# Friendship in the Axiverse

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**Based on arXiv:2109.09755**
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**Astrodark**

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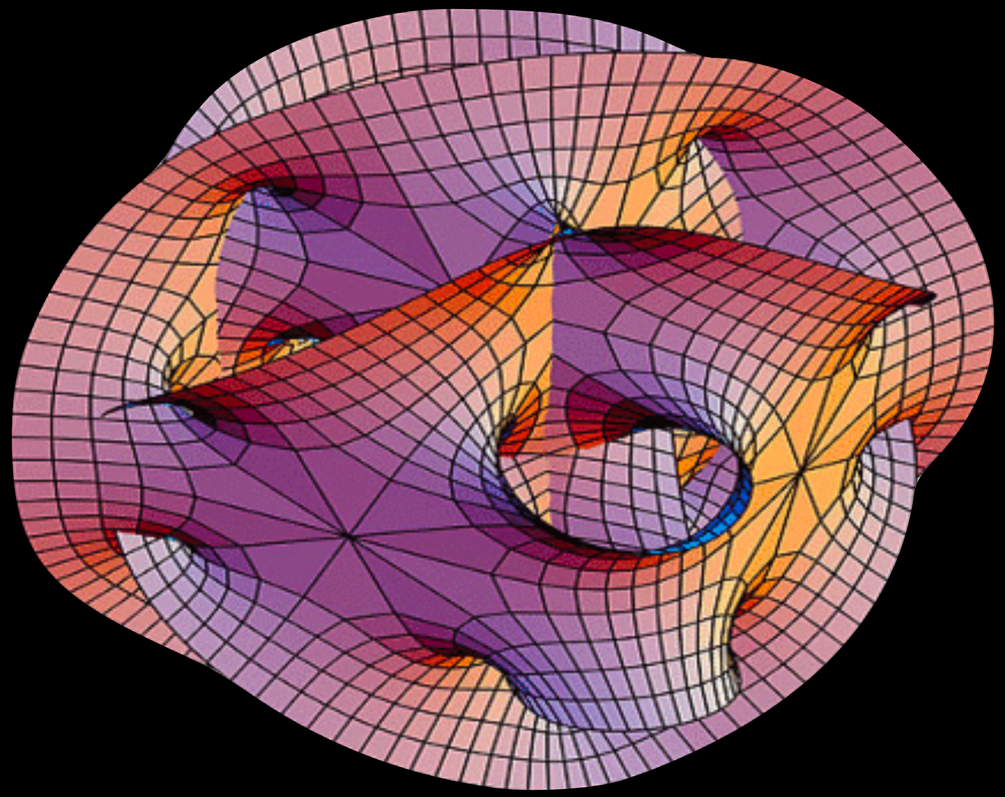
# Background & Motivation

## Axiverse

- String theory→large number of axions
  - Axiverse
- $V(\phi) \sim \Lambda^4(1 - \cos \phi/f)$
- Each string axion can be produced through misalignment mechanism
  - $V(\phi(t = 0)) \sim \Lambda^4 \equiv m^2 f^2$
  - Expectation: $\rho_{\mathrm{Final}} \propto m^{1/2} f^2$



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# More-realistic potential

$$V(\phi_1, \ldots, \phi_N) = \sum_{i=1}^{M} \Lambda_i^4 \left[ 1 - \cos\left( \sum_{j=1}^{N} Q_{ij} \frac{\phi_j}{f_j} + \delta_i \right) \right]$$

- $\Lambda_i^4 \sim M_{\rm UV}^4 e^{-S_i}$
- Some masses may be close to one another: “Friendly axions”

Friendly axions:

➡ Similar dynamical timescales

➡ Dynamical Resonance

➡ Enhanced observational prospects

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**Take-home message:**

**Axion friendship leads to enhanced signatures**

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# Outline

- Background & Motivation
- Friendly Dynamics
- Signatures

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# Friendly Dynamics

# Two-Axion Model

$$V(\phi_S, \phi_L) = \Lambda_1^4 \left( 1 - \cos\left( \frac{\phi_S}{f_S} + \frac{\phi_L}{f_L} \right) \right) + \Lambda_2^4 \left( 1 - \cos\left( \frac{\phi_L}{f_L} \right) \right)$$

