DarkCosmoGrav
January 23–25, 2023
PISA, ITALY

New Frontiers in Particle Physics, Gravity, and Cosmology

Axion Free-kick Misalignment Mechanism

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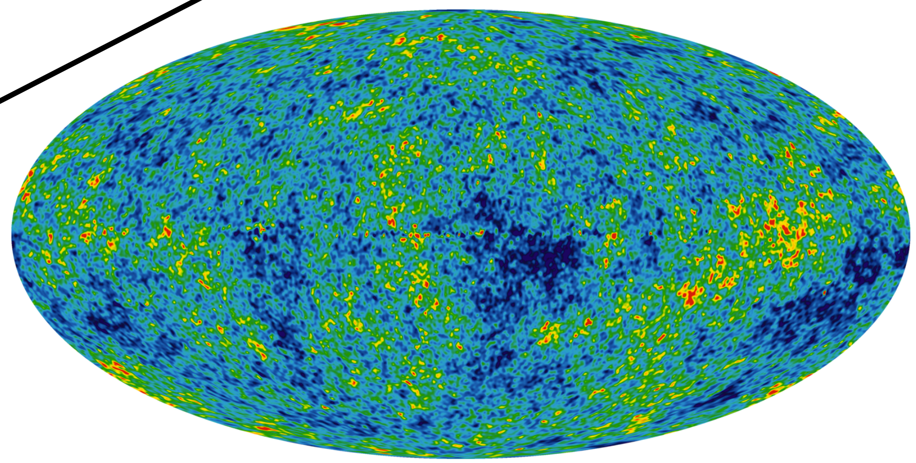
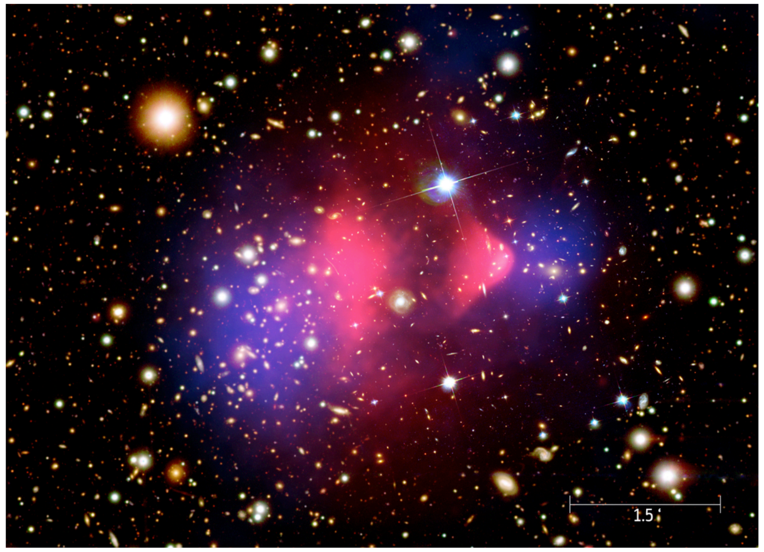
with Seokhoon Yun, hep-ph/2211.13074

Dark matter exists

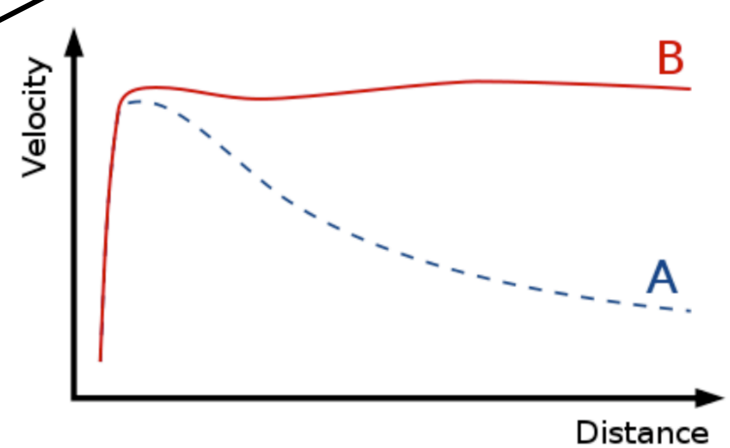
Universe



Galaxy clusters



Galaxies



Microscopic nature of dark matter

very few constraints:

- Upper bound ~ 10^{48} GeV, due to the observed absence of gravitational lensing.

