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GW Forest from String Axiverse

In collaboration with Naoya Kitajima and Yuko Urakawa

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String axiverse

QCD axion

Resolve the Strong CP problem

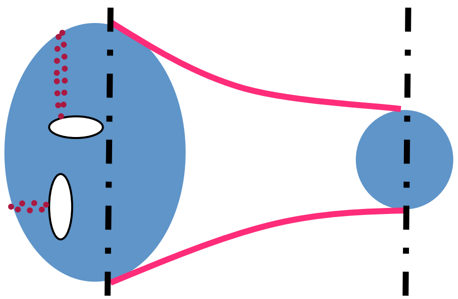
$$m_a \approx 6\times10^{-6}\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

f_a : decay constant

string axions are ubiquitous

Model independent axion $H = dB = *d\theta$

Model dependent axion $a_i = \int_{C_{p_i}} F_p$



$$m_a \approx \frac{\mu^2}{f_a} e^{-\#\mathrm{moduli}/2}$$

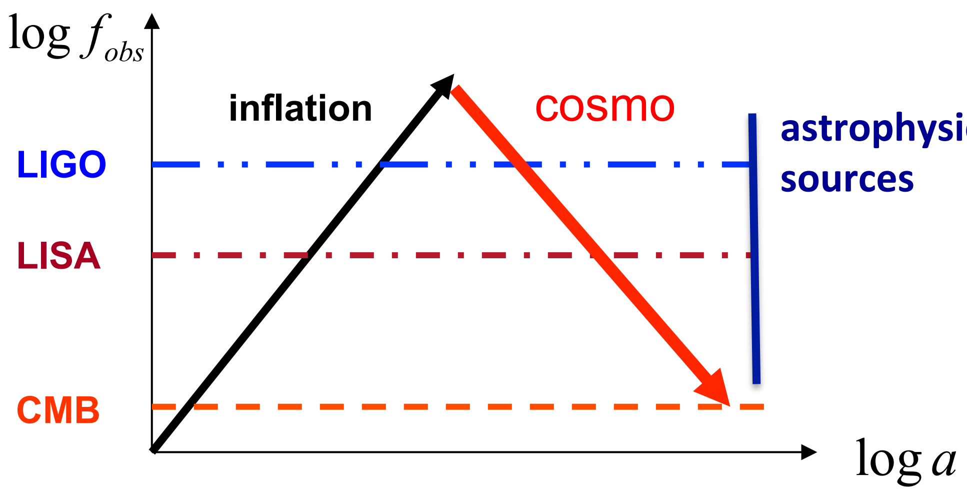
Mass distribution is logarithmically flat

String axiverse

GW sources

Cosmologically, a typical frequency is given by the free fall time $f \sim \sqrt{G\rho} \sim H$

We observe the redshifted frequency $f_{obs} \sim H\left(\frac{a_0 = 1}{a}\right)^{-1} \sim \dot{a}$



Multi-frequency gravitational wave observations will explore inflation, black holes and various phase transitions which produce topological defects.

On top of these, we would like to probe extra-dimensions and compactification in string theory.

Axion potential with plateau

Conventional axion potential

$$V(\phi) = m^2 f^2 \left[1 - \cos\frac{\phi}{f} \right]$$

◆ If the dilute gas approximation is not good, we may have more general potentials.
For example, pure Yang-Mills theory yields the following potential

$$V(\phi) = M^4 \left[1 - \frac{1}{\left(1 + (\phi / F)^2\right)^{\beta}} \right]$$

Nomura & Yamazaki 2018

◆ Multiple cosine terms give rise to the potential with plateau.

Czerny & Takahashi 2014

◆ Non-minimal kinetic term leads to potential with a plateau.
The alpha-attractor type potentials belong this class.