$$V(\theta_S, \theta_L) = \underset{\substack{m \equiv m_S \\ f \equiv f_S}}{m^2 f^2} \left[ \Big( 1 - \cos\left( \theta_S + \theta_L \right) \Big) + \underset{\mu^2 F^2 \gtrsim 1}{\mu^2 F^2} \left( 1 - \cos\theta_L \right) \right]$$

$$f_L / f_S = F \qquad\qquad m_L / m_S = \mu$$

$F \gtrsim 3$ (or much larger): $S$ = Short, $L$ = Long

$0.5 \lesssim \mu < 1$: nearby masses = Friendly

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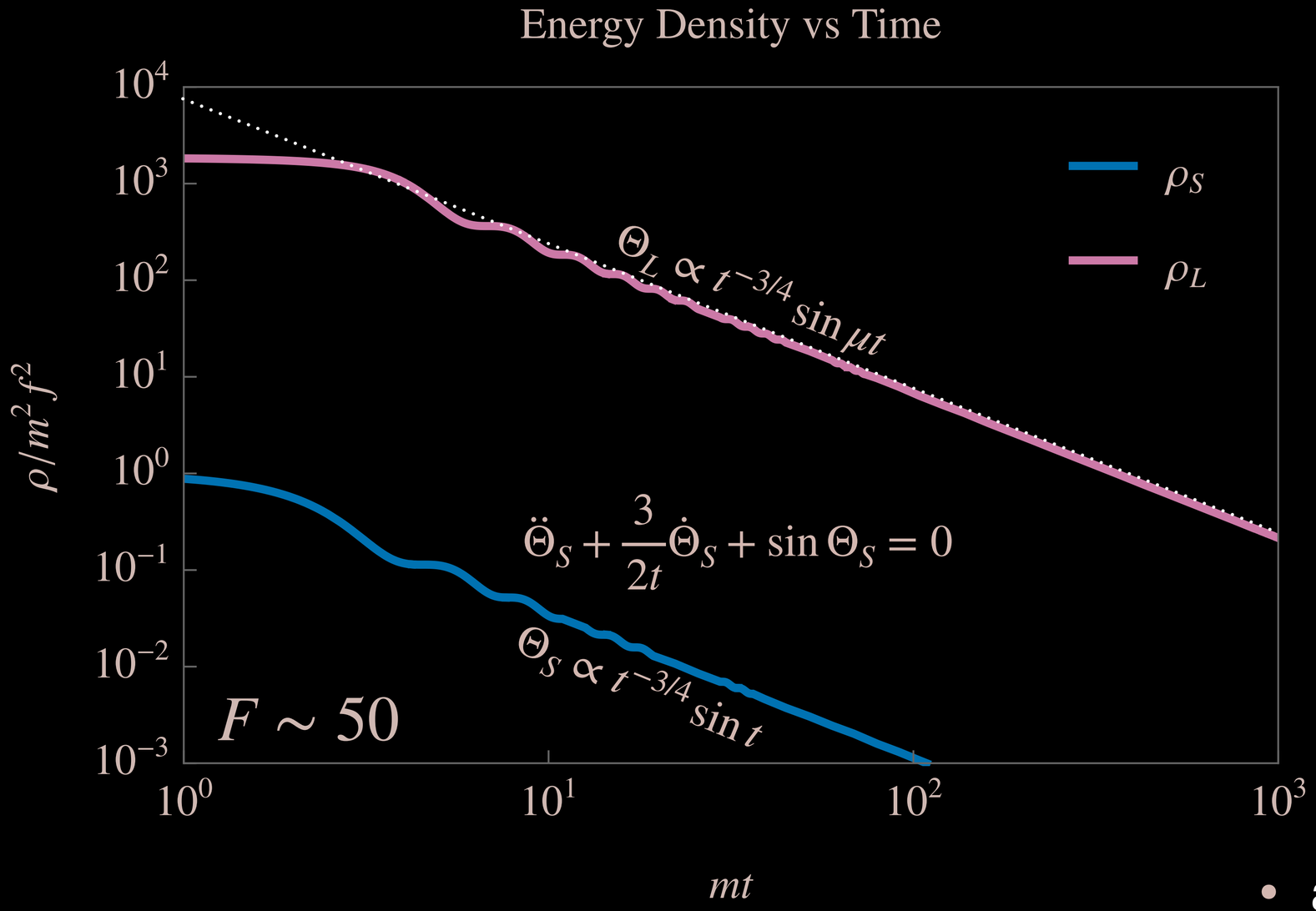
$$V(\theta_S, \theta_L) = m^2 f^2 \left[ \left( 1 - \cos\left( \theta_S \qquad \right) \right) + \mu^2 F^2 \left( 1 - \cos\theta_L \right) \right]$$

