Highly-visible coupled axions and implications for direct detection

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arXiv:2109.09755, 2208.05501
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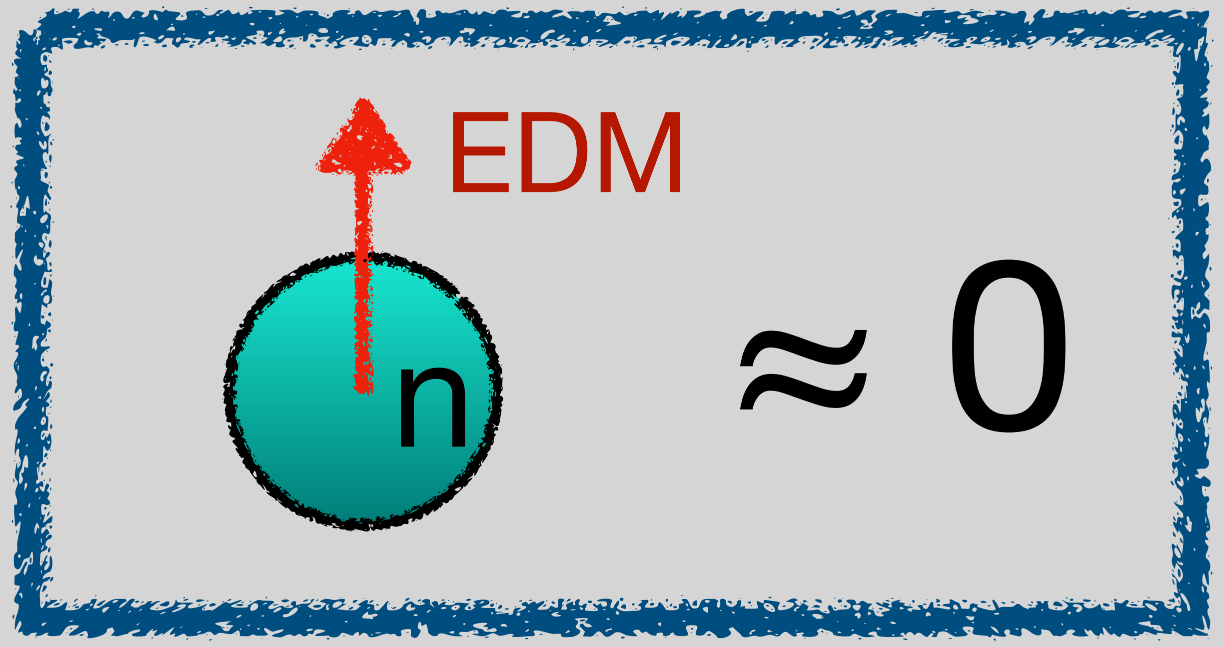
INT 22-2b Workshop, 8/25/2022

Motivation: Axions

Well motivated extensions to SM

- **QCD axion**: solves strong CP problem



- Axions are quite generic in string models: “**String axiverse**”
- Goldstone bosons, potential from nonperturbative breaking of symmetry

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

Decay constant f suppresses coupling to SM

For QCD axion: $m^2 f^2 = \Lambda_{QCD}^4$

Motivation: Misalignment axion cosmology

- Example: Single axion with potential $V(\phi) \simeq m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$
- Misalignment: Initial angle randomly drawn from $\theta \in [-\pi, \pi]$
  - Typical initial energy density $\rho \sim m^2 f^2$

Damped pendulum

- Homogeneous equation of motion: $\partial_t^2\Theta + 3H\partial_t\Theta + m^2 \sin\Theta = 0$
- Field frozen until $H \sim m$, then begins damped oscillations
- Late-time solution during radiation domination: $\Theta(t) \propto \Theta_0 t^{-3/4} \cos(mt)$

$$\rho \propto a^{-3}$$

Motivation: An axiverse

Many axions

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

$$\Lambda_i^4 \propto \Lambda_{UV}^4 e^{-S_i}$$

- Smooth spread in $S_i \implies$ roughly log-flat distribution of axion masses
- Number of axions depends on topology, can easily be $\mathcal{O}(100)$

What are the dynamics and signatures of multiple axions in an axiverse?

Concrete example

Focus on a single pair of coupled axions

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

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

$f \equiv f_S \qquad \mathscr{F} \equiv \frac{f_L}{f_S} \qquad \mu \equiv \frac{m_L}{m_S}$

<u>Short</u> and **<u>Long</u>** refer to decay constants

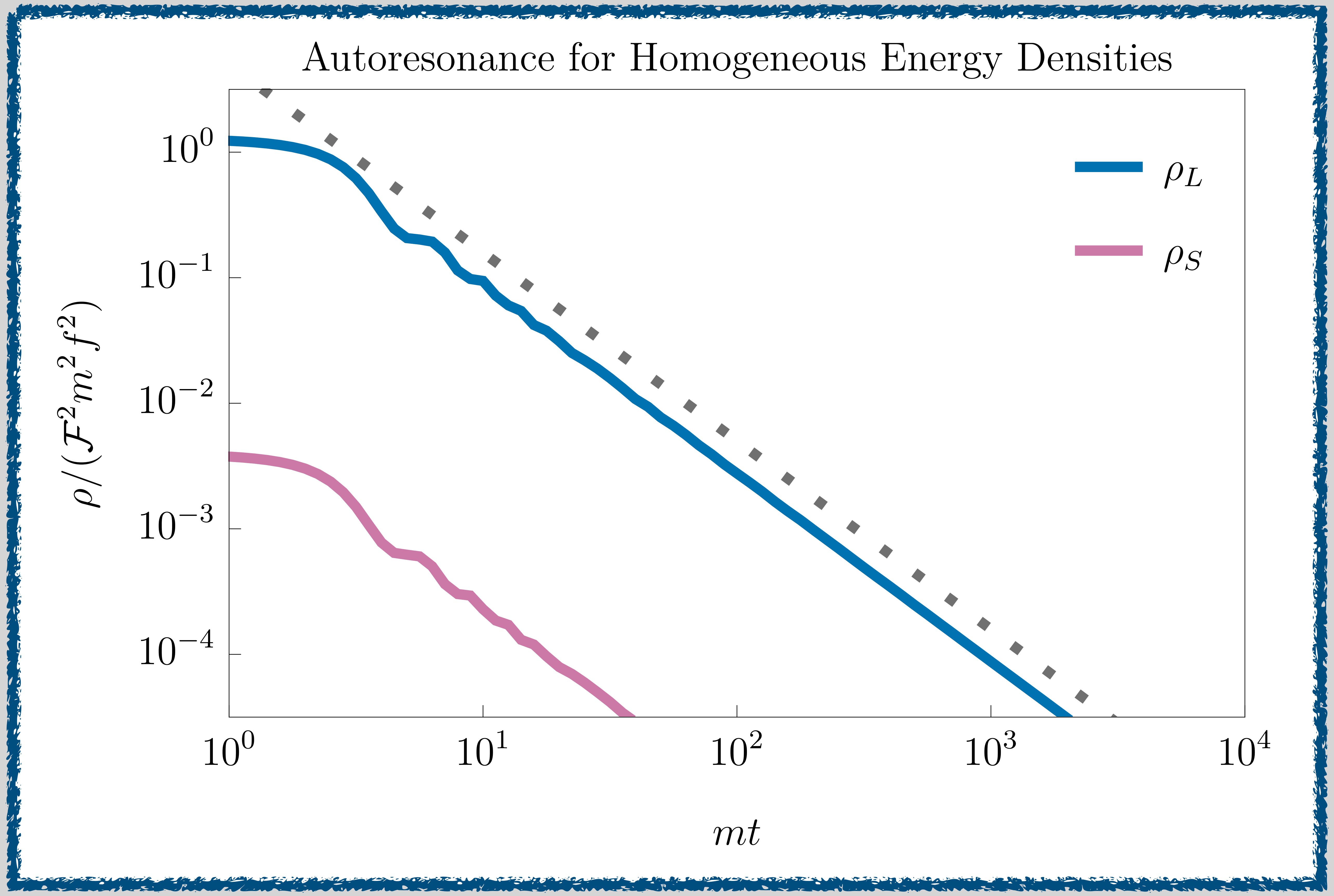
Interesting new dynamics occur when $\mathscr{F} \gtrsim 3 \qquad 0.7 \lesssim \mu < 1$