Kallosh & Linde 2013

Alpha attractor model

Axion potential with plateau:

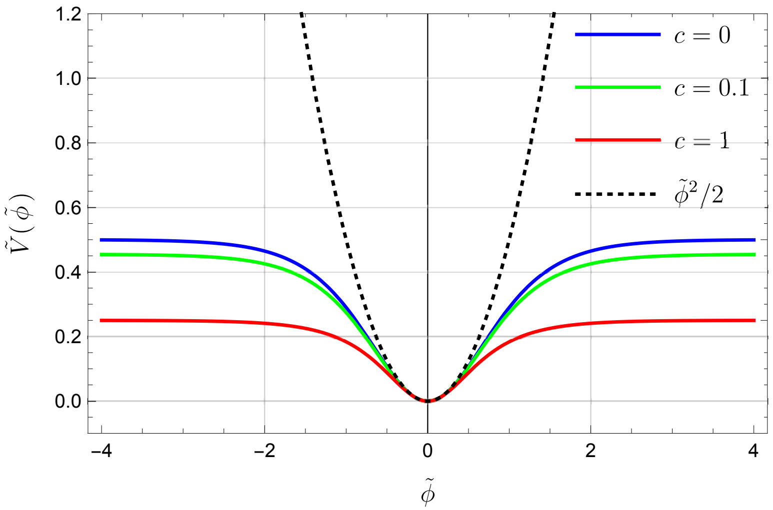
$$V(\phi) \to \frac{1}{2} m^2 \phi^2 \quad \text{in the limit} \quad \phi \to 0$$

$$\frac{V_\phi(\phi)}{\phi} \ll m^2 \quad \text{for} \quad \phi \geq f$$

Here we take the alpha attractor model as an example.

