Generation of Axion/ALP Dark Matter

arXiv:2507.13127

CDM

- Accounts 23% of total energy density of universe while baryonic matter accounts 4%.
- Properties:

a. Pressureless

Primordial velocity is very small , at most ~ $10^{-8}c$ today .

b.Collisionless

Cold dark matter is weakly interacting (so dark), except for gravity.

$$m_0 \approx 6 \times 10^{-5}\text{eV}(\frac{10^{11}\text{GeV}}{f_a})$$

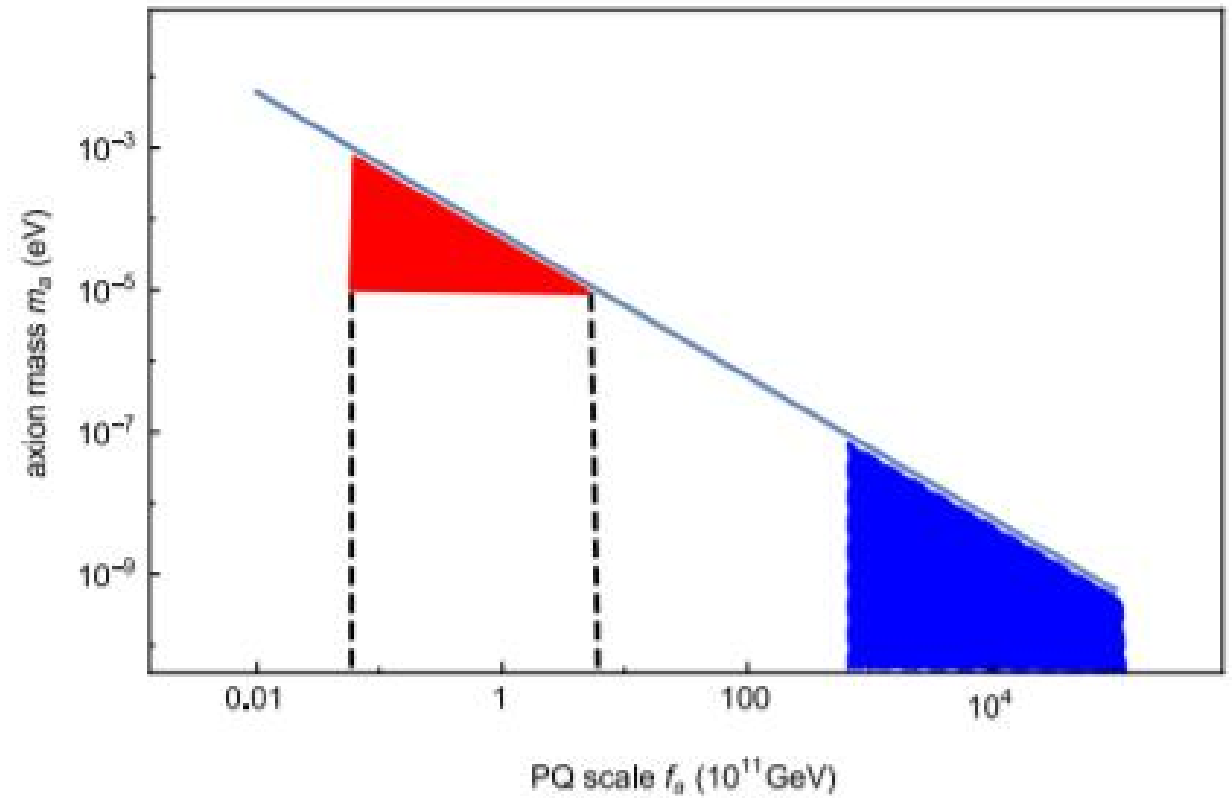
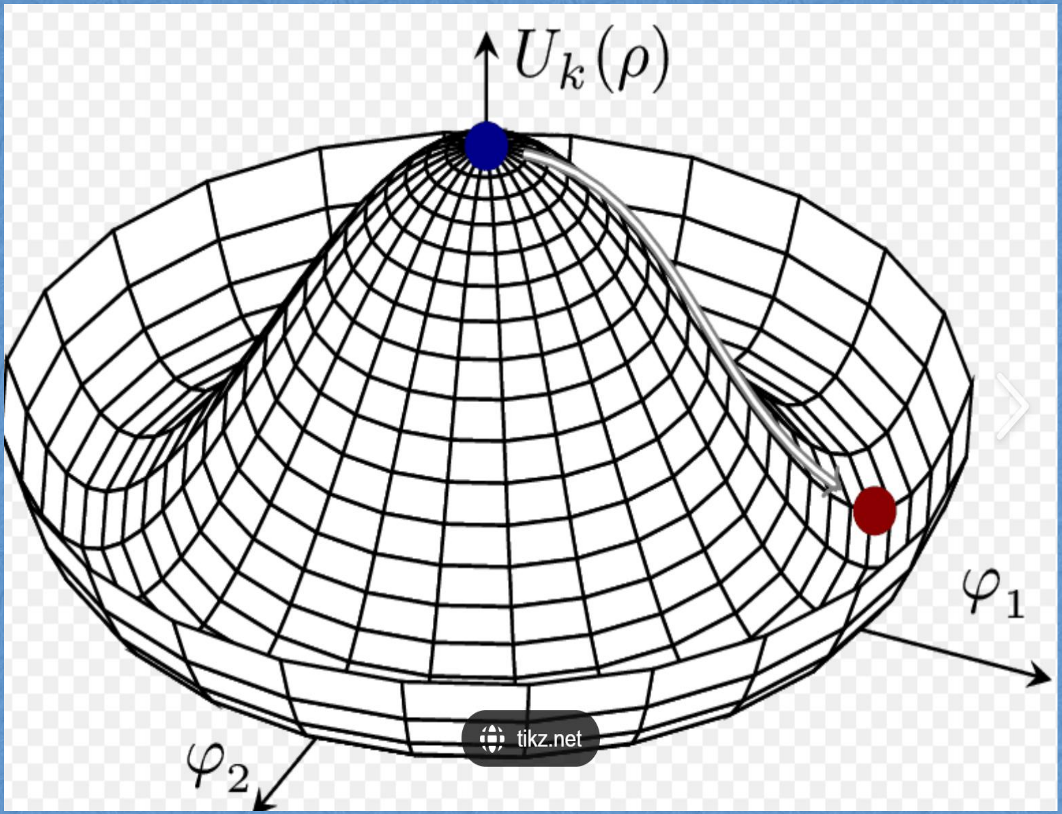