"Friendly"

Homogeneous dynamics

Review: Uncoupled axions

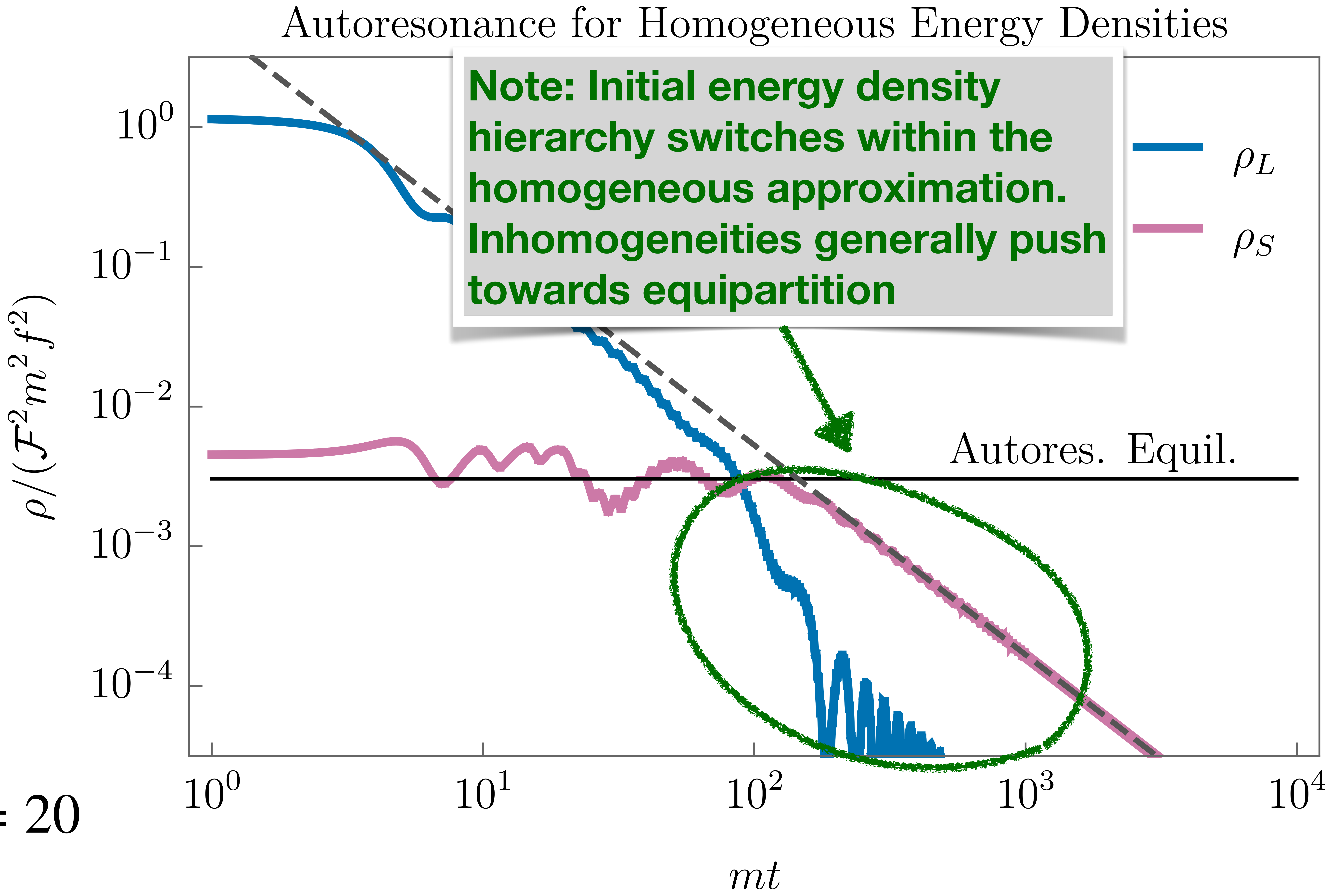
- Each axion begins with energy density $\rho \sim \mathcal{O}(m_i^2 f_i^2)$ with $i = S, L$
- For axions with similar masses, both enter horizon and begin redshifting at similar times
- Late times: long axion will dominate energy density by $\rho_L / \rho_S \sim \mathcal{F}^2$



Homogeneous dynamics

Coupled friendly axions

- Axions are akin to coupled pendulums
- Long axion has larger decay constant $\Longrightarrow$ "more inertia"
    - Can drive short axion
- $\mu < 1$: long axion has smaller frequency
- Coupled linear oscillators: resonance is <u>required</u> for significant energy transfer
- Short axion can adjust its frequency by adjusting its amplitude
    - Adjust amplitude to achieve resonance and stay there: <u>**autoresonance**</u>



Autoresonance for Homogeneous Energy Densities
Note: Initial energy density hierarchy switches within the homogeneous approximation. Inhomogeneities generally push towards equipartition
ρ_L
ρ_S
Autores. Equil.
$\rho/(\mathcal{F}^2 m^2 f^2)$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3
10^4
mt

$\mathscr{F} = 20$

Homogeneous dynamics

$$\partial_t^2\Theta_L + \frac{3}{2t}\partial_t\Theta_L + \frac{1}{\mathcal{F}^2}\sin(\Theta_S + \Theta_L) + \mu^2\sin\Theta_L = 0$$