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

Soda & Urakawa 2017



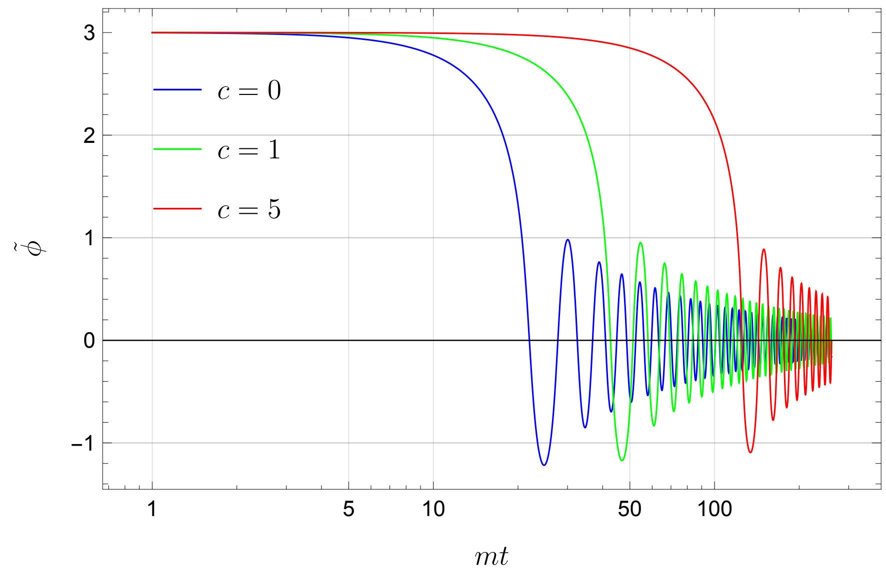
Background axion dynamics

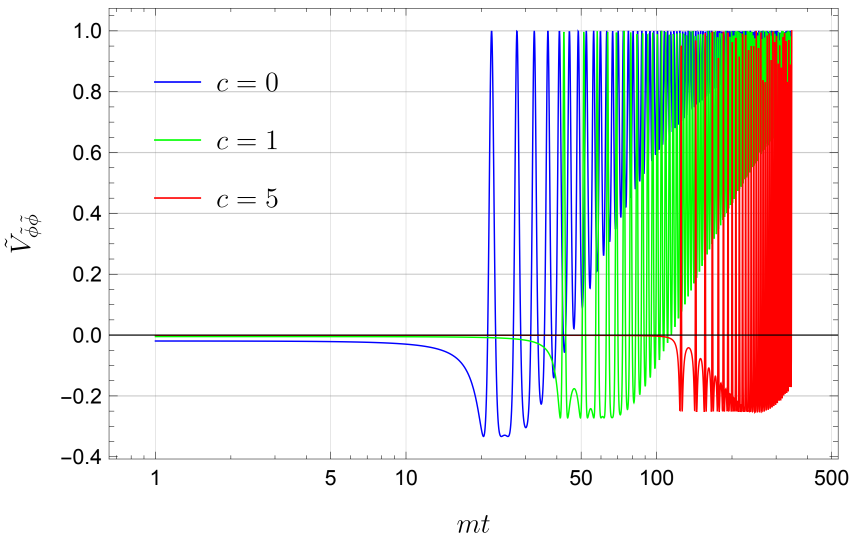
Soda & Urakawa 2017

Delayed oscillation

$$\frac{H_{osc}}{m} \approx \sqrt{\frac{V_\phi}{m^2\phi}} \ll 1 \quad \Longleftarrow \quad \frac{d^2\phi}{dt^2} \approx H^2\phi \approx -V_\phi$$

In the case of potential with plateau, there occurs the strong parametric resonance.

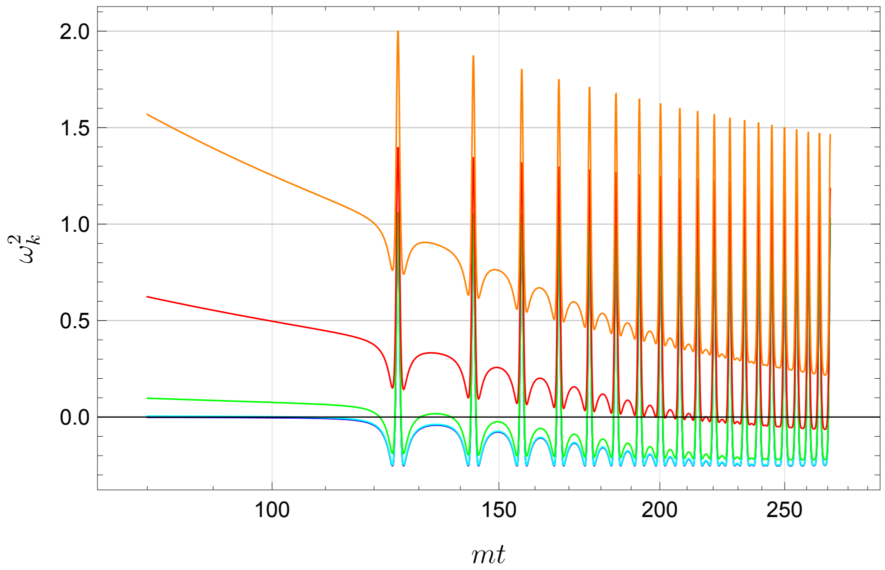


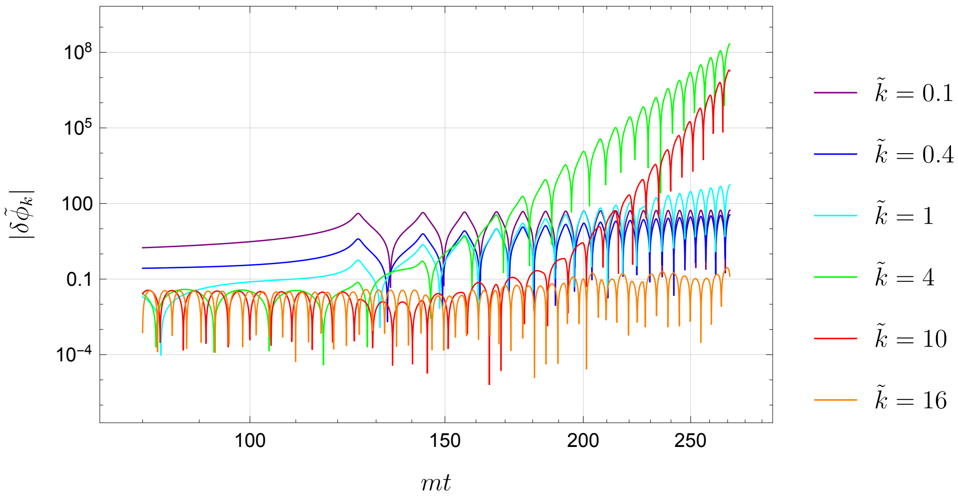


Axion dynamics in the linear stage

In the case of potential with plateau, there occurs the strong resonance.