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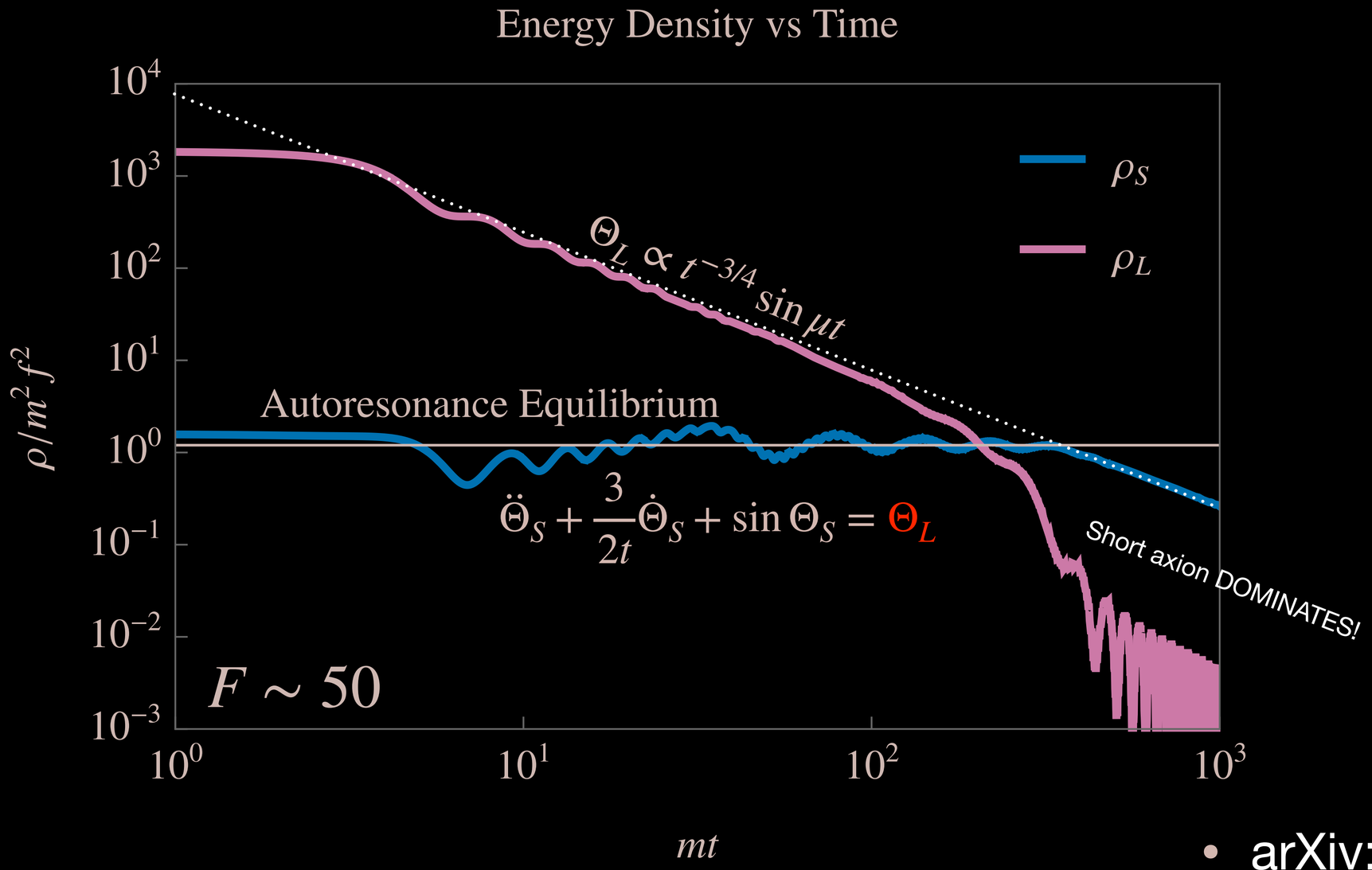
$$V(\theta_S, \theta_L) = m^2 f^2 \left[ \left( 1 - \cos\left(\theta_S + \theta_L\right) \right) + \mu^2 F^2 \left( 1 - \cos\theta_L \right) \right]$$