$$\mathcal{F} \gg 1 \implies \Theta_L(t) \propto \Theta_{L,0}t^{-3/4}\cos\mu t$$

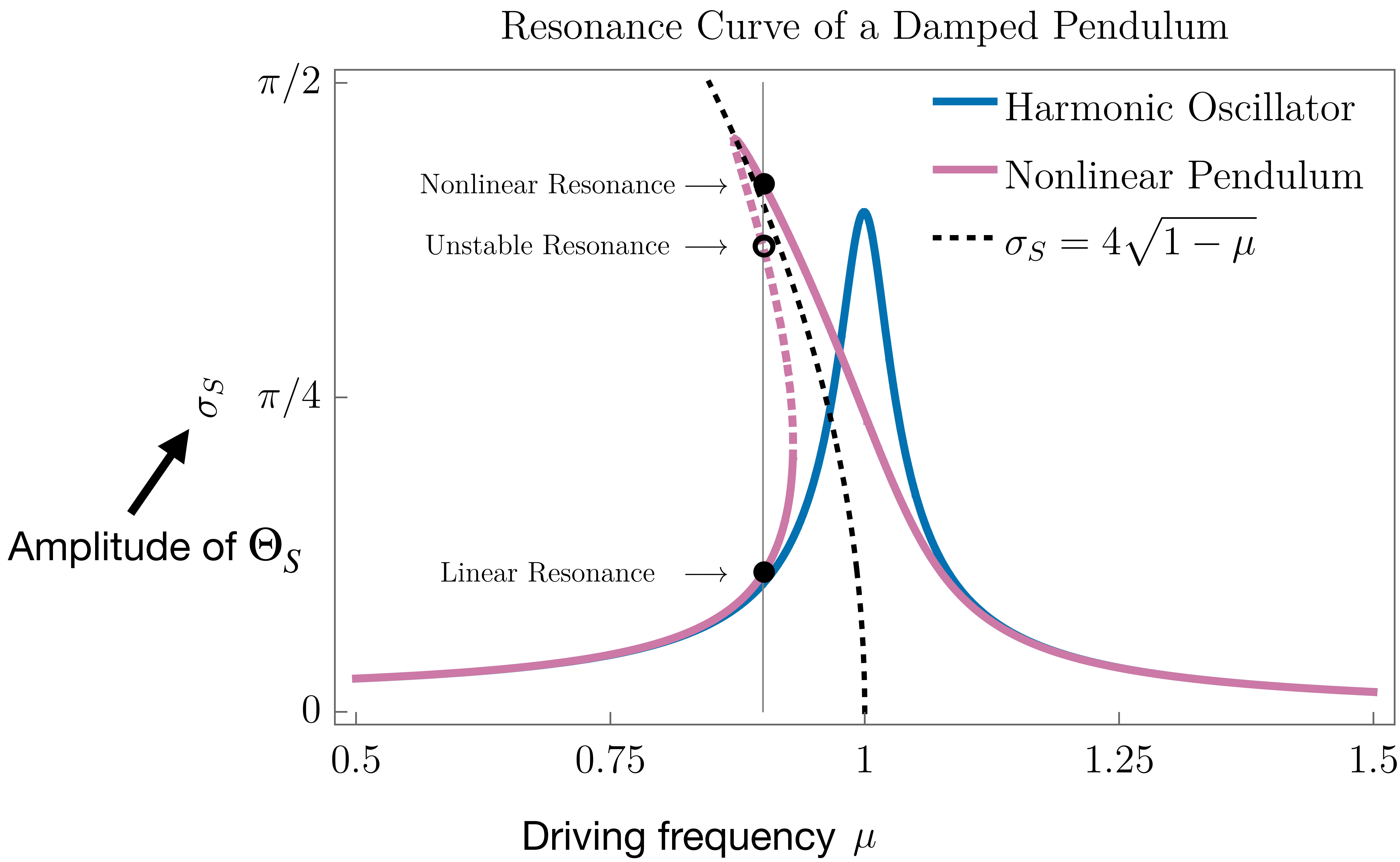
When $\Theta_S \gtrsim \mathcal{F}^2\Theta_L$, approximation breaks down: end of autoresonance

Predicts $\rho_S/\rho_L \sim \mathcal{F}^2$

$$\partial_t^2\Theta_S + \frac{3}{2t}\partial_t\Theta_S + \sin(\Theta_S + \Theta_L) = 0$$

If the amplitude of Θ_S is too large this breaks down: autoresonance not possible

$$\partial_t^2\Theta_S + \frac{3}{2t}\partial_t\Theta_S + \sin\Theta_S \approx -\Theta_L\cos\Theta_S \approx -\Theta_L$$



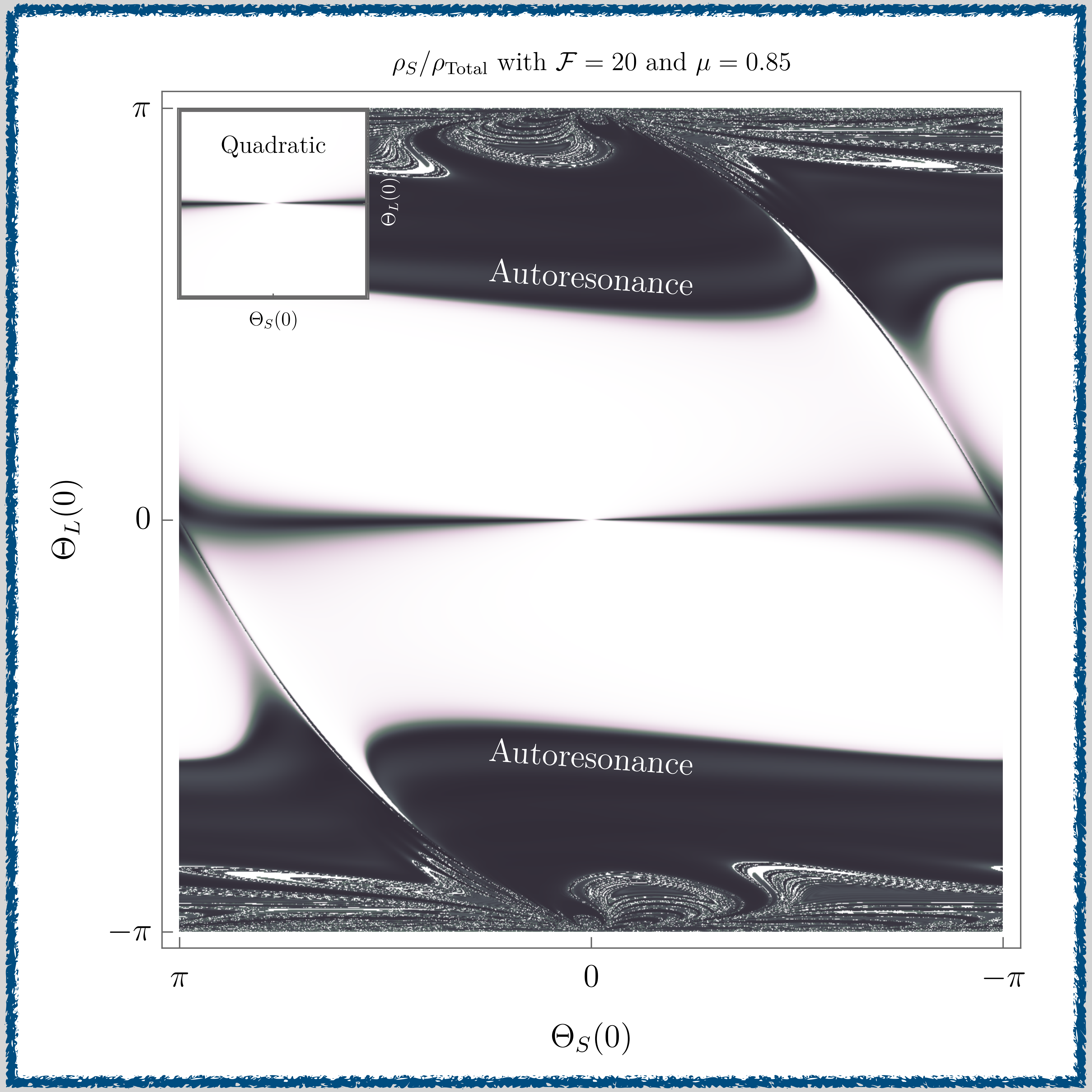
Resonance Curve of a Damped Pendulum
π/2
π/4
0
Nonlinear Resonance ⟶
Unstable Resonance ⟶
Linear Resonance ⟶
Harmonic Oscillator
Nonlinear Pendulum
$\sigma_S = 4\sqrt{1-\mu}$
σ_S
Amplitude of Θ_S
0.5
0.75
1
1.25
1.5
Driving frequency μ