$$\omega_k^2 = \left(\frac{k}{a}\right)^2 + V_{\phi\phi}$$



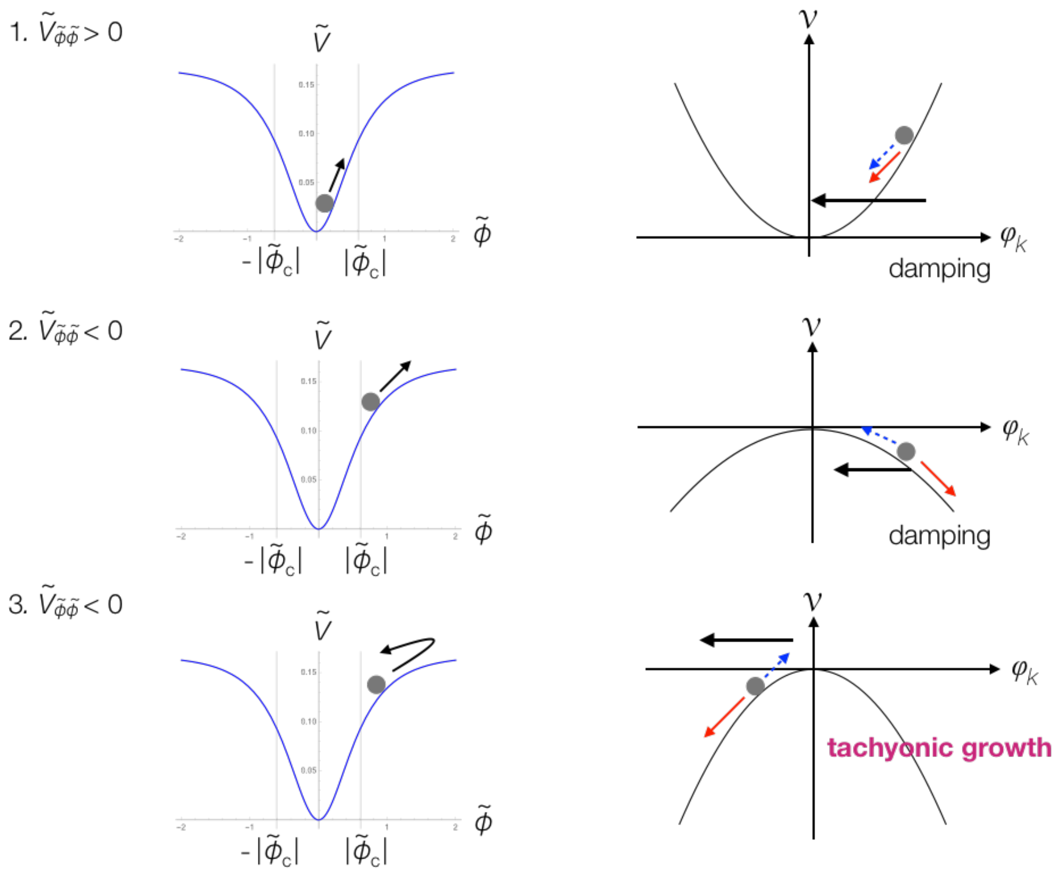


We named this strong resonance the flapping resonance.

Flapping resonance

Kitajima, Soda & Urakawa 2018

For large k, flapping never occurs.



For very small k, damping and enhancement compensate exactly.