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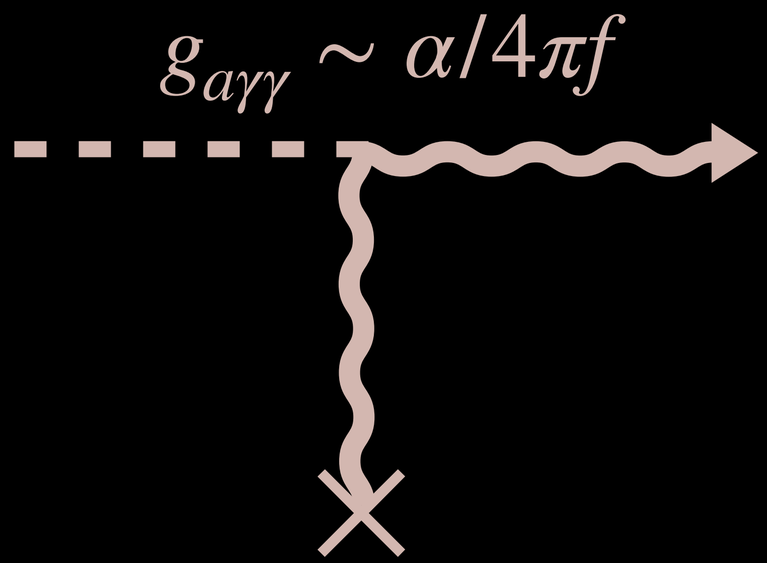
# Signatures: Direct Detection

# Direct Detection

- Haloscopes are sensitive to the combination $g_{a\gamma\gamma}^2 \rho$

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# Direct detection prospects: Lonely Axion

- Consider a lonely axion, living in a cosine potential

$$V(\phi) = m^2 f^2 (1 - \cos \phi/f)$$

- Relic abundance:

$$\frac{\rho_{\text{Lonely}}}{\rho_{\text{crit}}} \sim 0.4 \left(\frac{\Theta(0)}{\pi/2}\right)^2 \left(\frac{m}{10^{-17}\text{eV}}\right)^{1/2} \left(\frac{f}{10^{16}\text{GeV}}\right)^2$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f}$$

- Signal strength of a single axion is independent of $f$:

$$\left(g_{a\gamma\gamma}^2 \frac{\rho_{\text{Lonely}}}{\rho_{DM}^0}\right)^{1/2} \sim 2.3 \times 10^{-17}\text{GeV}^{-1} \left(\frac{\Theta(0)}{\pi/2}\right) \left(\frac{m}{10^{-17}\text{eV}}\right)^{1/4}$$