Initial conditions for autoresonance

- Decently likely for $0.7 \lesssim \mu < 1$

- Roughly independent of $\mathscr{F}$

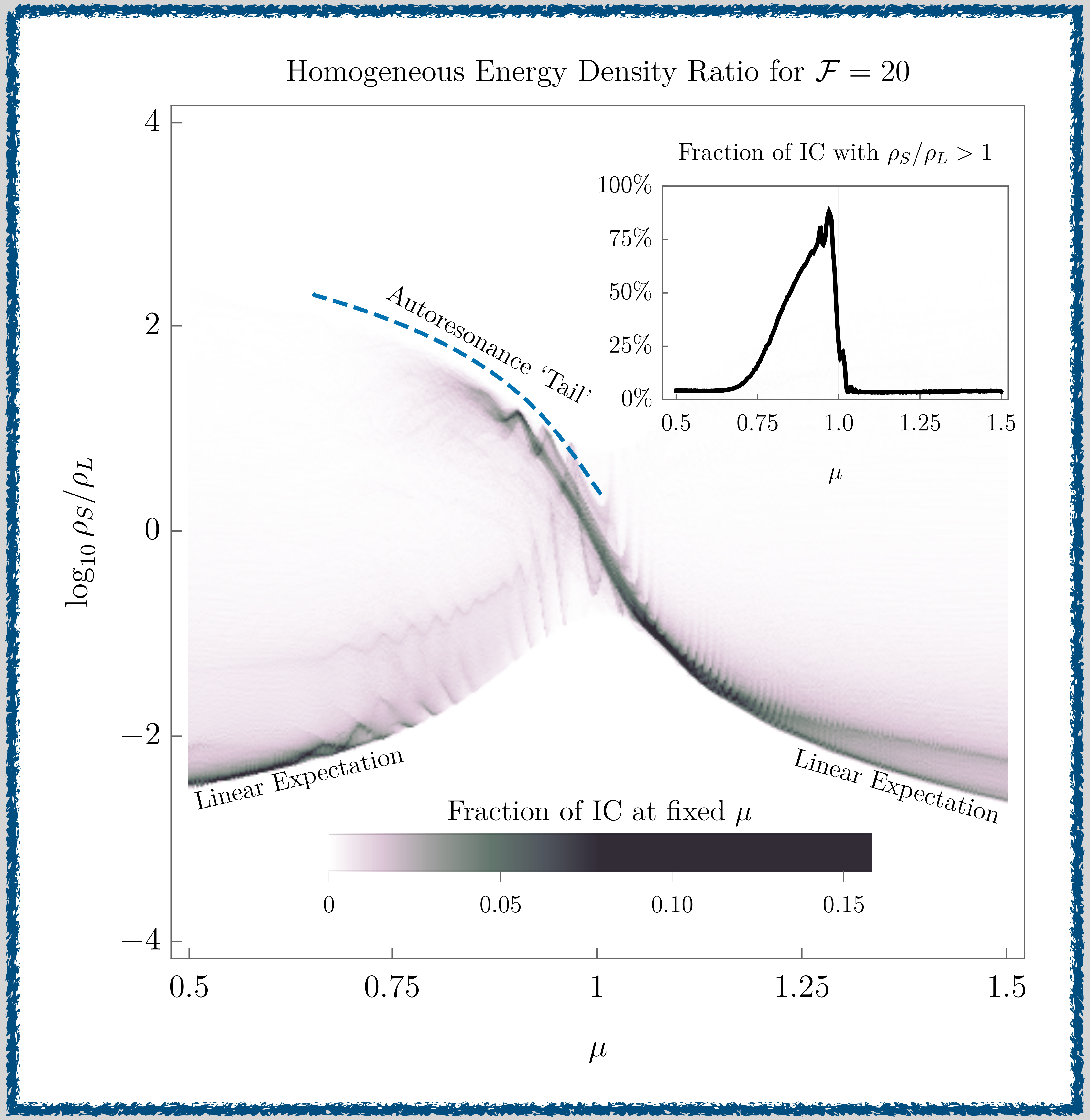
- Main determiner is initial amplitude of the long axion



Homogeneous dynamics

Key takeaways

- Axion dynamics are simply those of coupled nonlinear oscillators
- Analytically tractable
- Autoresonance can be quite generic provided the two axions are similar in mass ($0.7 \lesssim \mu < 1$)
    - $\mathcal{O}(1)$ of initial misalignment angles result in autoresonance



Implications for direct detection

Review

- Axions generically couple to SM suppressed by decay constant f

- Example: Axion-photon coupling $\mathscr{L} \supset -\frac{g_{a\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\phi \vec{E} \cdot \vec{B}$

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

- Haloscope experiments sensitive to $g_{a\gamma\gamma}^2 \rho_{axion}$

Implications for direct detection

Review: Detecting a lonely axion

- Uncoupled axion with potential $V(\phi) = m^2 f^2 (1 - \cos(\phi/f))$

$$\Omega_{axion} \approx 0.4 \left(\frac{\Theta_0}{\pi/2}\right)^2 \left(\frac{m}{10^{-17}\,\mathrm{eV}}\right)^{1/2} \left(\frac{f}{10^{16}\,\mathrm{GeV}}\right)^2$$

- Naïve misalignment: Axions with larger f have more energy density, but couple more weakly to SM. These two effects cancel exactly

$$\left(g_{a\gamma\gamma}^2 \frac{\rho_{axion}}{\rho_{DM}^0}\right)^{1/2}_{\text{uncoupled}} \sim 2.3 \times 10^{-17}\,\mathrm{GeV}^{-1} \left(\frac{\Theta_0}{\pi/2}\right) \left(\frac{m}{10^{-7}\,\mathrm{eV}}\right)^{1/4}$$

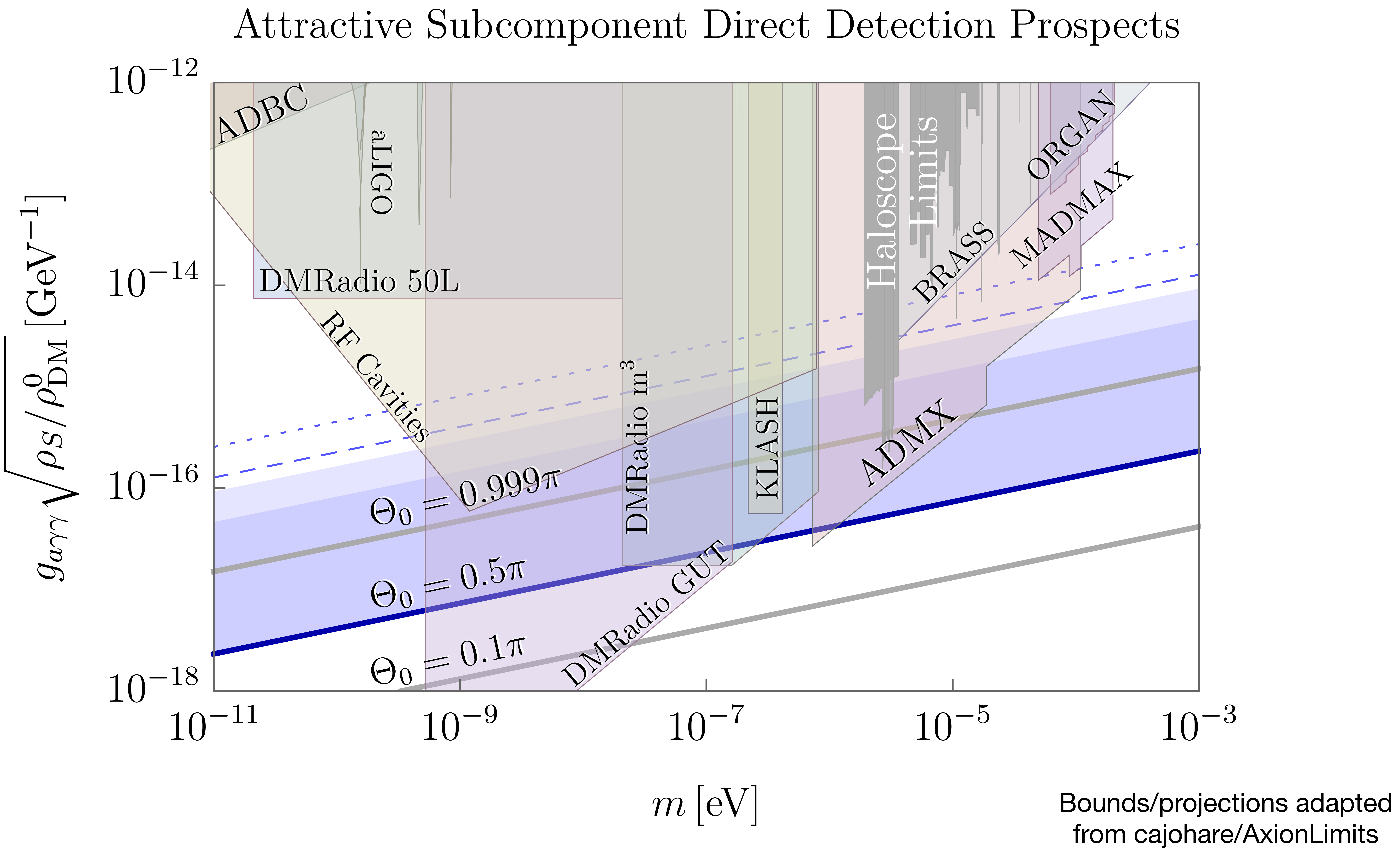
Implications for direct detection

Detecting a friendly axion pair

Best of both worlds!