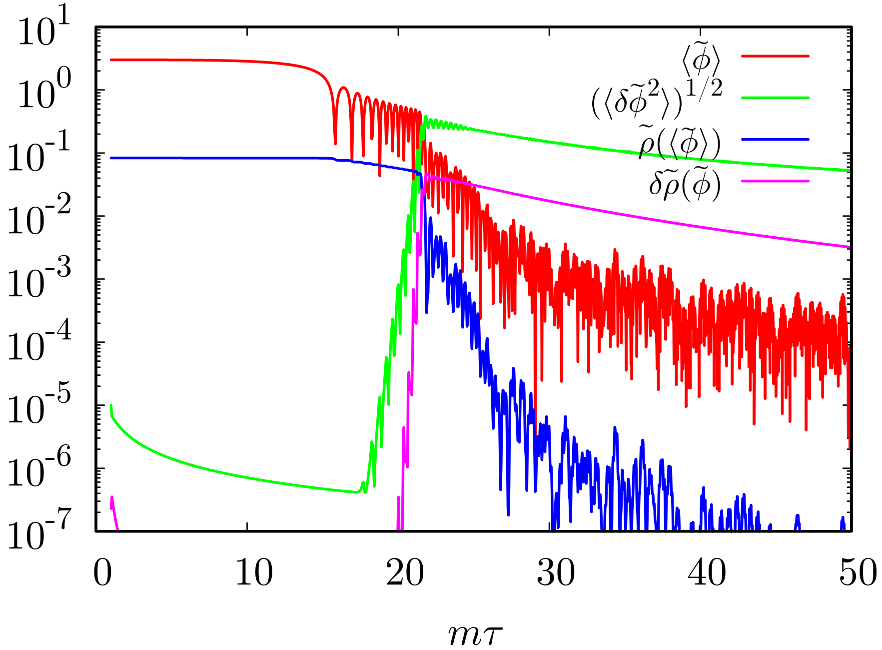
For moderate k, gradient makes the damping time short.

Thus, there appears a peak in the spectrum of axion fluctuations.