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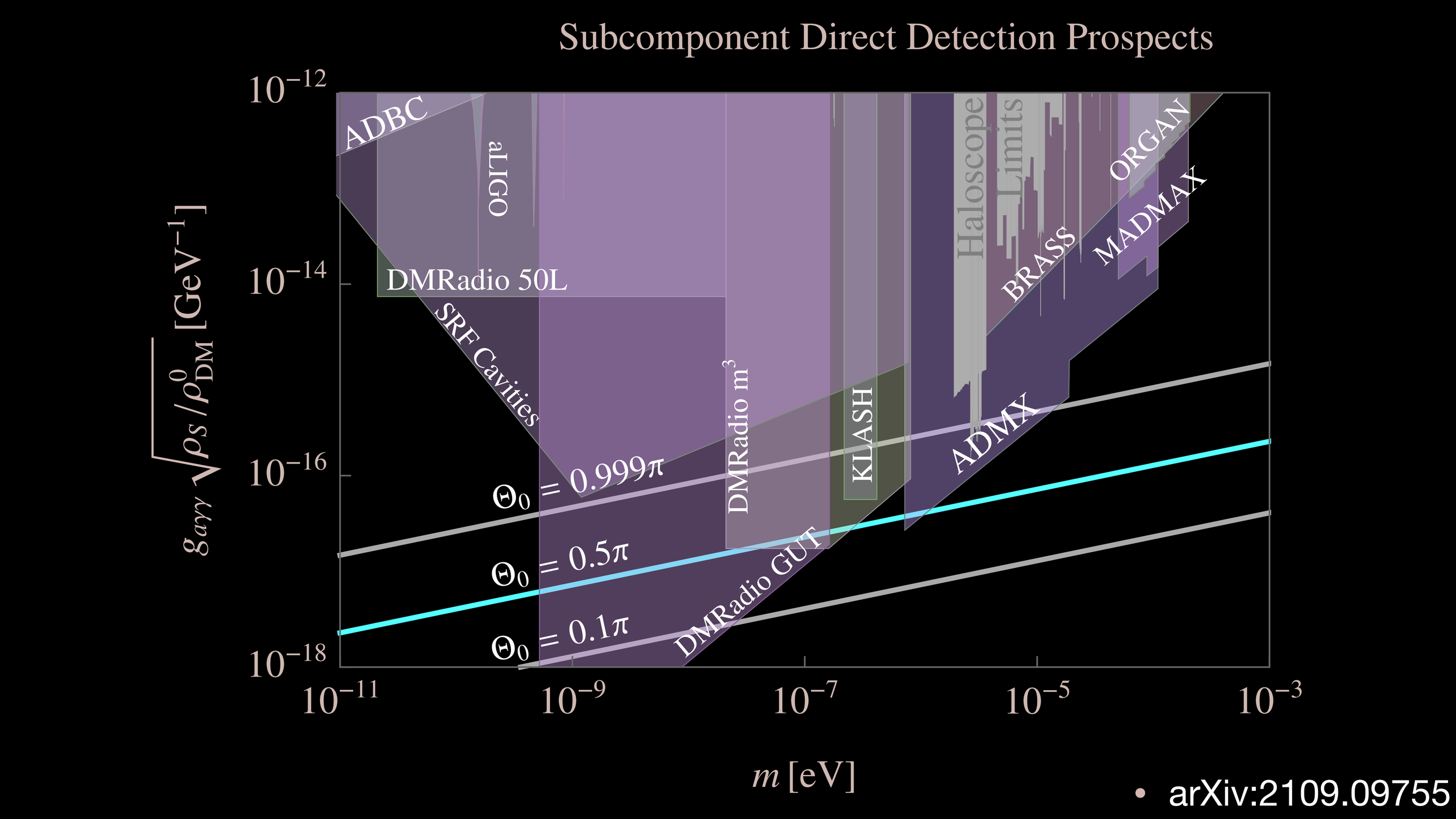
Subcomponent Direct Detection Prospects
$10^{-12}$
$10^{-14}$
$10^{-16}$
$10^{-18}$
$g_{a\gamma\gamma}\sqrt{\rho_S/\rho^0_{\rm DM}}$ [GeV$^{-1}$]
$10^{-11}$
$10^{-9}$
$10^{-7}$
$10^{-5}$
$10^{-3}$
$m$ [eV]
ADBC
aLIGO
DMRadio 50L
SRF Cavities
DMRadio m$^3$
KLASH
Haloscope Limits
BRASS
ORGAN
MADMAX
ADMX
DMRadio GUT
$\Theta_0 = 0.999\pi$
$\Theta_0 = 0.5\pi$
$\Theta_0 = 0.1\pi$
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# Direct detection prospects: Friendly Axion

- The energy transferred from $\theta_L$ to $\theta_S$ enhances $\rho_S$ relative to the lonely-axion expectation:

$$\rho_S \approx F^2 \rho_{\text{Lonely}}$$

- $\theta_S$ has a smaller $f$, *and* enhanced energy density:

**Best of both worlds**

- Stronger coupling *and* more axions.