- Short axion is typically coupled more strongly to SM, but can receive $\mathcal{O}(1)$ of long axion's energy density

- Long axion can be slightly harder to see, but properly taking inhomogeneities into account implies energy densities equalize for most $\mathcal{F} \lesssim 20$
- Look for long axion by resonant scanning over narrow mass range
- Boost to visibility *even if the friendly pair are only a subcomponent of DM*



Attractive Subcomponent Direct Detection Prospects
$g_{a\gamma\gamma}\sqrt{\rho_S/\rho^0_{\rm DM}}\,[{\rm GeV}^{-1}]$
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
$m\,[{\rm eV}]$
ADBC
aLIGO
DMRadio 50L
RF Cavities
DMRadio m^3
KLASH
Haloscope Limits
BRASS
ORGAN
MADMAX
ADMX
DMRadio GUT
$\Theta_0 = 0.999\pi$
$\Theta_0 = 0.5\pi$
$\Theta_0 = 0.1\pi$
Bounds/projections adapted
from cajohare/AxionLimits

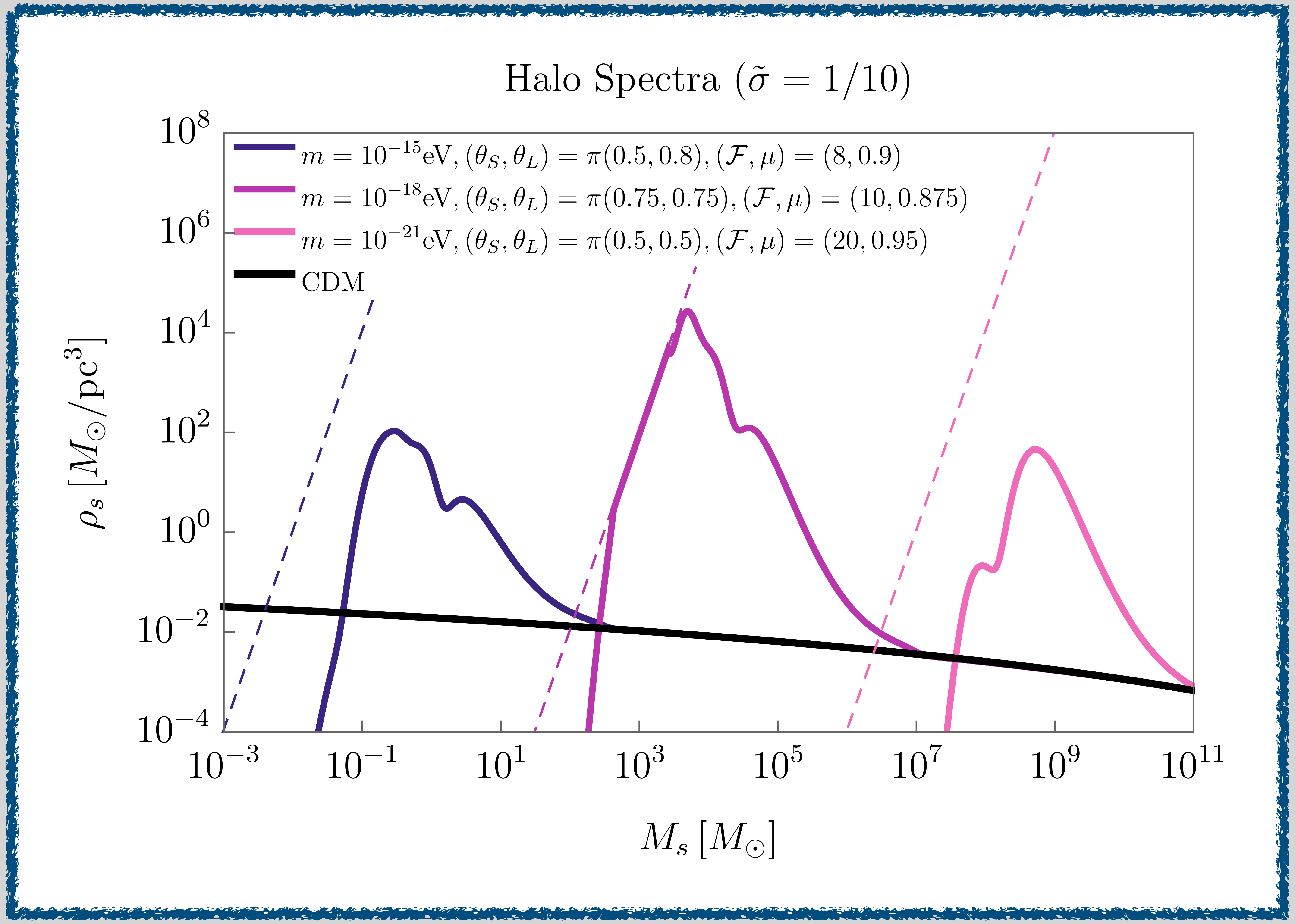
Beyond homogeneity

What about spatial perturbations?