- Lower bound ~ 10^{-22} eV for boson, otherwise the de Broglie wave length would be too large for it to fit within galaxy.

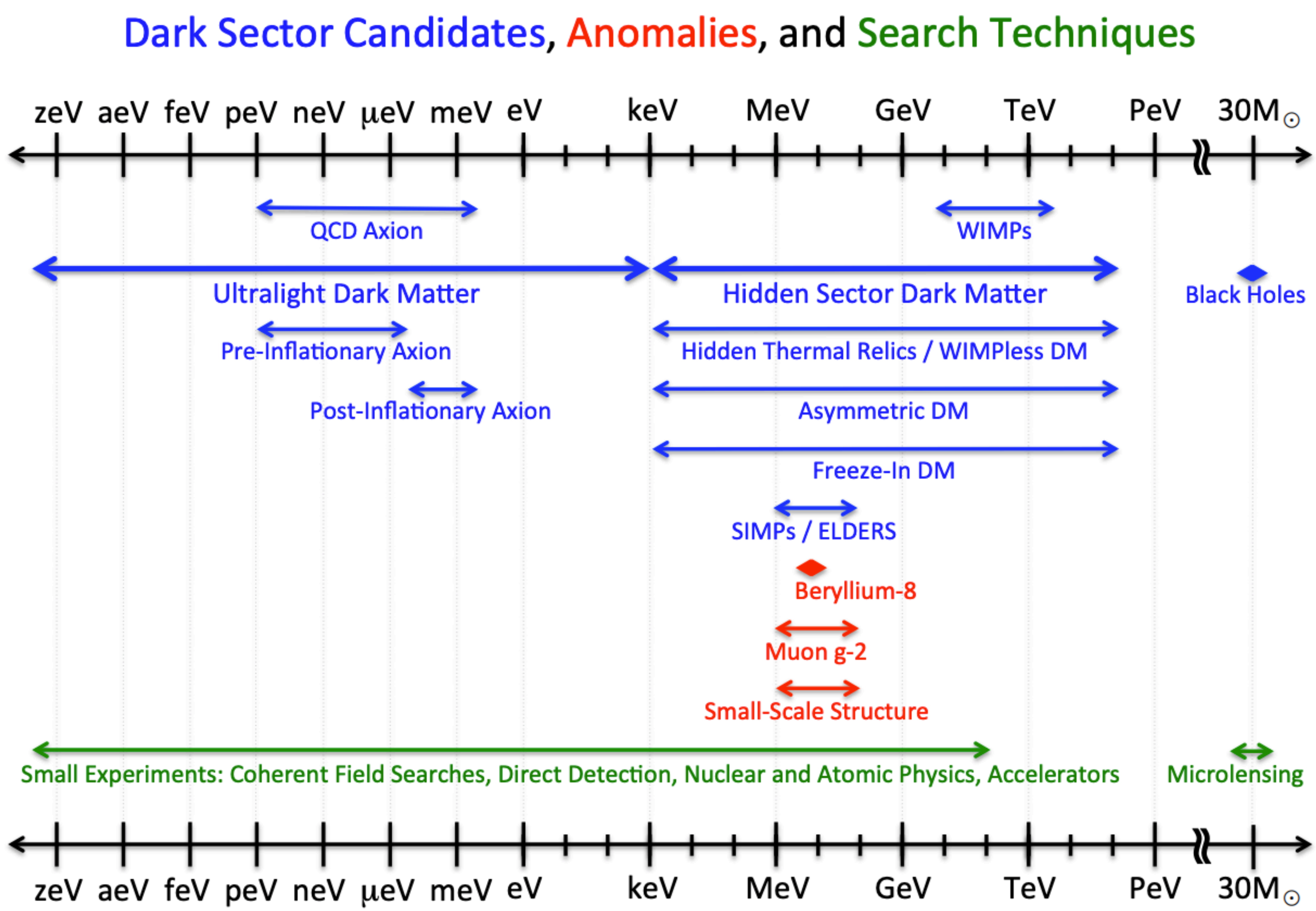
- Lower bound ~ 10 eV for fermion, otherwise the number density would be too large for it to fit in galaxy while still obey Pauli exclusion principle.