- Does not depend on whether the friendly pair is the DM

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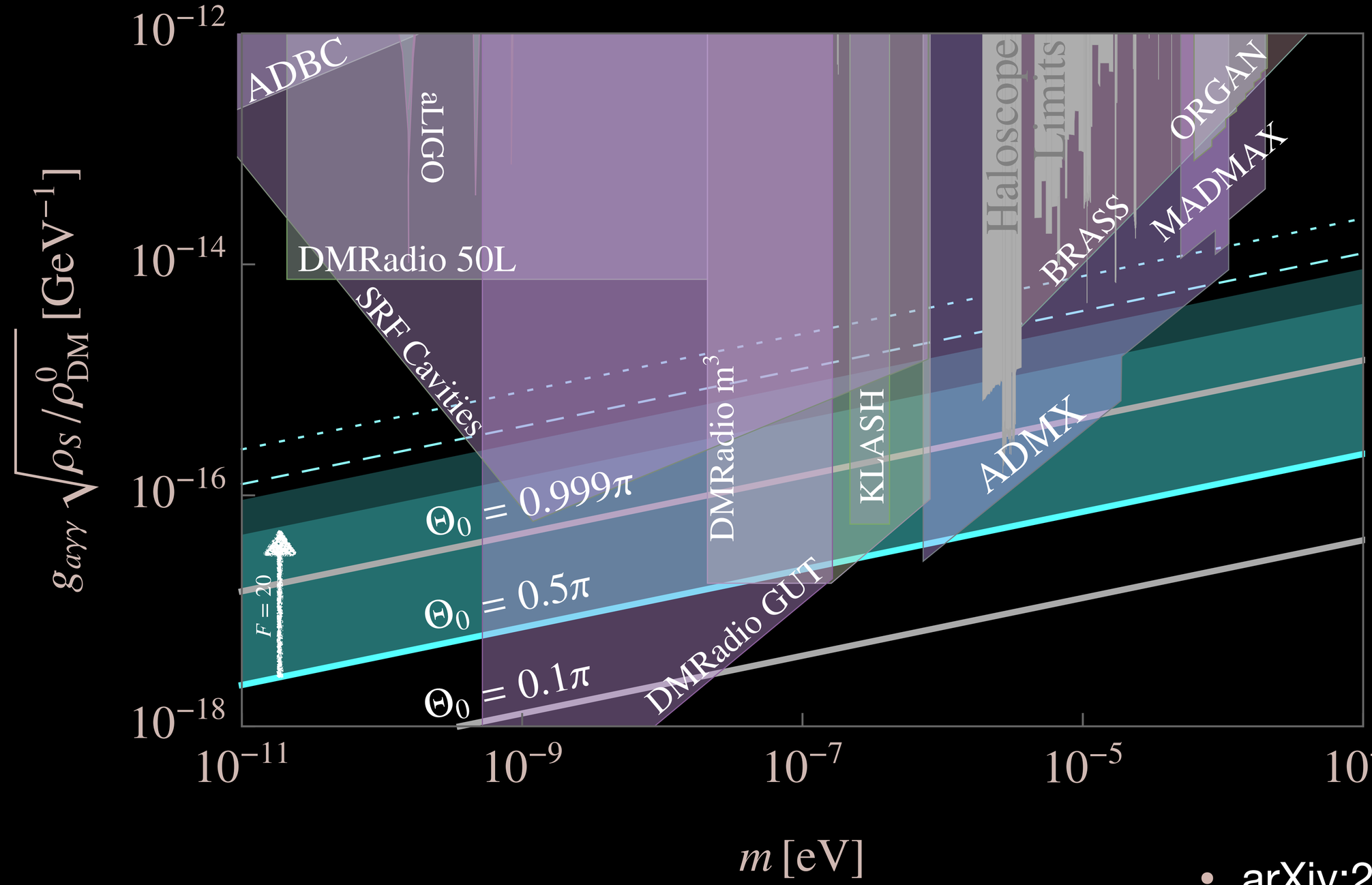
# Attractive Subcomponent Direct Detection Prospects

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# Summary

# Summary

- Friendly axions are more visible than lonely axions
  - Independent of whether they are the DM
- Discovering a highly-visible axion should prompt a search for more weakly coupled axions at nearby masses
- Discovery of a friendly pair would be evidence that we live in a dense axiverse
- More signatures in arXiv:2109.09755

