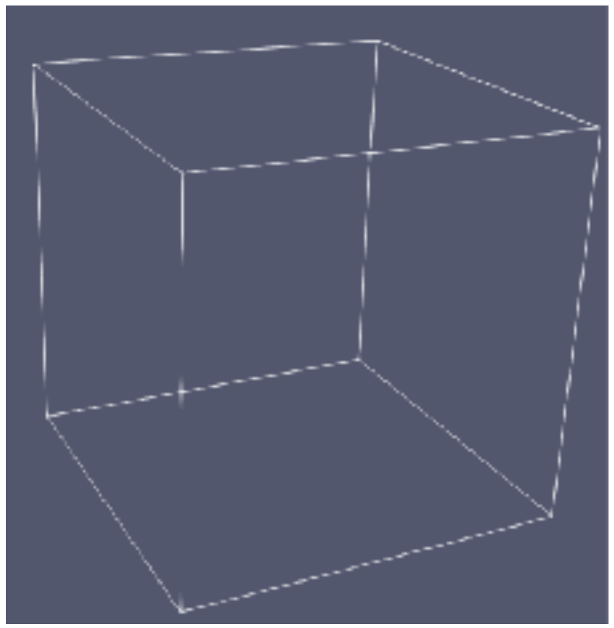
eg. Kofman, Linde, Starobinsky

Oscillon formation

Preliminary

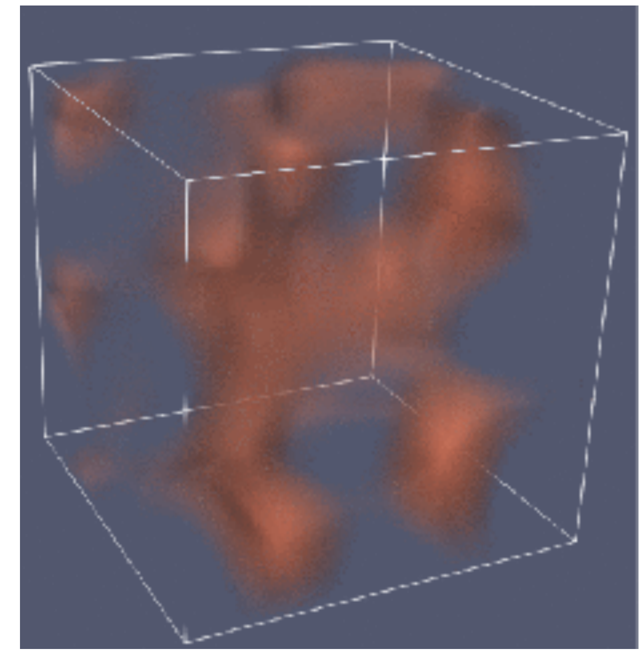
Kitajima, Soda, Y.U. (in preparation)