- Self interactions of DM should be small enough, there is less than $\mathcal{O}(1)$ scattering at the time scale when galaxy clusters merge.

- DM interacts weakly (if at all) with SM besides gravity, and needs to be stable/long-lived.

numbers taken from hep-ph/2204.03085 by Rajendran

Huge theory landscape



hep-ph/1707.04591

US Cosmic Visions: New ideas in Dark Matter

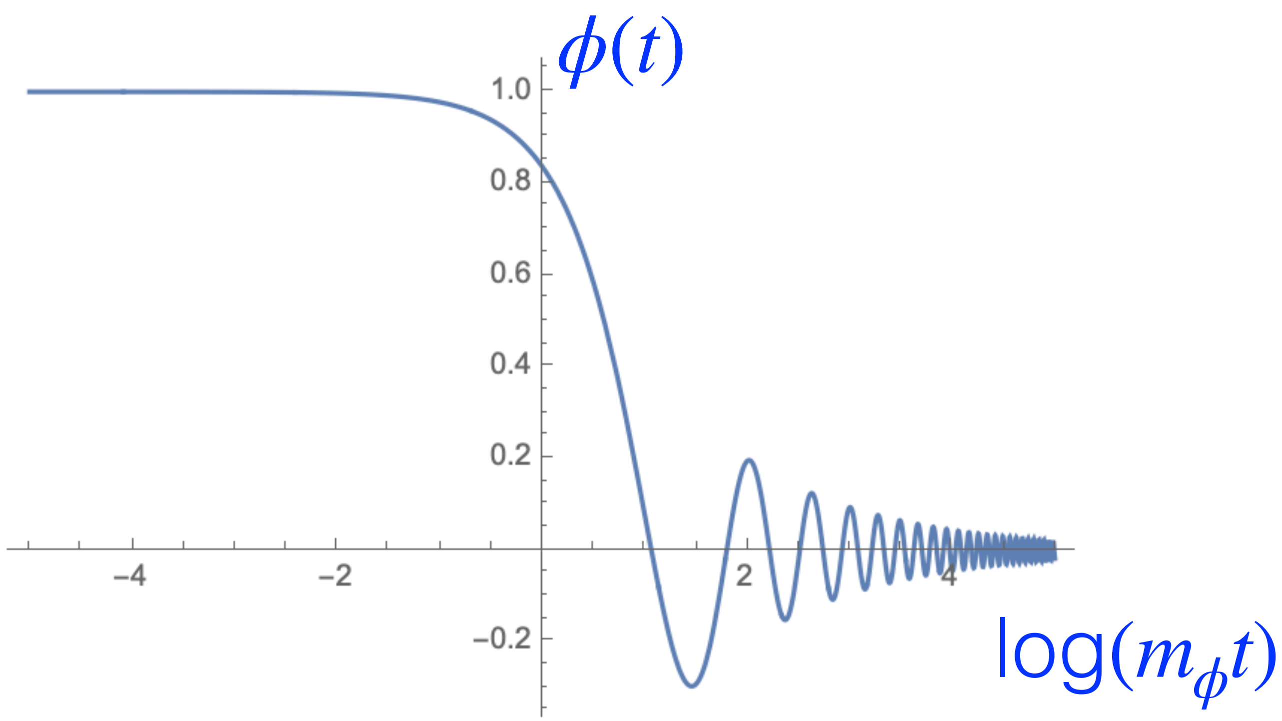
The conventional misalignment mechanism

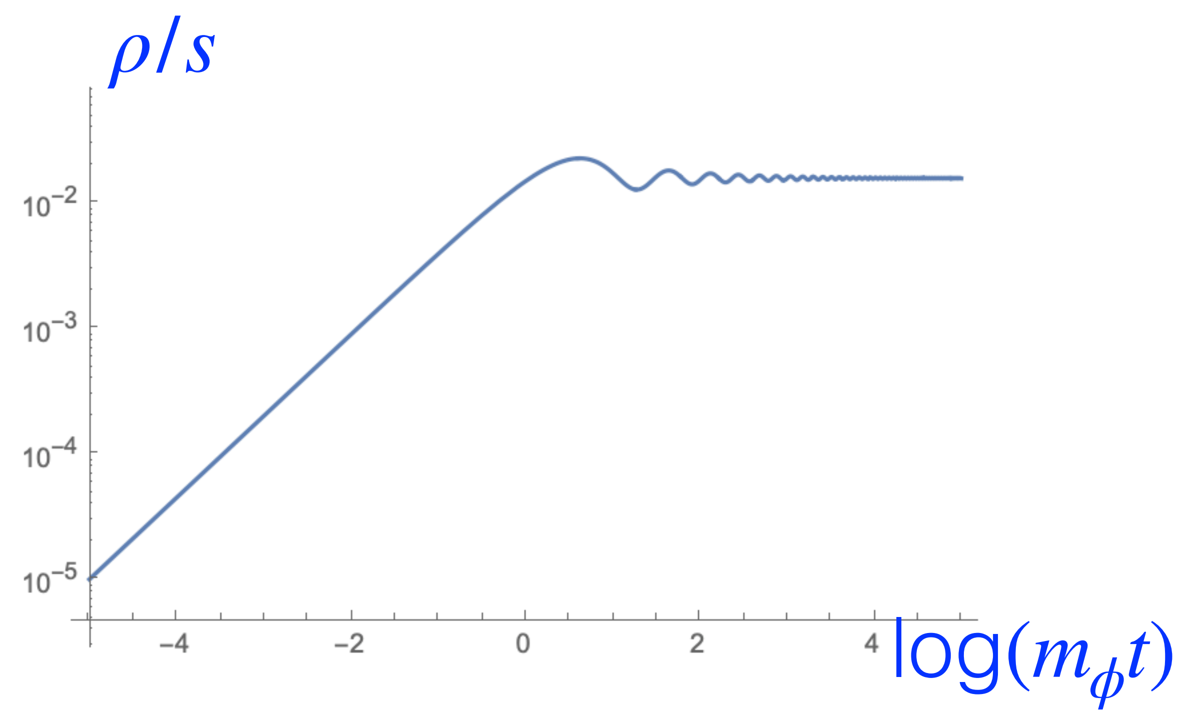
Preskill, Wise, Wilczek; Abbott, Sikivie; Dine, Fischler, 83

Consider a spatially-homogeneous real scalar field in an expanding universe:

$$\frac{1}{\sqrt{|g|}}\mathscr{L} = \frac{1}{2}(\partial^\mu \phi^*)(\partial_\mu \phi) - \frac{m_\phi^2}{2}\phi^*\phi$$

equation of motion: $\boxed{\ddot{\phi}(t) + 3H\dot{\phi}(t) + m_\phi^2 \phi(t) = 0}$





$H \sim 1/t$

Ultralight scalars are ubiquitous

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→ {
dark matter (Preskill, Wise, Wilczek; Abbott, Sikivie; Dine, Fischler, 83)
baryogenesis (Affleck, Dine, 85)
Inflation (Guth, 81; Linde, 82)
}

→ {
Solving strong CP problem – axion (Peccei, Quinn, 77; Weinberg, 78; Wilczek, 78)
Selecting cosmological constant (Abbott, 85)
Solving the hierarchy problem – relaxion (Graham, Kaplan, Rajendran, 15)
}

→ String axiverse (Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, 09)

a lot more recent activities, e.g. many Snowmass 2022 papers

Ultralight scalars are ubiquitous

- Ultralight scalars can arises from many theoretical frameworks.

- Ultralight scalars are (will be) under phenomenological/ experimental scrutiny.

- Theories of scalars are not ‘rigid’, as reflected in the hierarchy problem or the quality problem.

➡ The standard misalignment mechanism can be over-simplified and be easily modified.

Nontrivial interplay are expected if multiple scalars are present.