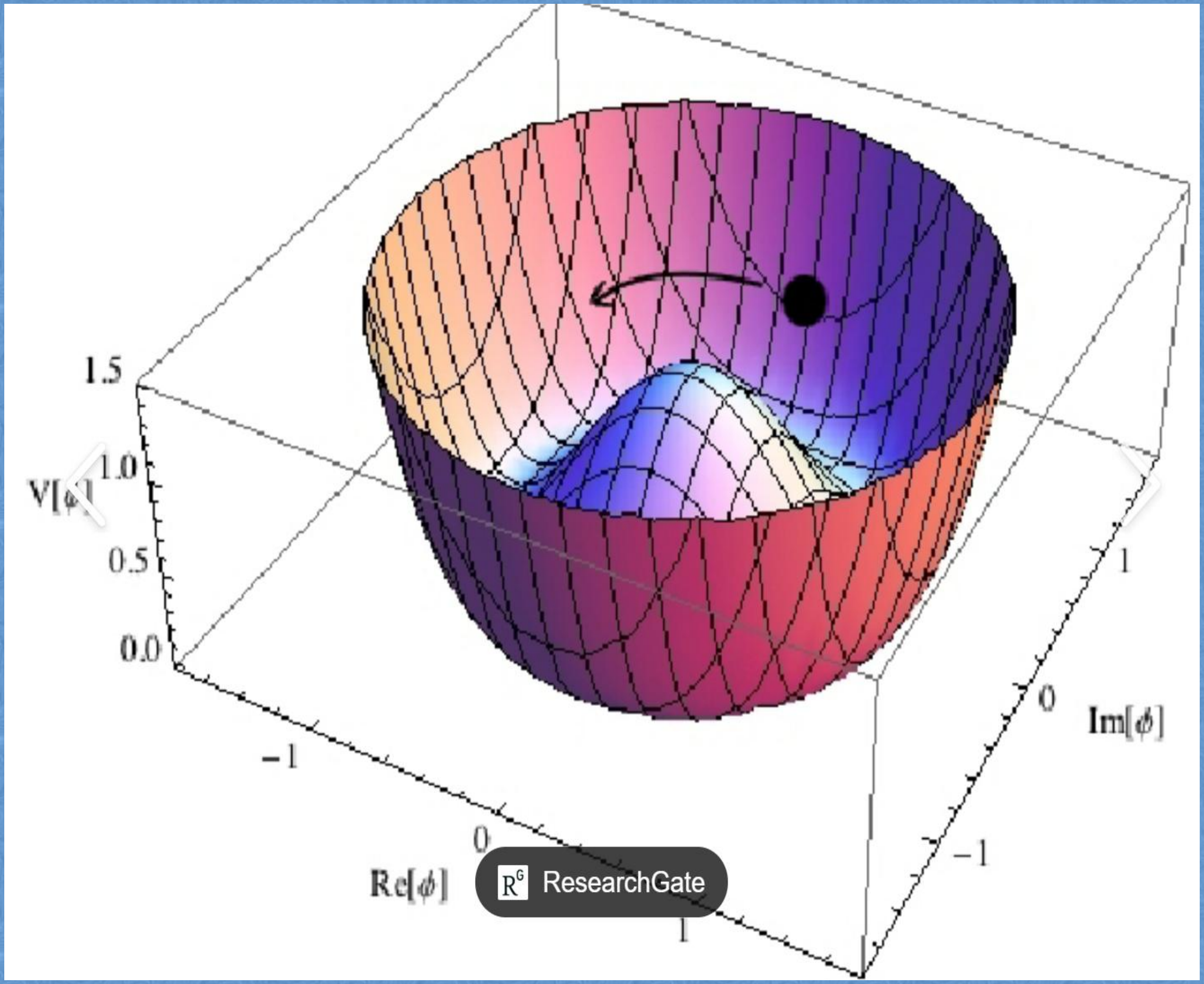
FIG. 1: The two possible windows of the dark matter axions. The upper-left one is often called the classical window and the lower-right one is the anthropic window assuming that $H_I < 10^{10}$GeV and the PQ symmetry was not restored after inflation.

Misalignment Mechanism

PQ symmetry breaking



Misalignment Mechanism



$$-\partial_t^2\phi + \frac{1}{a^2}\partial_j^2\phi - 3H\partial_t\phi - m^2(T(t))\phi - f(\vec{x},t,\phi) = 0$$