Non-linear lattice calculations

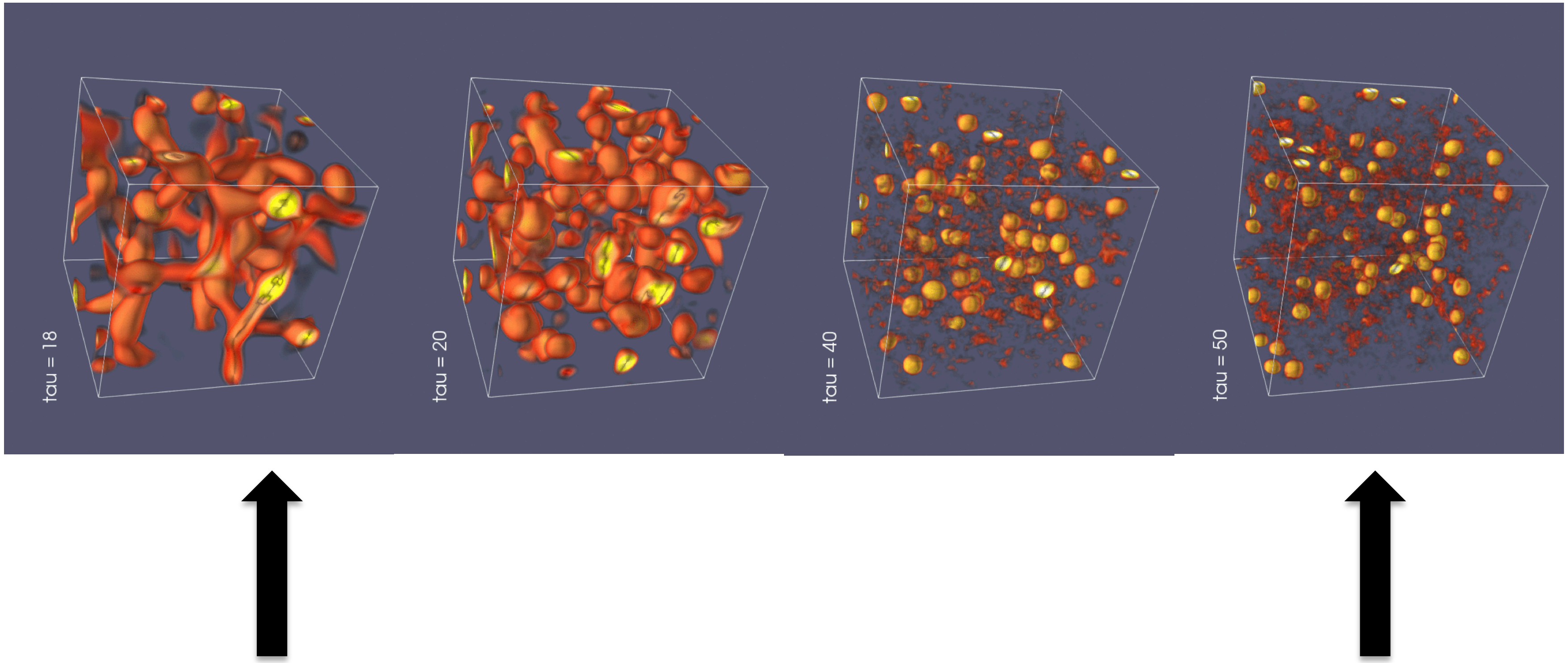
Kitajima, Soda & Urakawa 2018

When fliuctuations catch up the background amplitude, we
Need to resort to numerical calculations.



What is going on actually can be seen in the snapshot.

When are GWs mostly generated?



Violent power transfer occurs

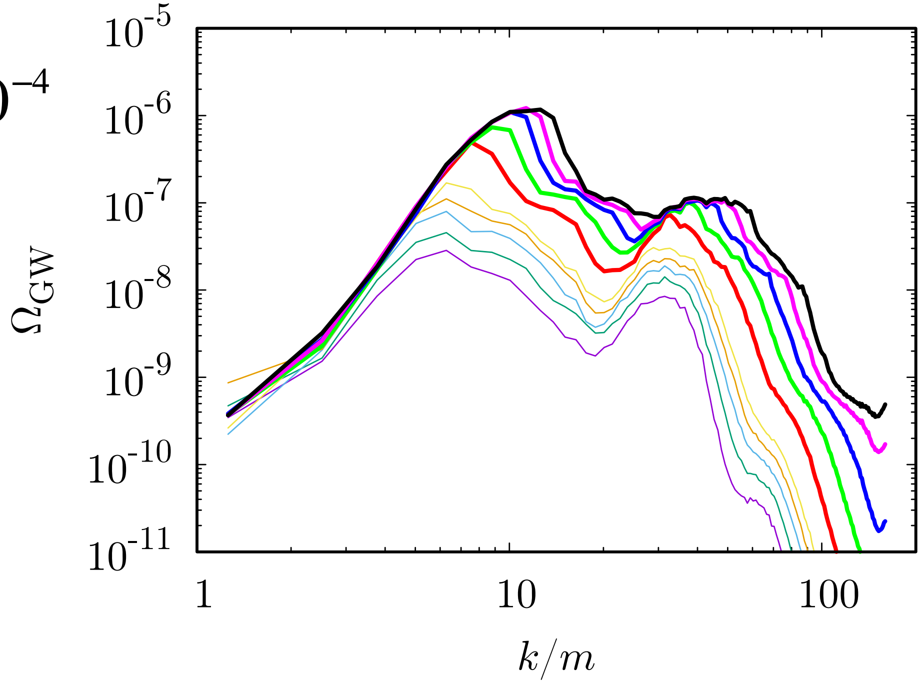
Oscillon formation

GW production triggered by flapping resonance

Kitajima, Soda & Urakawa 2018

During the violent power transfer of fluctuations, GWs will be produced efficiently.