A new misalignment mechanism

based on nontrivial interplay between axion (ALP) and a light dilaton (DLP)

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$$\mathcal{L} = \sqrt{|g|}\left\{\frac{f_\theta^2\hat{\chi}^2}{2}(\partial_\mu\theta)^2 + \frac{1}{2}(\partial_\mu\chi)^2 - V(\sigma,\theta)\right\}$$

$$\chi = F\hat{\chi} = Fe^{\frac{\sigma(x)}{F}}$$

Weyl compensator

$$\left\{\begin{aligned} V(\sigma,\theta) &= V(\sigma) + \hat{\chi}^4\ V(\theta) \\ &= V(\sigma) + m_\theta^2 f_\theta^2 \hat{\chi}^4\ (1-\cos[\theta]) \\ V(\sigma) &= \lambda F^4\left(-\frac{4}{4-\epsilon}\hat{\chi}^{4-\epsilon} + \hat{\chi}^4\right) + \lambda F^4\frac{\epsilon}{4-\epsilon} \end{aligned}\right.$$

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Global minima: $\langle\sigma\rangle = 0$ $\qquad \langle\theta\rangle = 0 \bmod 2\pi$

Equations of motion and initial conditions

$$\begin{cases} \ddot{\theta}(t) + \left(3H + \frac{2}{F}\dot{\sigma}(t)\right)\dot{\theta}(t) + m_\theta^2\ e^{2\frac{\sigma(t)}{F}} \sin\left[\theta(t)\right] = 0 \\ \frac{\ddot{\sigma}(t)}{F} + \left(3H + \frac{\dot{\sigma}(t)}{F}\right)\frac{\dot{\sigma}(t)}{F} + \frac{m_\sigma^2}{\epsilon} e^{2\frac{\sigma(t)}{F}}\left(1 - e^{-\epsilon\frac{\sigma(t)}{F}}\right) = -\mathcal{K}(\theta) \end{cases}$$

Kick term: $\mathcal{K}(\theta) \sim \frac{4m_\theta^2 f_\theta^2\left(1-\cos[\theta]\right)e^{2\frac{\sigma(t)}{F}} - f_\theta^2\dot{\theta}^2}{F^2}$