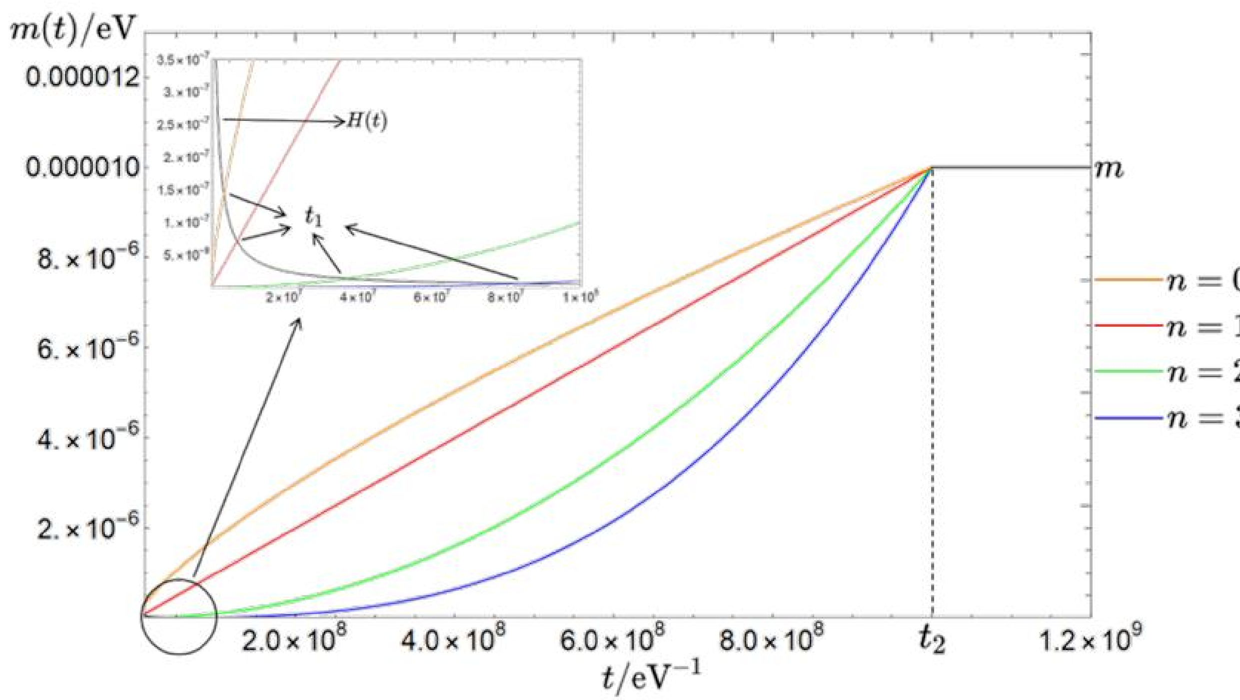


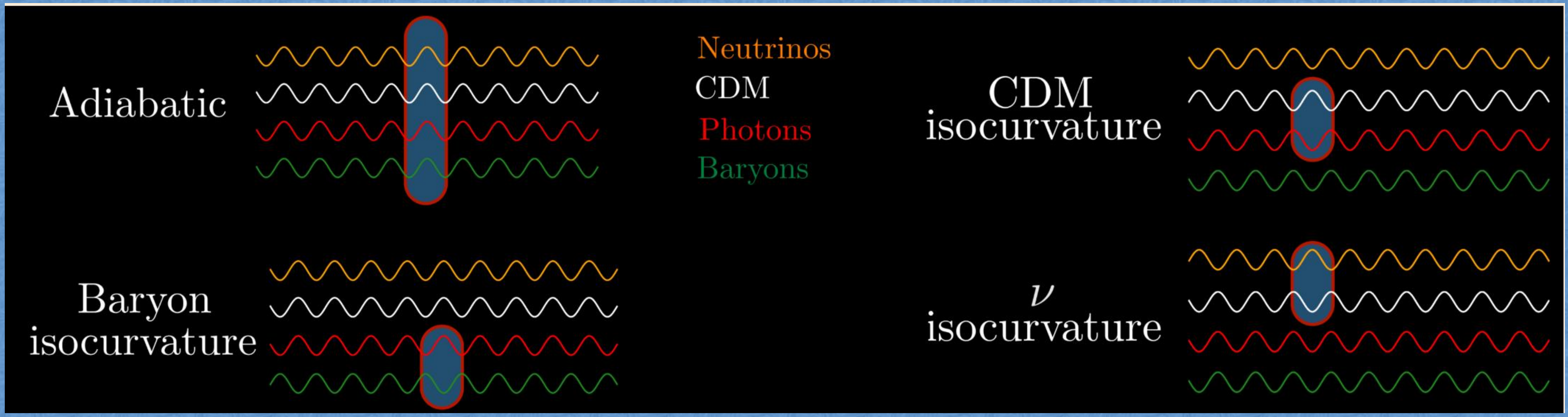
FIG. 1: The mass function of time t.

$$m(t) = \begin{cases} 0 & t \ll t_1 \\ m\left(\frac{t}{t_2}\right)^n & t_1 \le t \le t_2 \\ m & t > t_2\,. \end{cases}$$

Why resonant cavity?

The resonance matches forced oscillator and on resonance achieves a large axion-induced excitation.