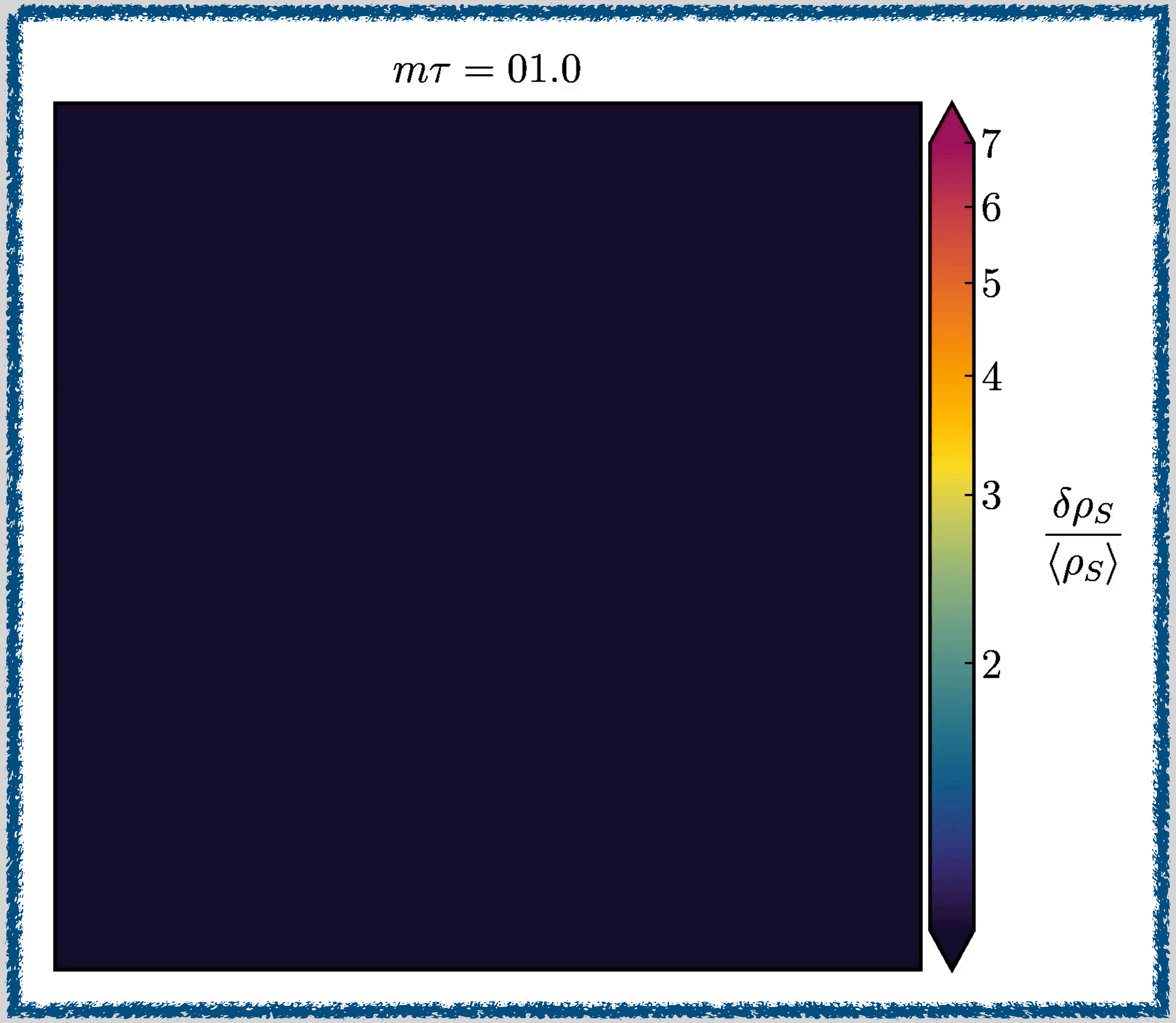
- During autoresonance, Θ_S is large $\implies$ strong self-interactions
- Parametric resonant growth in spatial perturbations of short axion
    - Similar to large-misalignment scenarios [arXiv:1909.11665]
- Length of time spent in parametric resonance controlled by $\mathscr{F} \equiv f_L/f_S$
- Small $\mathscr{F}$: Axion overdensities grow, lead to DM substructure
- Large $\mathscr{F}$: Overdensities grow nonperturbative, quench autoresonance

Beyond homogeneity

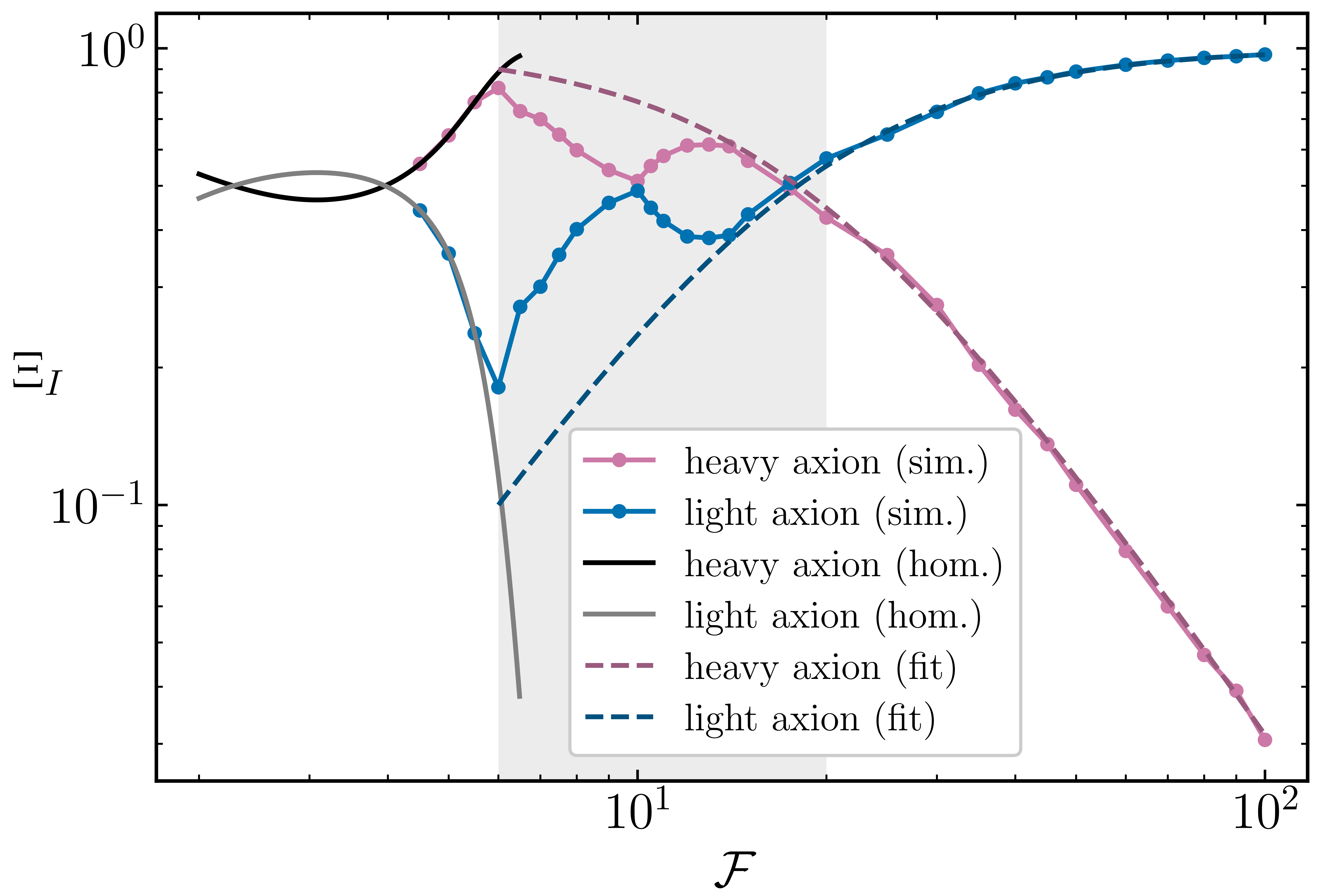
- Enhanced substructure on small scales depending on axion mass
- Halo mass $M_s \sim 12\, M_\odot \left(\frac{10^{-17}\,\mathrm{eV}}{m} \right)^{3/2}$
- Direct/indirect detection
  - Transient events
  - Distant stars on critical lensing caustics
  - Correlated weak lensing distortions