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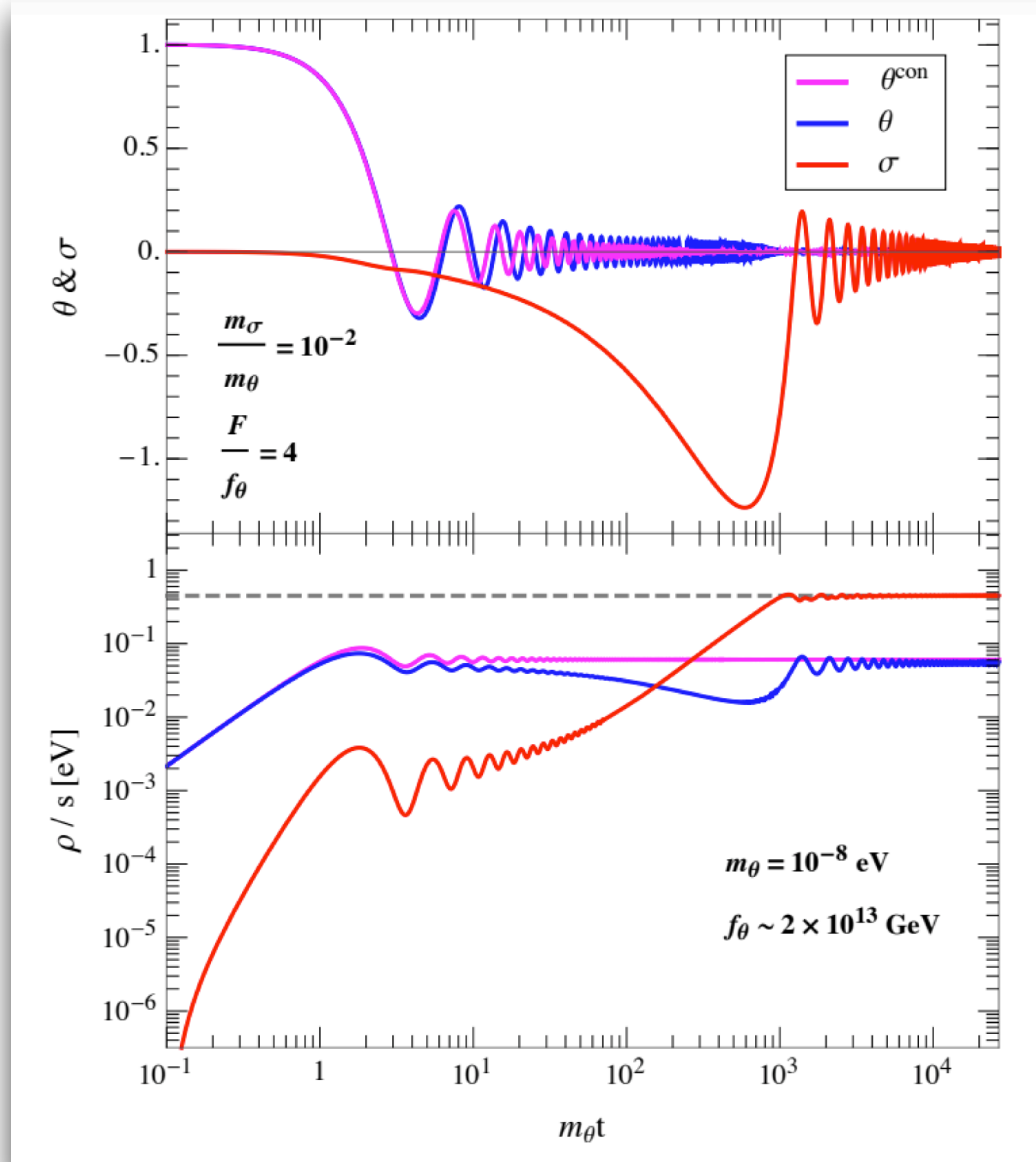
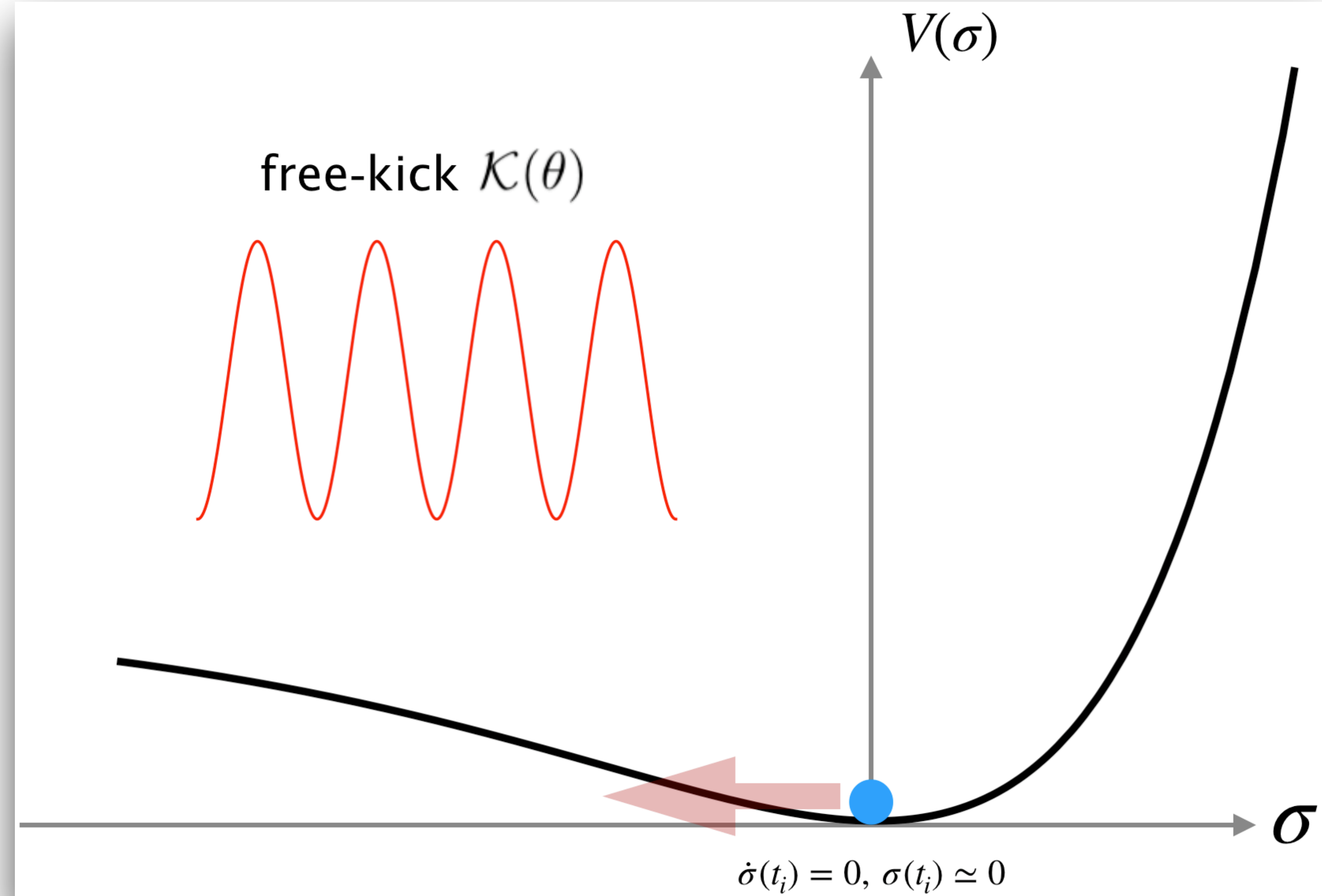
- Dilaton field-dependent Hubble friction, masses
- Various possible histories for field evolution, depending on initial conditions
- Let us consider $m_\theta > m_\sigma$ $\dot{\theta}(t_i) = \dot{\sigma}(t_i) = 0$