The isocurvature perturbation

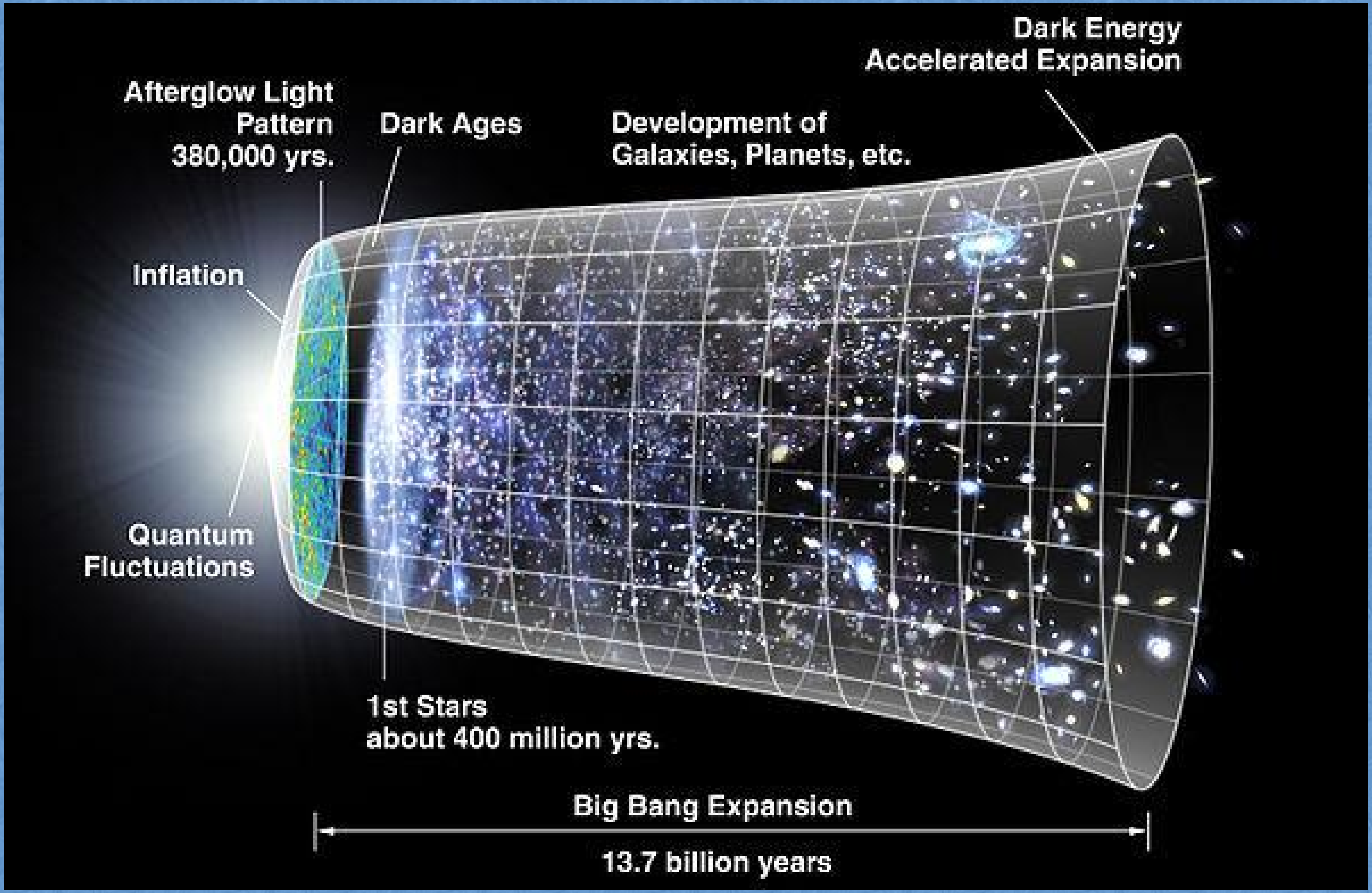


The isocurvature perturbation

Axion field existed before inflation
induce isocurvature perturbation

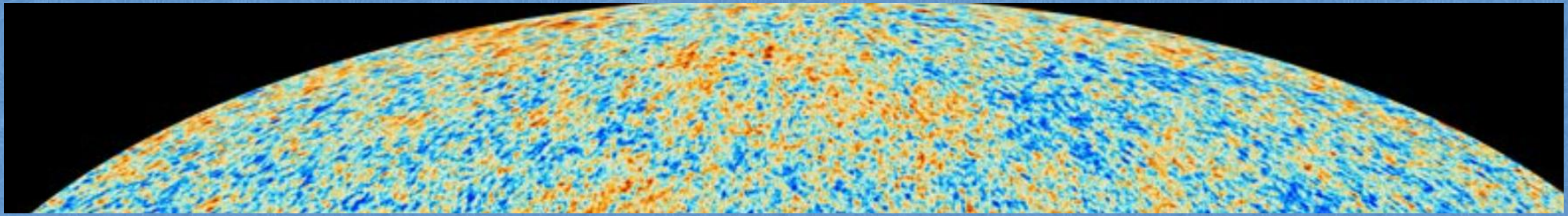
Axion field existed after inflation
produce topological defects