$a \sim a_0$



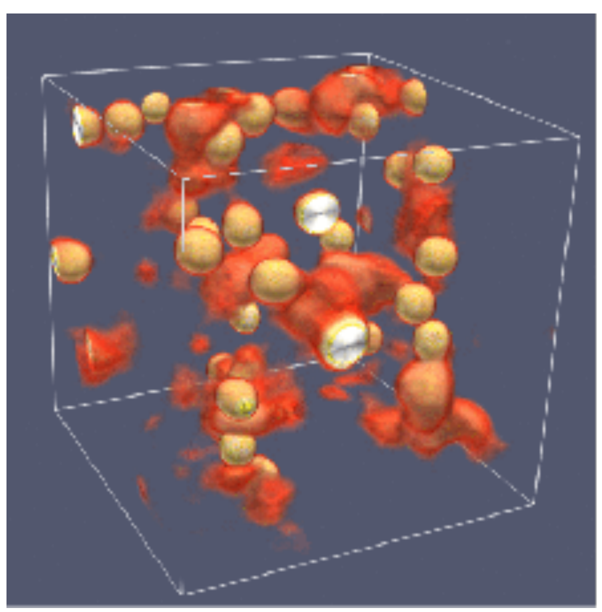
$a \sim 20\, a_0$

rescattering



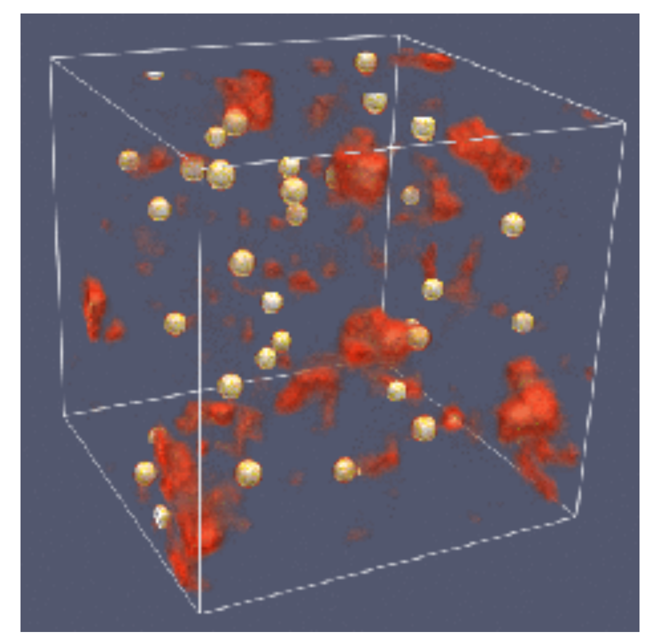
$a \sim 35 a_0$

turbulence



$a \sim 90\, a_0$

oscillon



$N_{grid} = (128)^3$

$f \sim 10^{-4} M_P$, $c=5$, $\phi i=5$ → $\Omega_{GW} \sim 10^{-15}$ in PTA band

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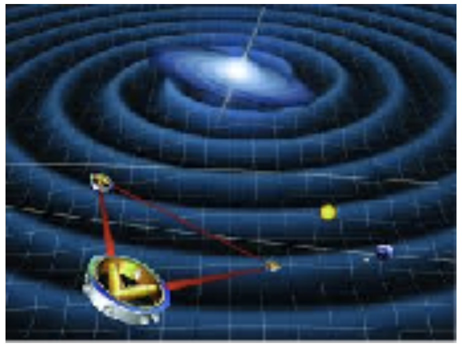