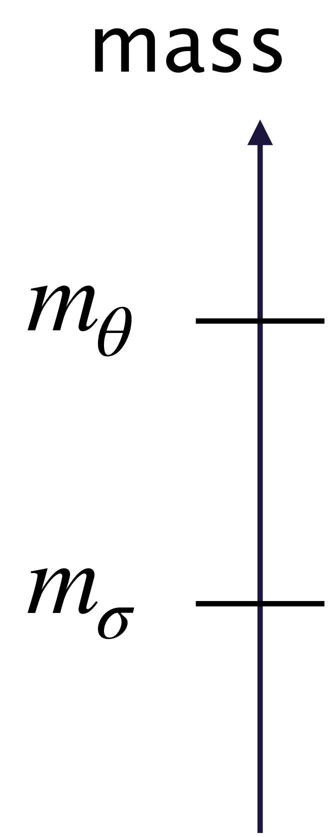
$\theta(t_i) \sim \mathcal{O}(1),\ \sigma(t_i) \simeq 0\ .$ ➡ axion misalignment



For fixed values of m_θ and f_θ, DM abundance is enhanced!

Axion ‘free-kick’ misalignment mechanism





Scalars		Roles
axion	→	a football player
dilaton	→	football

Conclusion and future directions

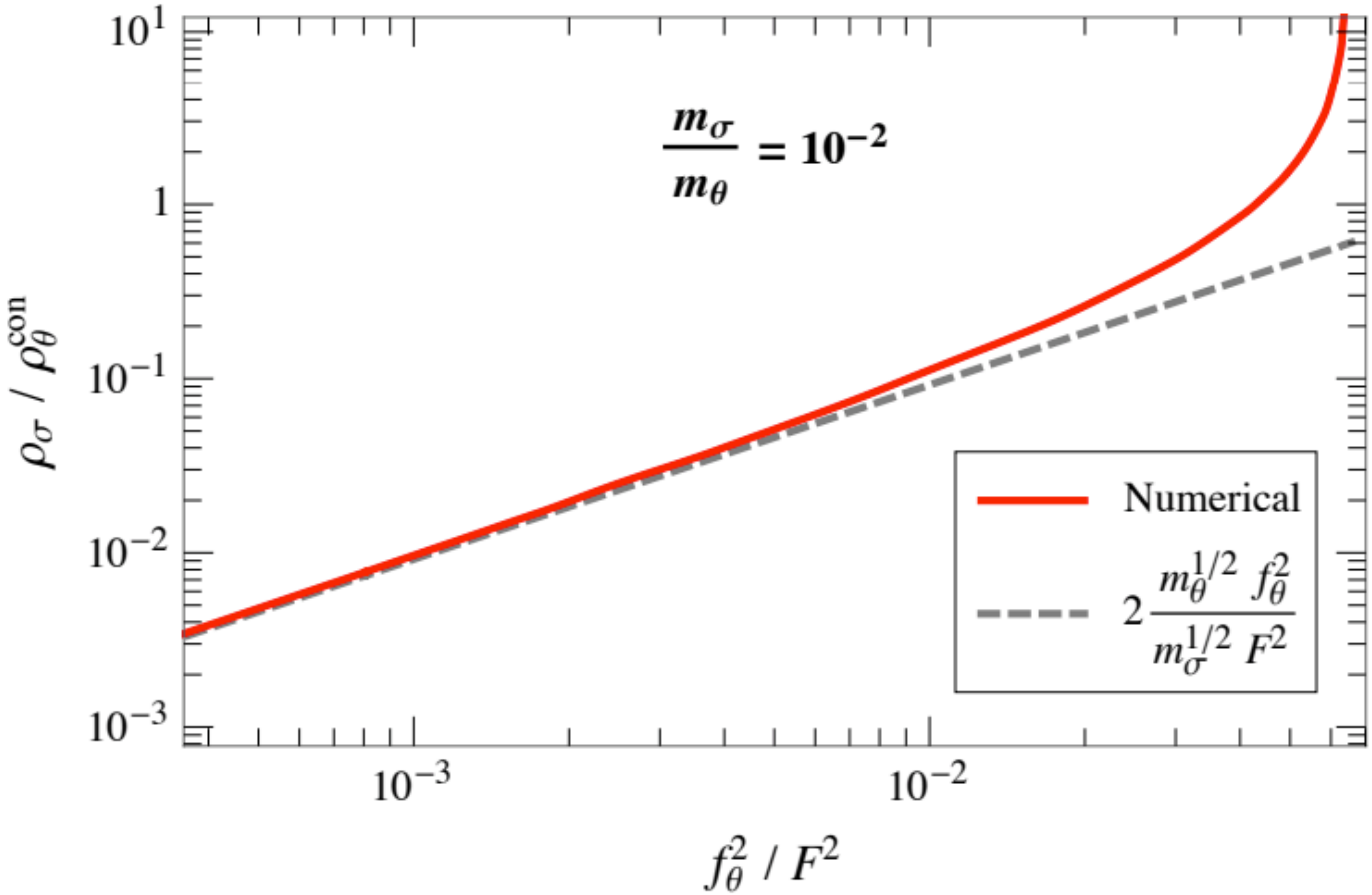
- We propose an alternative misalignment mechanism based on nontrivial interplay between axion and dilaton.
- The ‘kick’ effect is ubiquitous if multiple ultralight scalars are present in nature, as motivated by different problems and BSM scenarios.
- Work in progress to understand the implications to standard axion/relaxion dark matter scenarios.

Conclusion and future directions

- We propose an alternative misalignment mechanism based on nontrivial interplay between axion and dilaton.
- The ‘kick’ effect is ubiquitous if multiple ultralight scalars are present in nature, as motivated by different problems and BSM scenarios.
- Work in progress to understand the implications to standard axion/relaxion dark matter scenarios.
- What is the model-building price to pay to obtain a dilaton lighter than axion in a UV theory (i.e. hierarchy problem)?
- What is the optimal experimental strategy to measure the ‘kick’ effect between ultralight scalars?
- Implications to the “cosmological naturalness” paradigm?

Thank you!

backup



$$\frac{\rho_\sigma}{\rho_\theta^{\rm con}} \sim \left(\frac{m_\theta}{m_\sigma}\right)^{1/2} \left(\frac{f_\theta}{F}\right)^2 (1 - \cos\theta_i)$$