$\times 10^{-4}$



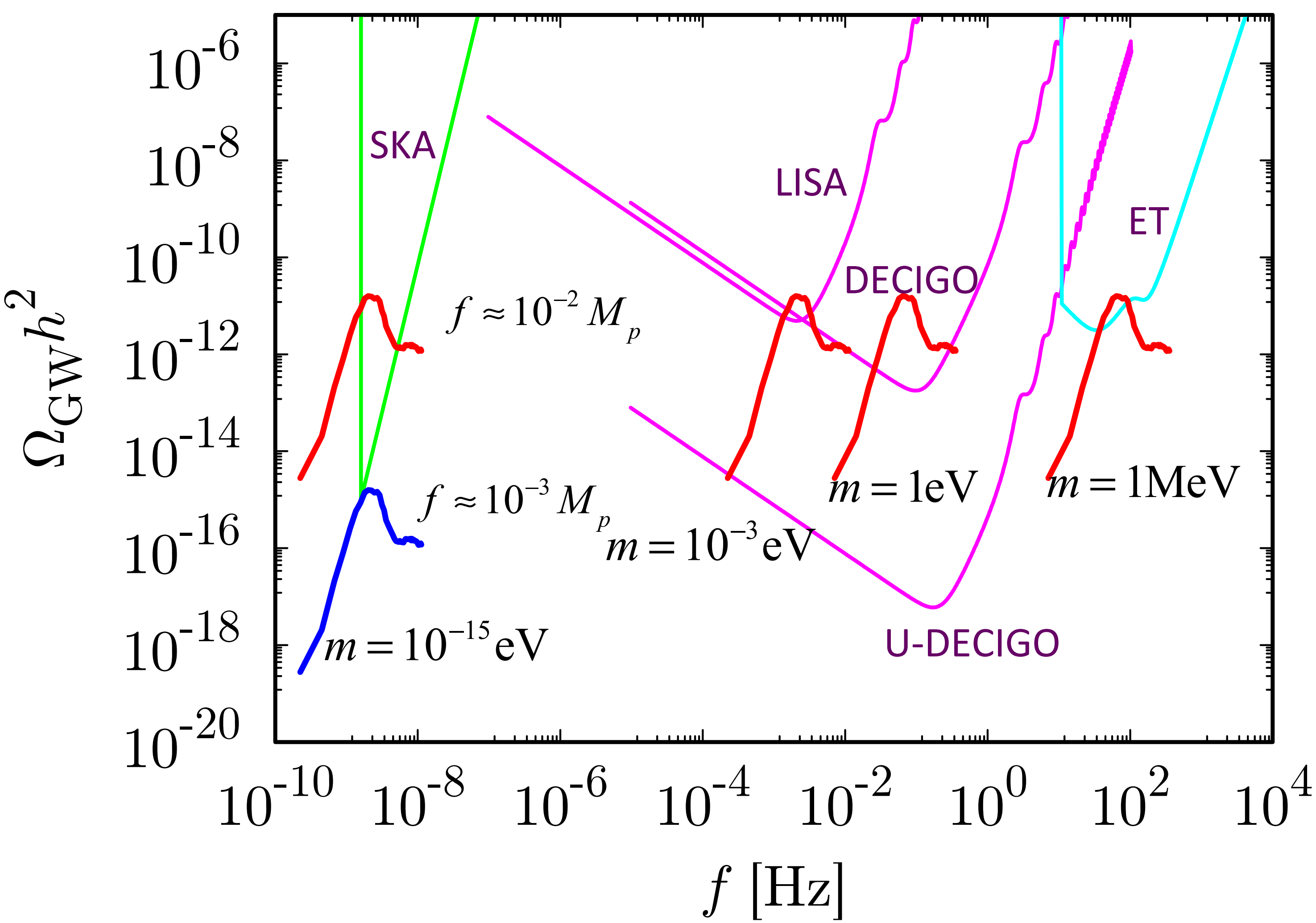
$f \approx 10^{-2} M_p$

From the peak frequency, we know the axion mass.
From the amplitude and profile,
we can get the information of the decay constant and model parameter.

GW Forest

Kitajima, Soda & Urakawa 2018

Since the string axions have broad spectrum, there must be many peak structure in the GW spectrum, which we named the GW forest.



Conclusion

- Axions are ubiquitous in string theory.
- Multi-frequency observation will be realized in future.

- The axion potential with a plateau exhibits the flapping resonance.
- String axiverse produces GW forest.
- Multi-frequency observations of GW forest would allow us to explore string compactification.