Beyond homogeneity: Oscillon formation

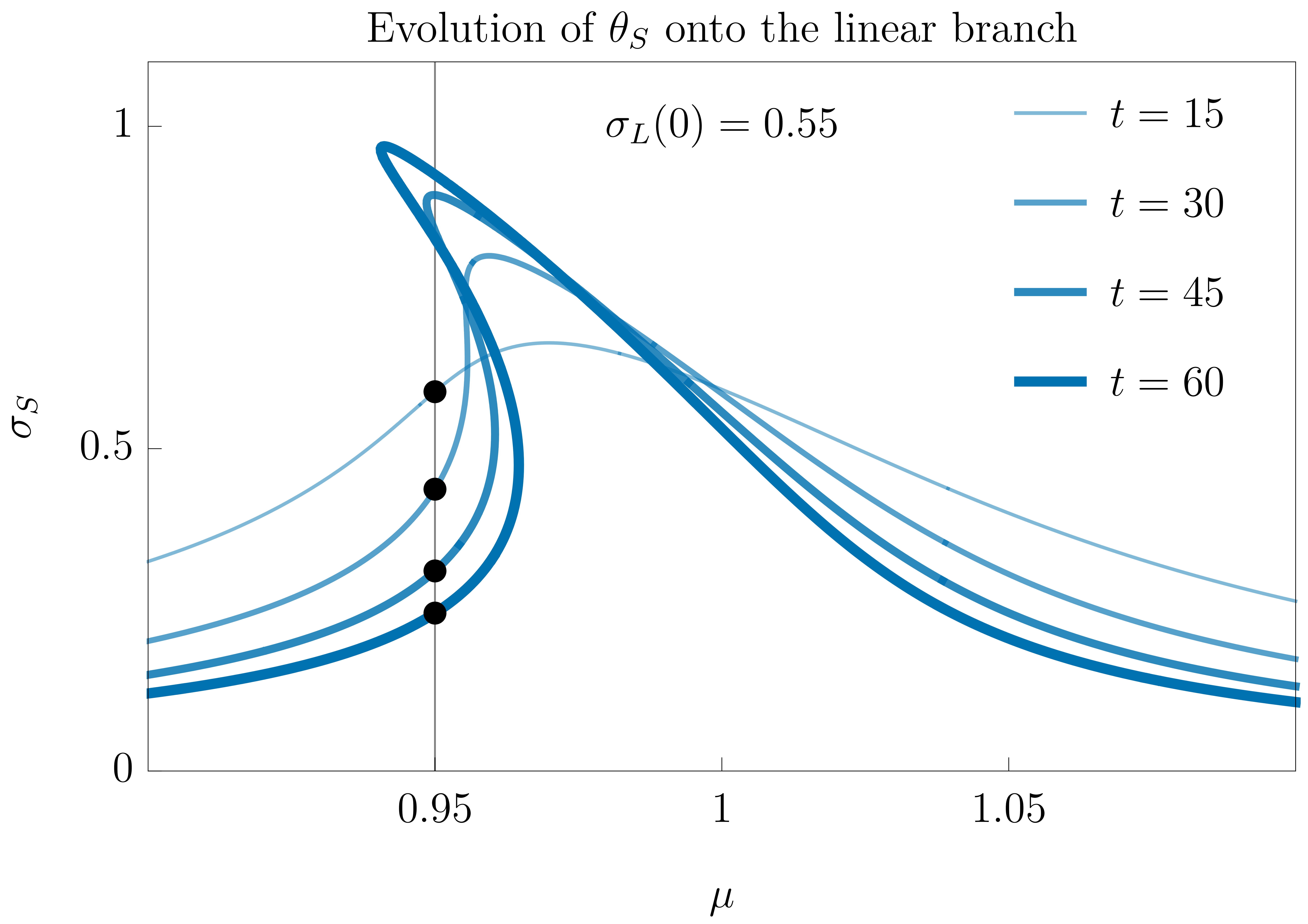


Energy partition in nonperturbative regime

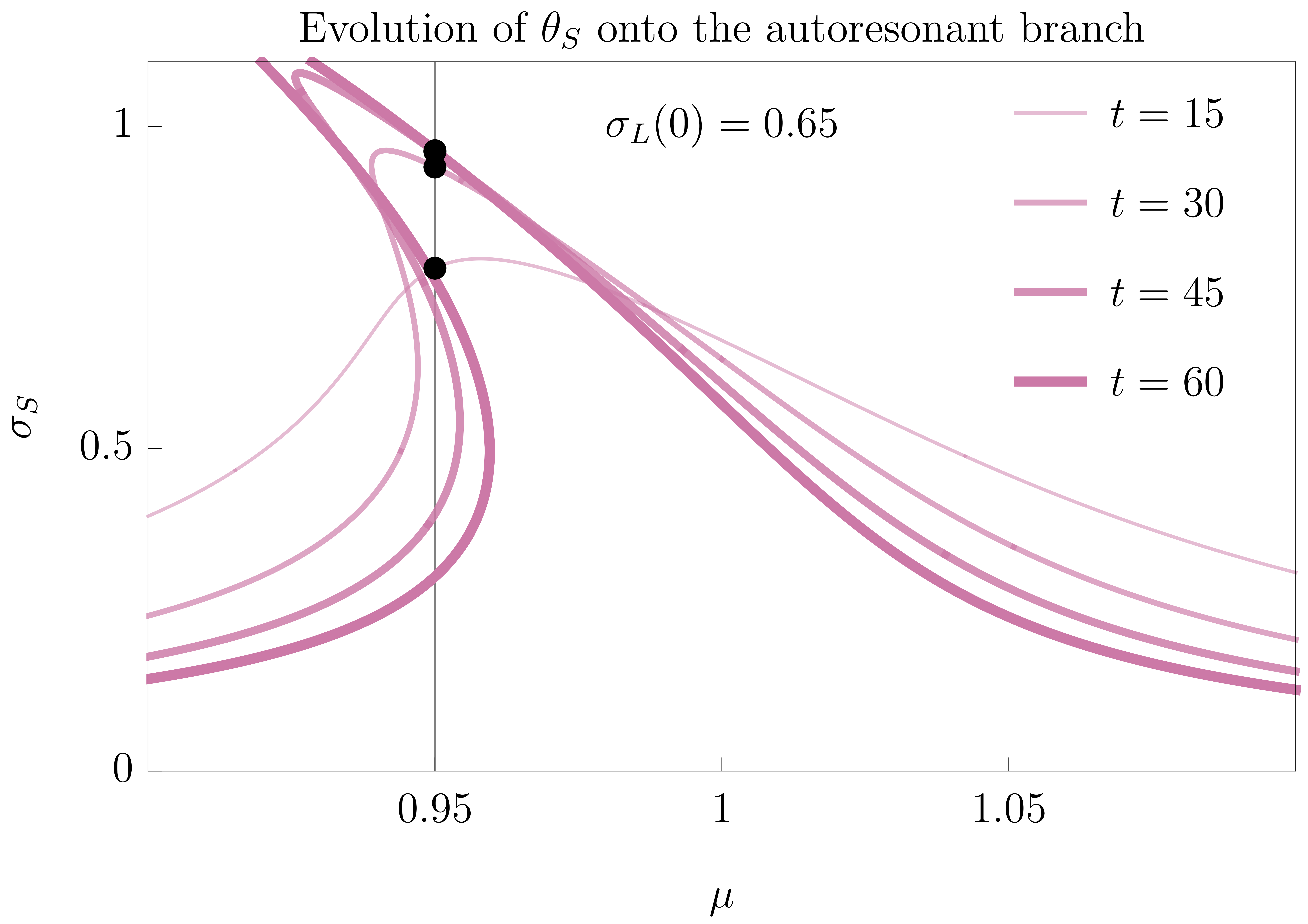


Summary

- $\mathcal{O}(1)$ coincidences in mass and untuned initial conditions can lead to a new type of resonant energy transfer (intrinsically nonlinear)
- Not all axions in an axiverse will have a friend, but a friendly pair can be significantly more visibile to direct detection experiments
- If DM is a friendly pair, can get visible boosts to small-scale substructure
    - Dynamics and signatures are similar to large initial misalignment angles
    - Probes of DM substructure can test many axion models