# Thank you!

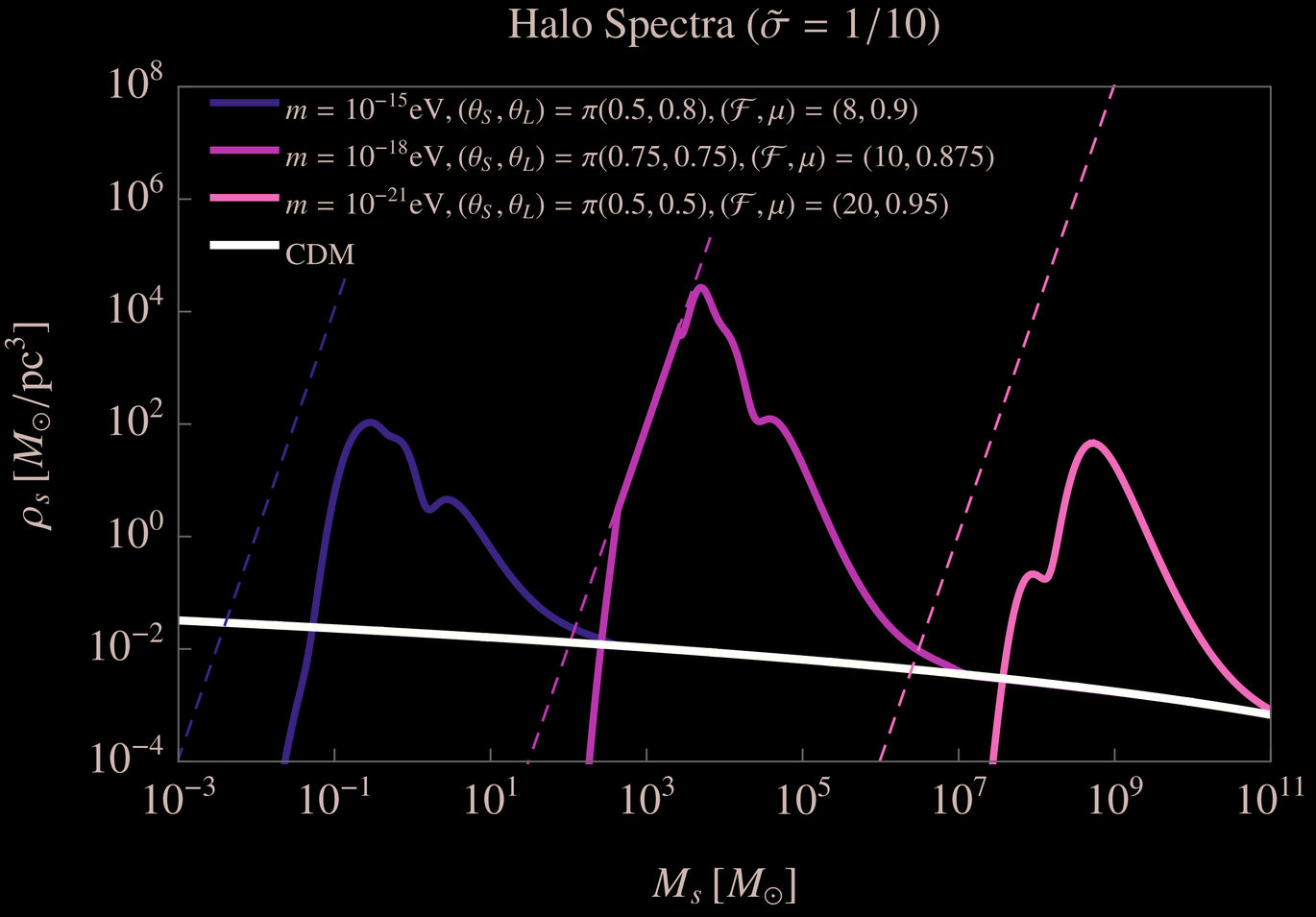
# Signatures: Gravitational Detection

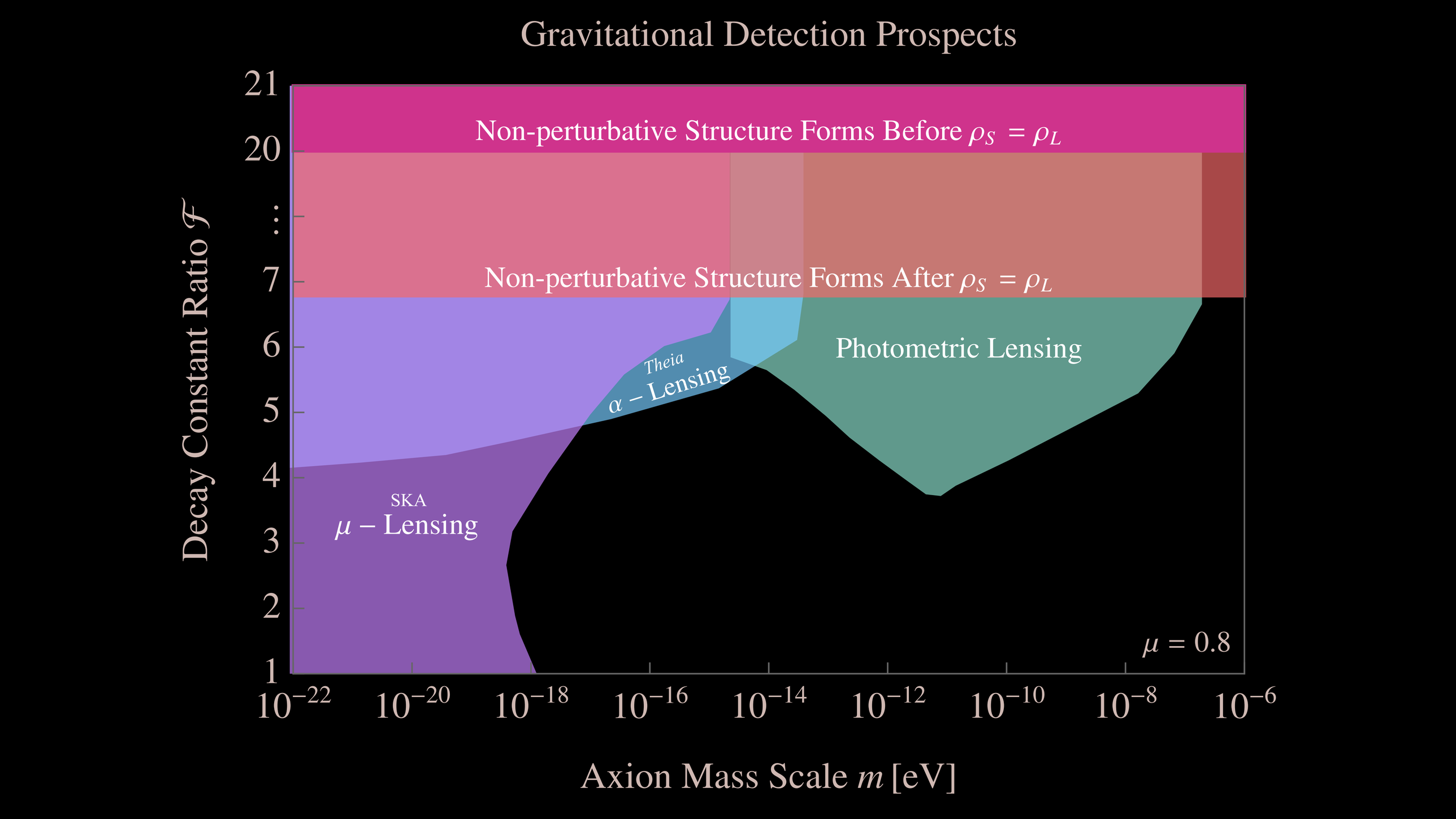
# Gravitational detection prospects

- If the friendly pair is the DM, density perturbations form axion mini halos:

$$M \sim 1.2 \times 10^4 M_\odot \left( \frac{10^{-19}\text{eV}}{m} \right)^{3/2}$$

- Gravitational signatures vanish if autoresonance is quenched by perturbation growth




Gravitational Detection Prospects
Non-perturbative Structure Forms Before $\rho_S = \rho_L$
Non-perturbative Structure Forms After $\rho_S = \rho_L$
Photometric Lensing
Theia
$\alpha$ – Lensing
SKA
$\mu$ – Lensing
$\mu = 0.8$
Decay Constant Ratio $\mathcal{F}$
21
20
⋮
7
6
5
4
3
2
1
$10^{-22}$
$10^{-20}$
$10^{-18}$
$10^{-16}$
$10^{-14}$
$10^{-12}$
$10^{-10}$
$10^{-8}$
$10^{-6}$
Axion Mass Scale $m$ [eV]