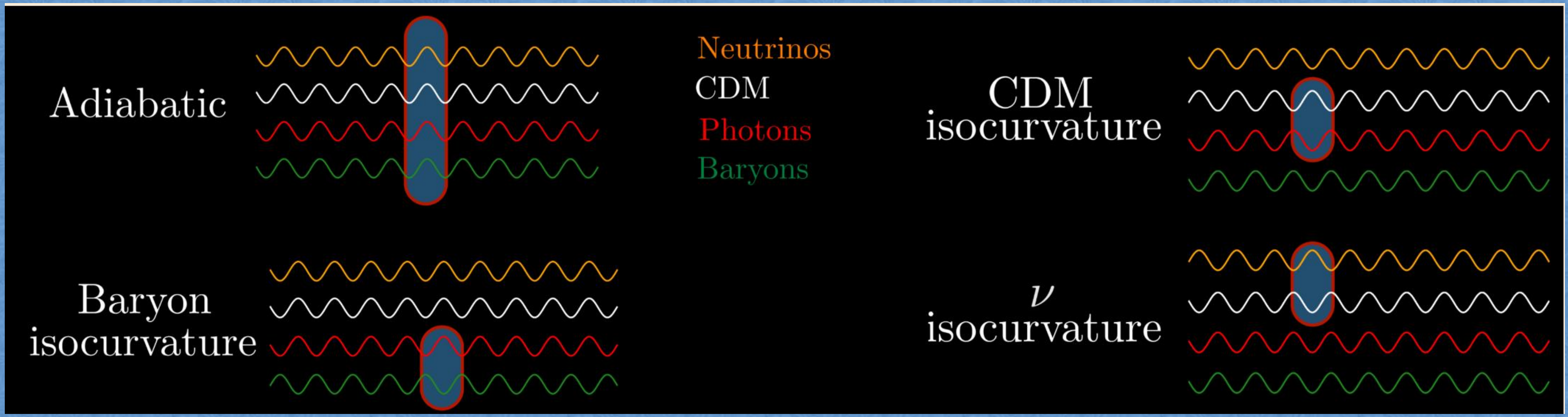
History of the Universe



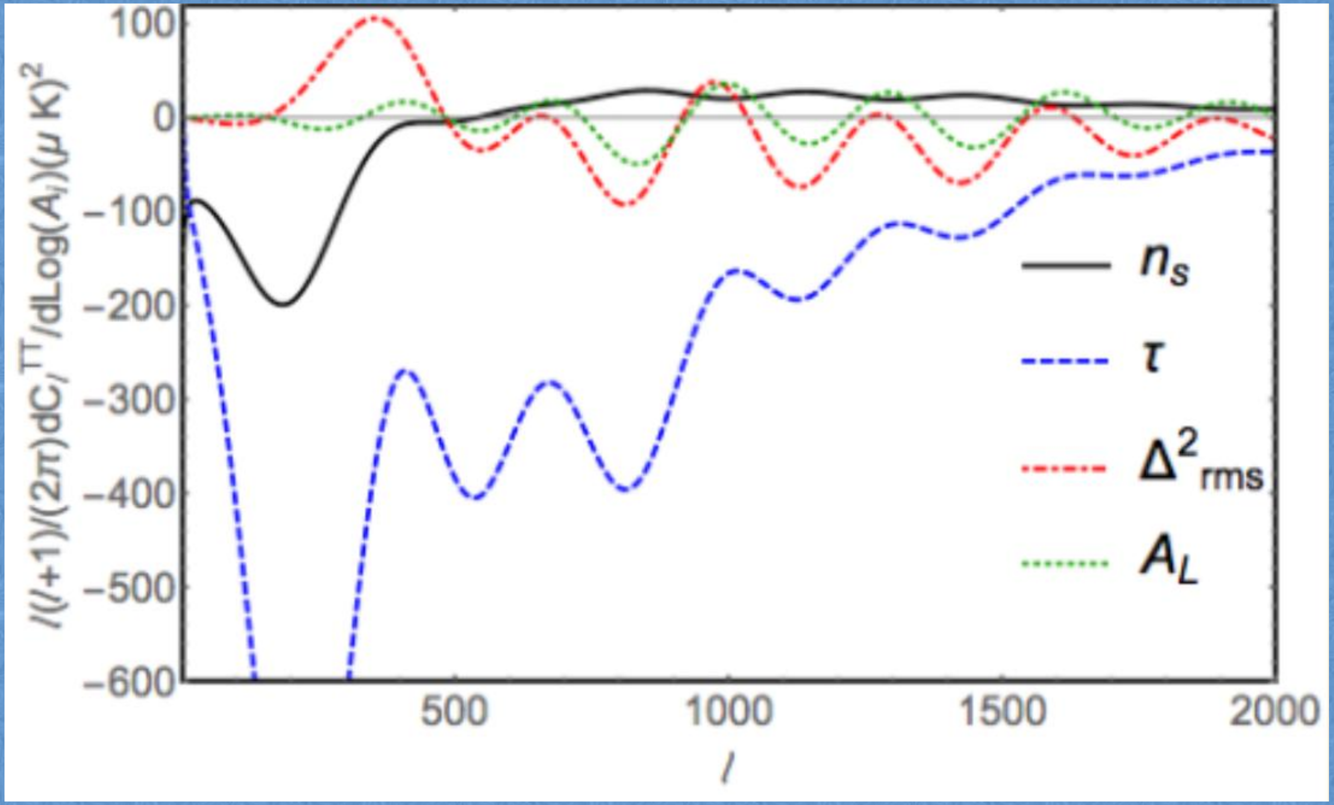
picture by NASA

The quantum properties of the Horizon





The quantum properties of the Horizon



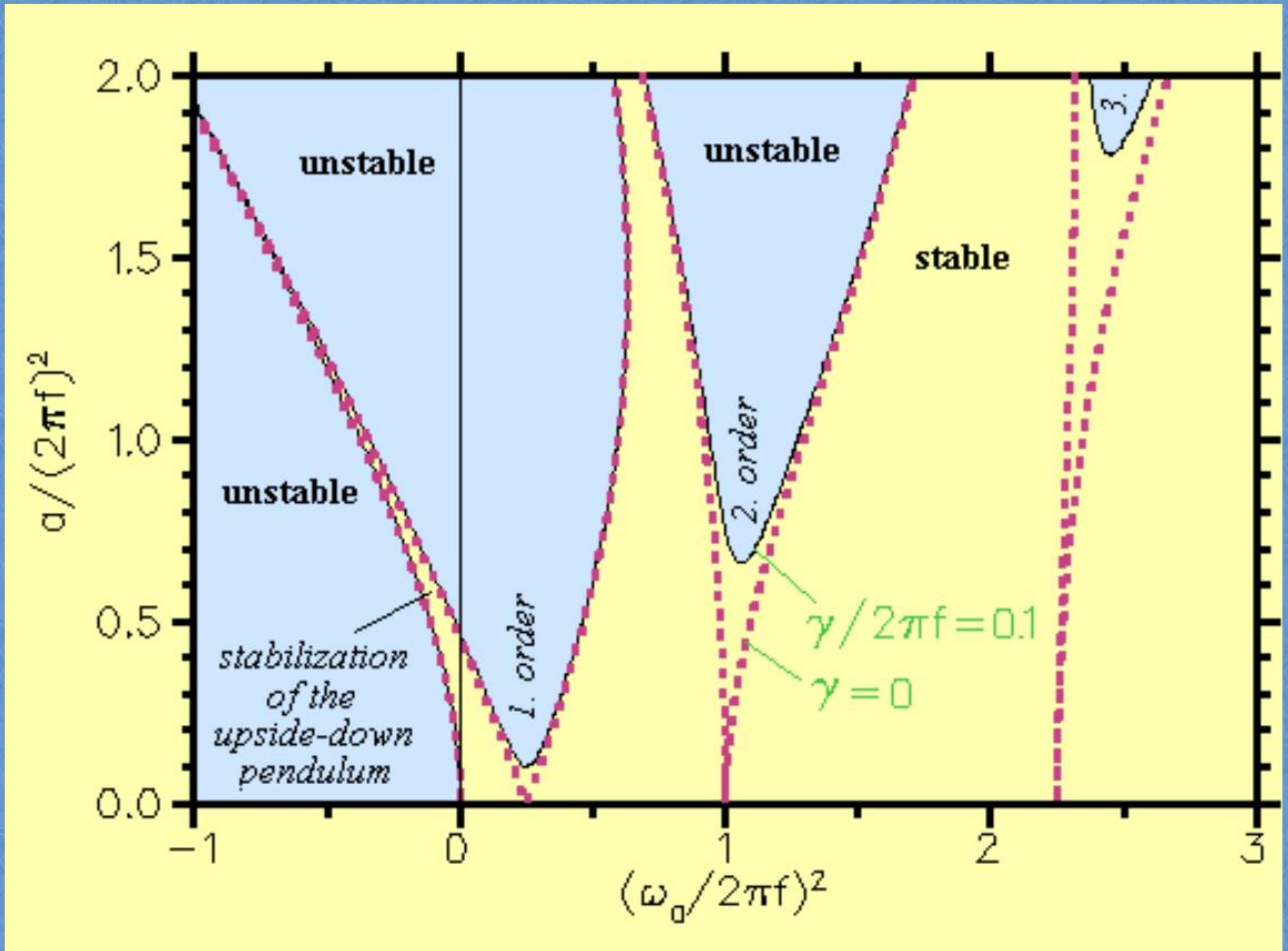
Parametric resonance

Mathieu equation:

$$\frac{d^2\varphi}{dt^2} + \gamma\frac{d\varphi}{dt} + (\omega_0^2 + a\cos 2\pi f t)\,\varphi = 0$$