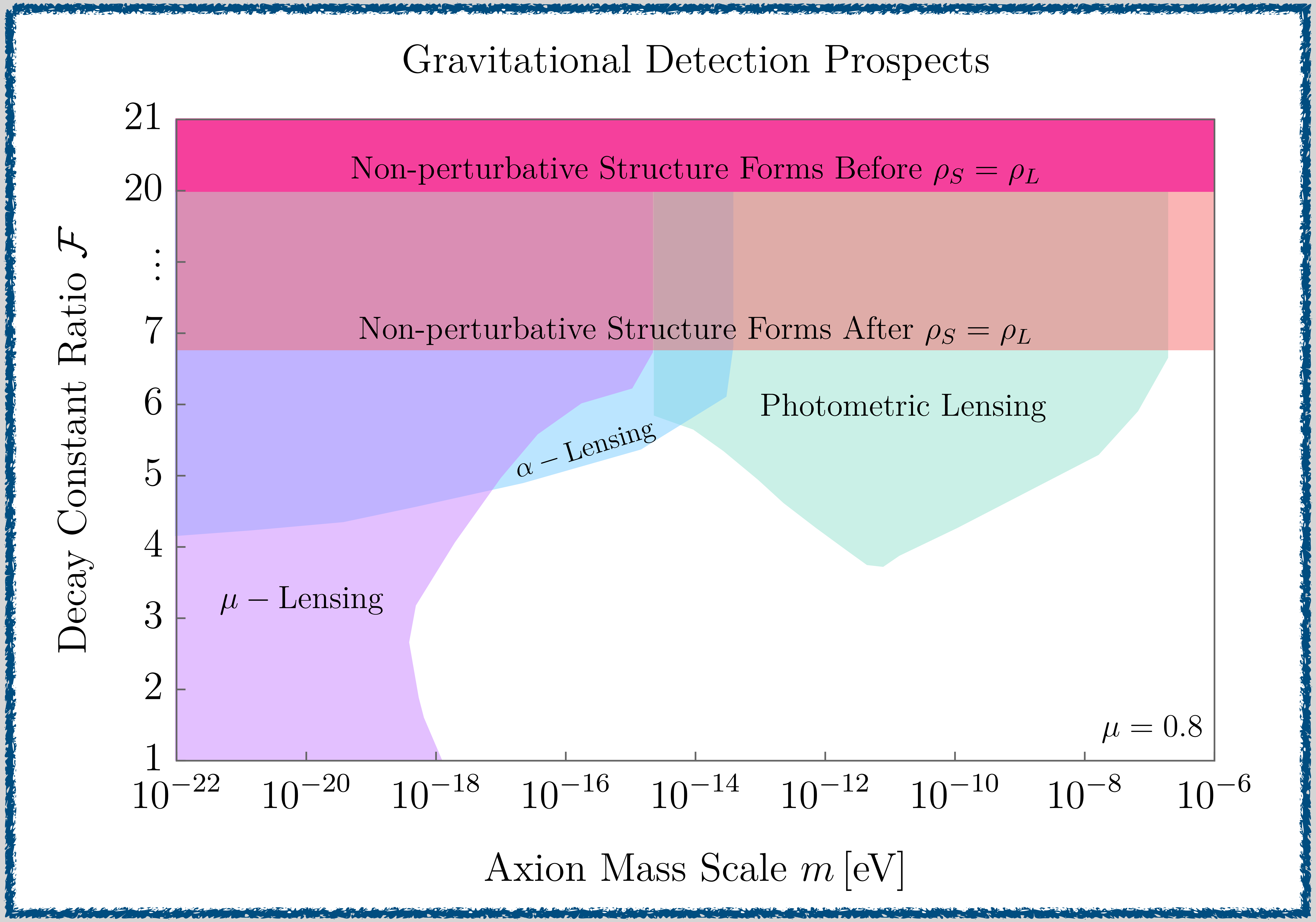


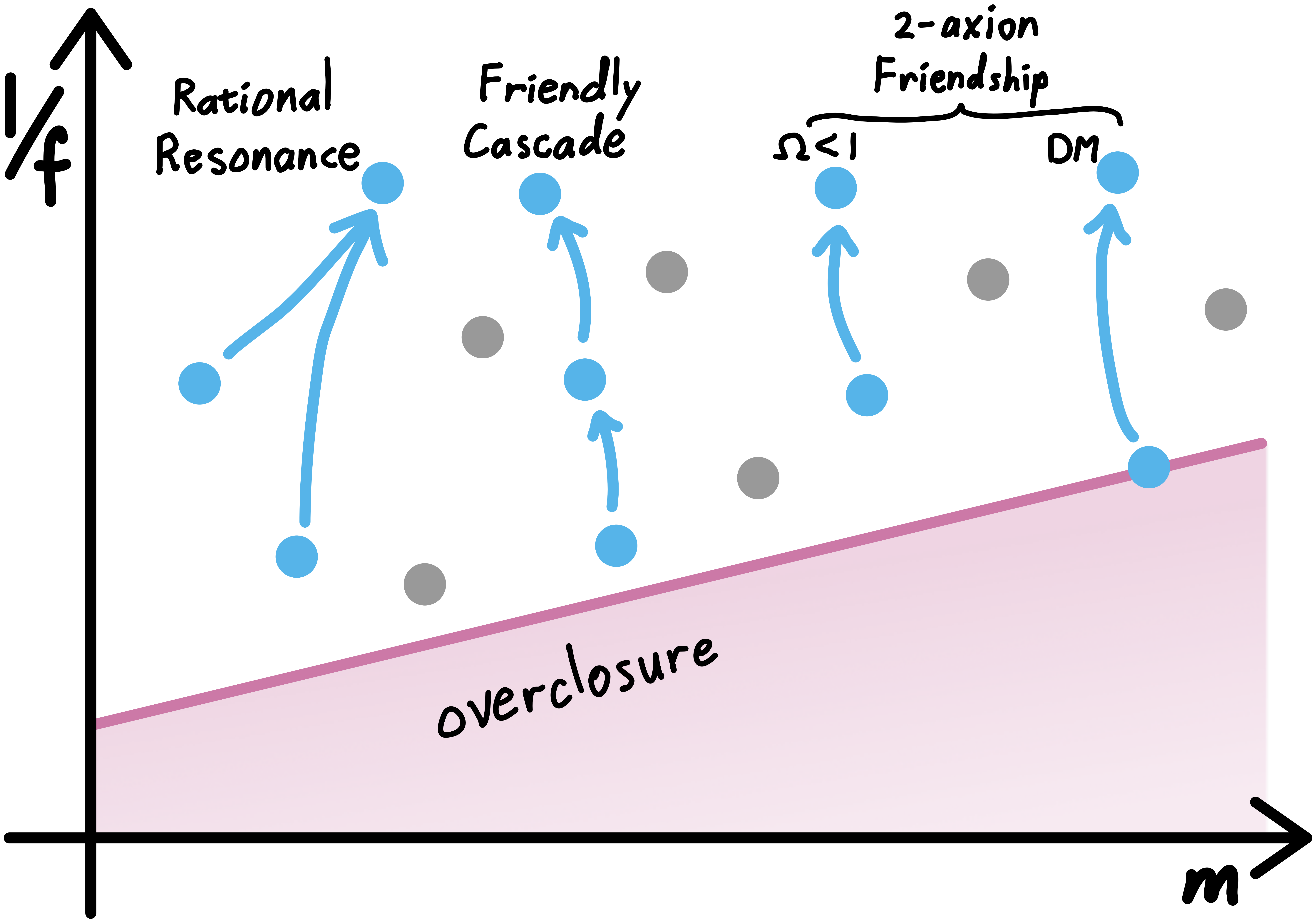
Evolution of θ_S onto the linear branch
$\sigma_L(0) = 0.55$
$t = 15$
$t = 30$
$t = 45$
$t = 60$
σ_S
1
0.5
0
0.95
1
1.05
μ



Evolution of θ_S onto the autoresonant branch
$\sigma_L(0) = 0.65$
$t = 15$
$t = 30$
$t = 45$
$t = 60$
σ_S
1
0.5
0
0.95
1
1.05
μ

Gravitational indirect detection





1/f
Rational Resonance
Friendly Cascade
2-axion Friendship
Ω<1
DM
overclosure
m