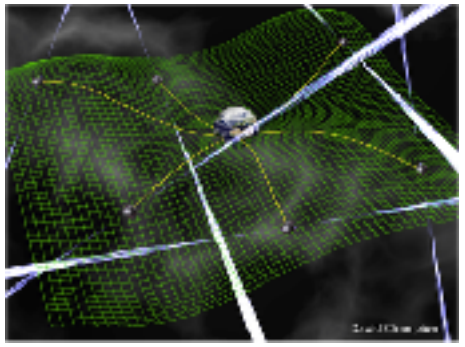

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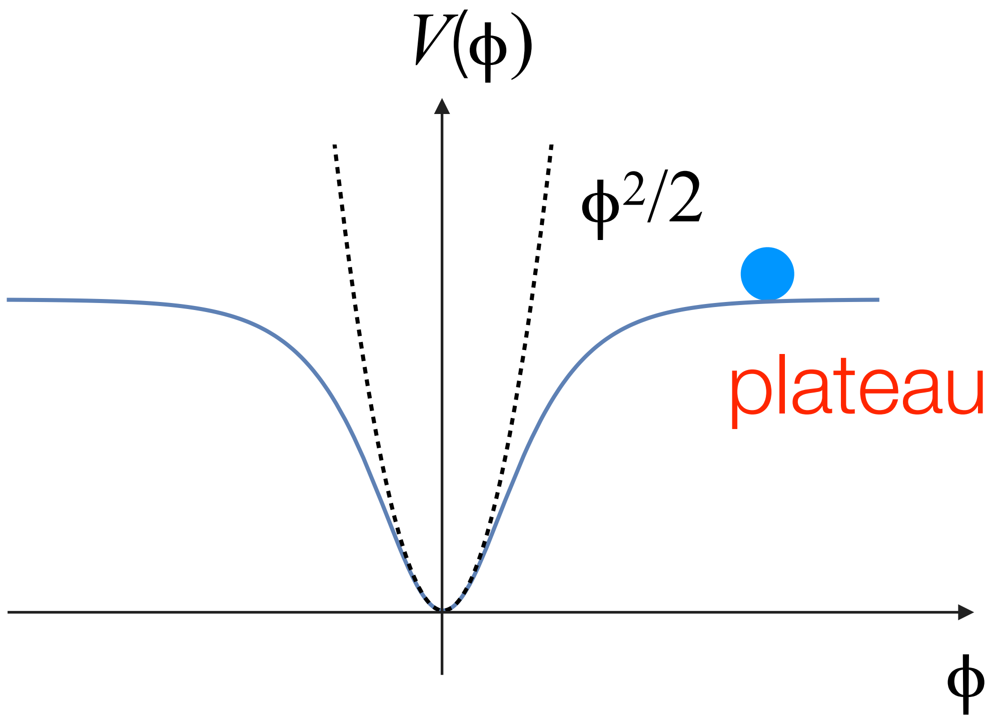


4. PR finished due to red-shift

Yet, for DM= axion, imprints on structure formation

Resonance peak in spectrum

Imprints for axion DM

<u>Alternative solution to small scale issues of ΛCDM??</u>

ULA w/ $m \sim 10^{-22} eV$

Recall Nagamine-san's

→ Emergent pressure smooths at $k > k_J$

k_J : Jeans scale

→ Tension with small scale observations?

Irsic et al. (17), Kim et al. (17), ⋯

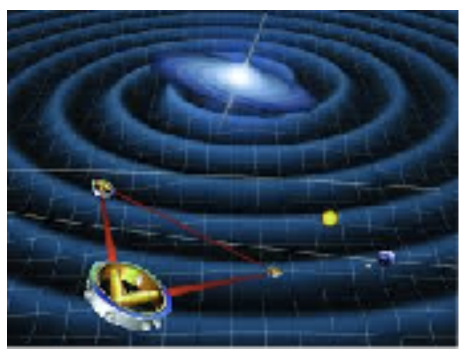
Note!! Resonance scale $k_r > k_J \propto a^{1/4}$

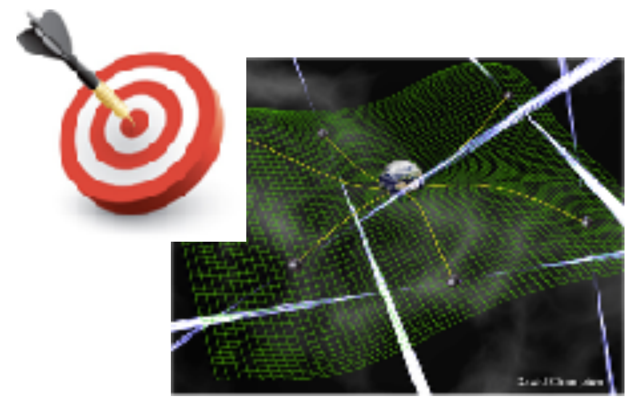
Evade tension? (in progress)

Summary

<u>Targets: Axions in plateau</u>

i) New window in string axiverse





ii) For Axion DM, enhancement of power spectrum at the scale determined by ~ the mass scale.

Remedy for tension of ULA w/small scale observations?

in progress

Ultralight axion (ULA)

What is often said….

$m > H_{eq} \sim 10^{-27}$ eV, ULA is quiet in cosmological scales.

→ Not ULA in plateau!

Jeans scale

ULA has pressure → Jeans scale $k_J(a) \simeq \sqrt{mH}\, a$

$k > k_J$ fluctuations are smoothed out

→ Tension with Lyman α forest observation

at equal time $k_r \simeq \sqrt{x_{osc}}\, k_J(a_{eq})$ Relaxing the tension?