Non-linear, different from the forced resonance

Parametric resonance



$$f_0 \equiv \frac{\omega_0}{2\pi} = \frac{f}{2}\,n$$

The Adiabatic fluctuation:

$$\Phi = 3\Phi_p(\vec{k}) \left(\frac{\sin\left(k\eta/\sqrt{3}\right) - \left(k\eta/\sqrt{3}\right)\cos\left(k\eta/\sqrt{3}\right)}{\left(k\eta/\sqrt{3}\right)^3} \right)$$

The Equation of Motion

$$\ddot{\phi}(\vec{k},t) + \frac{3}{2t}\dot{\phi}(\vec{k},t) + \left(k^2\frac{t_1}{t} + m^2(t)\right)\phi(\vec{k},t)$$

$$+ \left[\frac{9\Phi_p(\vec{k})}{2t^2} - \frac{3\Phi_p(\vec{k})}{2}\frac{dm^2(t)}{dT}T(t)\right]$$

$$\times \cos\left(2k\sqrt{\frac{t_1 t}{3}}\right)\phi(\vec{k},t) = 0 \ ,$$

The respective Mathieu equation

$$\phi''(\vec{k},z) + \left[3 + \frac{3m^2(t)}{k^2} - 2 \times \frac{9\Phi_p(\vec{k})}{4k^2} \times \frac{dm^2(t)}{dT} T(t)\cos(2z)\right]\phi(\vec{k},z) = 0 \ ,$$

The parametric resonance condition

$$\phi_k'' + (A_k - 2q\cos 2z)\,\phi_k = 0 \ .$$

$$A_k = 3 + \frac{3m^2(t)}{k^2} \ ;$$

$$q = \frac{dm^2(t)}{dT}\frac{9\Phi_p(\vec{k})T(t)}{4k^2} \ .$$

$$A_k = 3 + \frac{3m^2(t)}{k^2} \; ;$$

$$q = \frac{dm^2(t)}{dT} \frac{9\Phi_p(\vec{k})T(t)}{4k^2} \; .$$

$$A_k \approx 2^2 = 4.$$

$$\Delta\omega/\omega \sim \sqrt{1 \pm q^2}$$

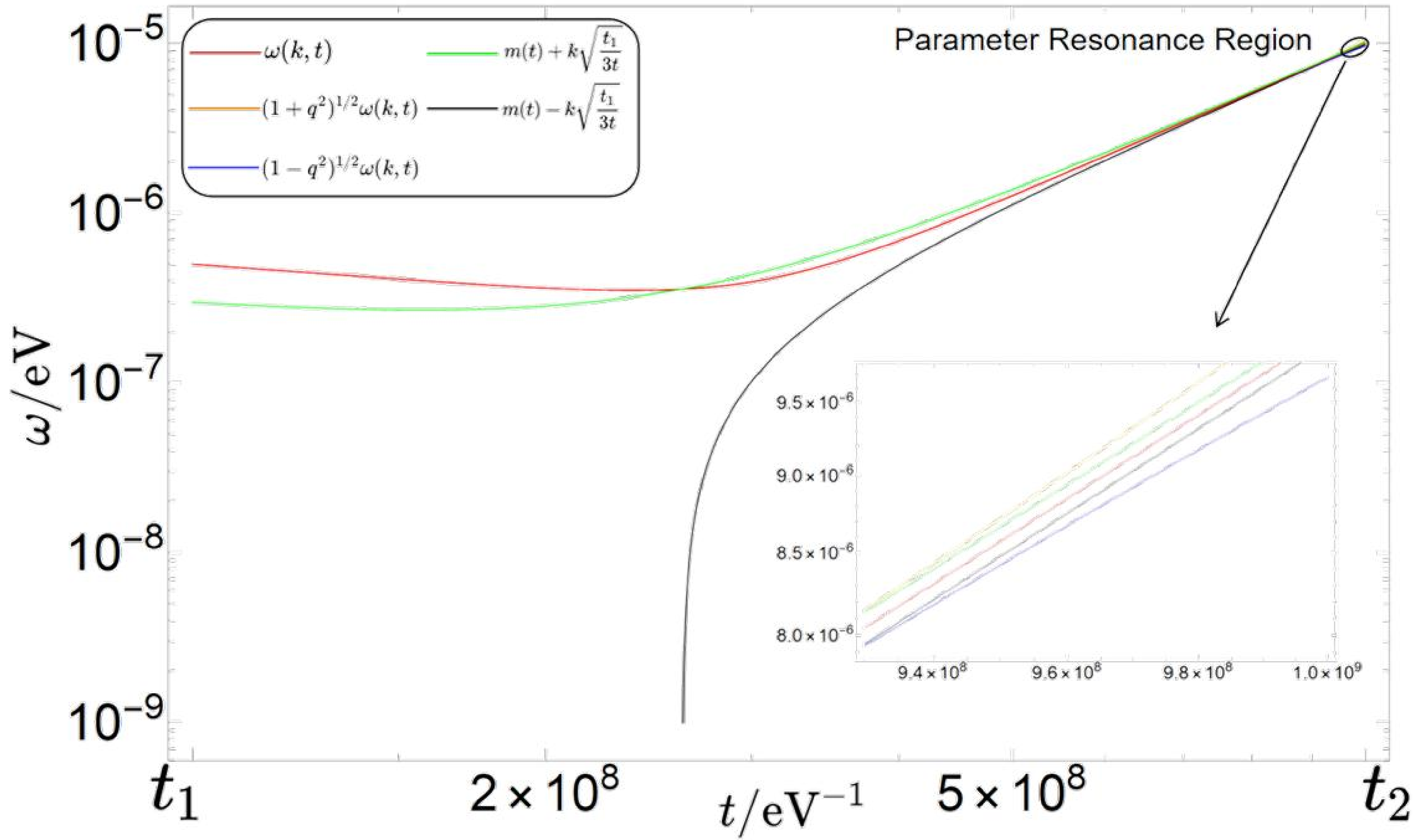


FIG. 6: The natural frequency ω and modulation frequencies $m \pm k\sqrt{t_1/3t}$ as a function of time t, with parameters $l = 2$, $n = 3$, $m = 10^{-5}\mathrm{eV}$, $t_2 = 10^9\mathrm{eV}^{-1}$, and $k = 50/t_1$.

The non-linear effect

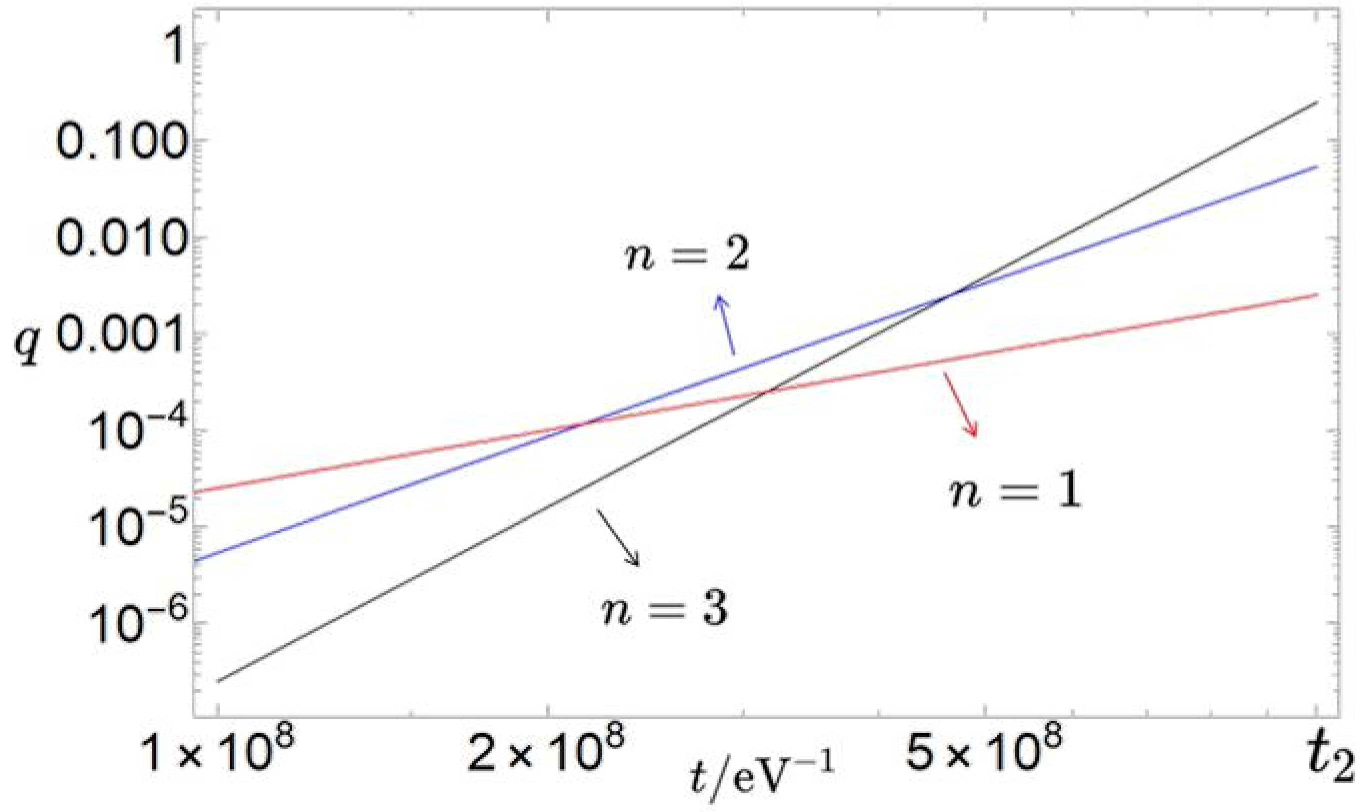
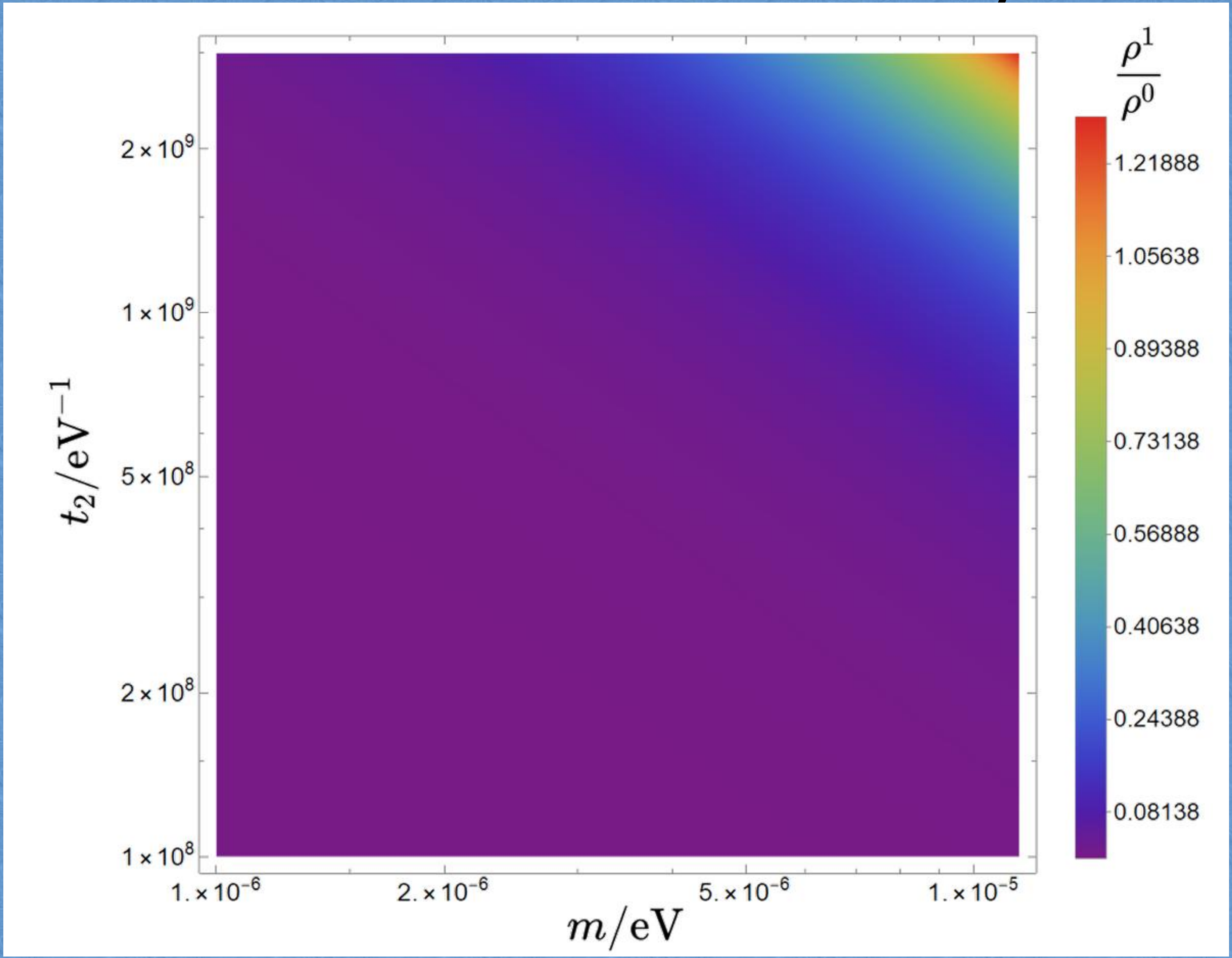


FIG. 3: The parameter q of Mathieu equation as a function of time t, where $l = 2$, $m = 10^{-5}\mathrm{eV}$, $t_2 = 10^9\mathrm{eV}^{-1}$, and $k = 50/t_1$.

The effective density



Benefit

no isocurvapoture perturbation

possible enlarged parametric space

solves the topological defects issue

future works and outlook

numerically simulations

does the scenario produce observable cosmological signals

Other effects

apply to dark photons,

modulis,

heavier axions can be substantial part of dark matter.

Hydrogen atoms are also ideal targets for the anthropic window

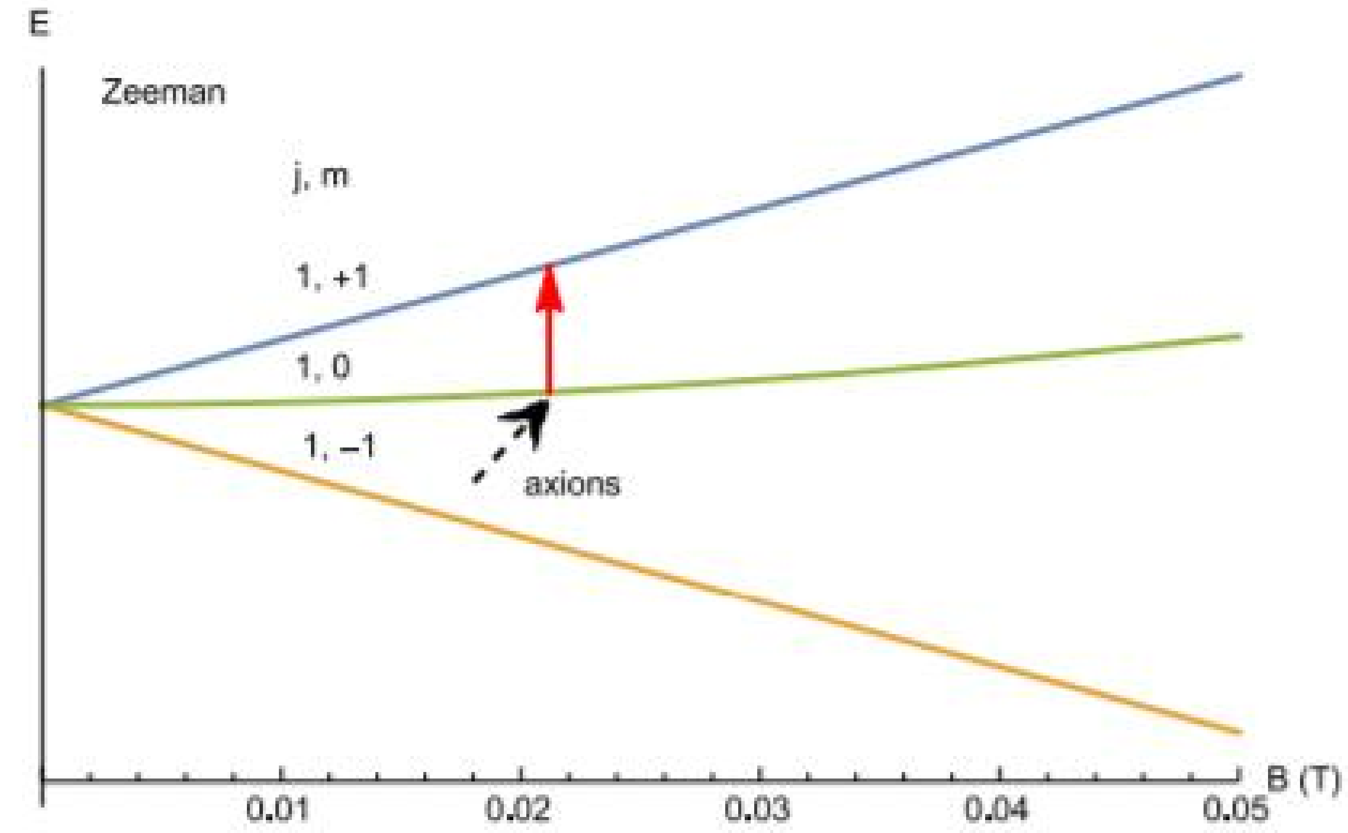


FIG. 3: The splitting of the hydrogen 1S triplet state. For the anthropic window $|1,0> \to |1,1>$ transition is suitable for the axion detection.