

The Large-Misalignment Mechanism for the Formation of Compact Axion Structures

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A. Arvanitaki, S. Dimopoulos, M. Galanis, L. Lehner, J. Thompson, KVT:
[arXiv 1909:tomorrow](#)

Large Misalignment for Compact Axion Structures

Axions behave exactly like Cold Dark Matter (CDM)*

*except under **certain conditions**, on some **length scales**, and at **times** when they do not

Symmetry breaking after inflation: isocurvature fluctuations → axion strings & miniclusters [Malte's talk]

Symmetry breaking before inflation, small misalignment: density fluctuations suppressed below Jeans scale

Symmetry breaking before inflation, large misalignment:

density fluctuations enhanced for **semi-relativistic modes** when the axion starts oscillating

cosine

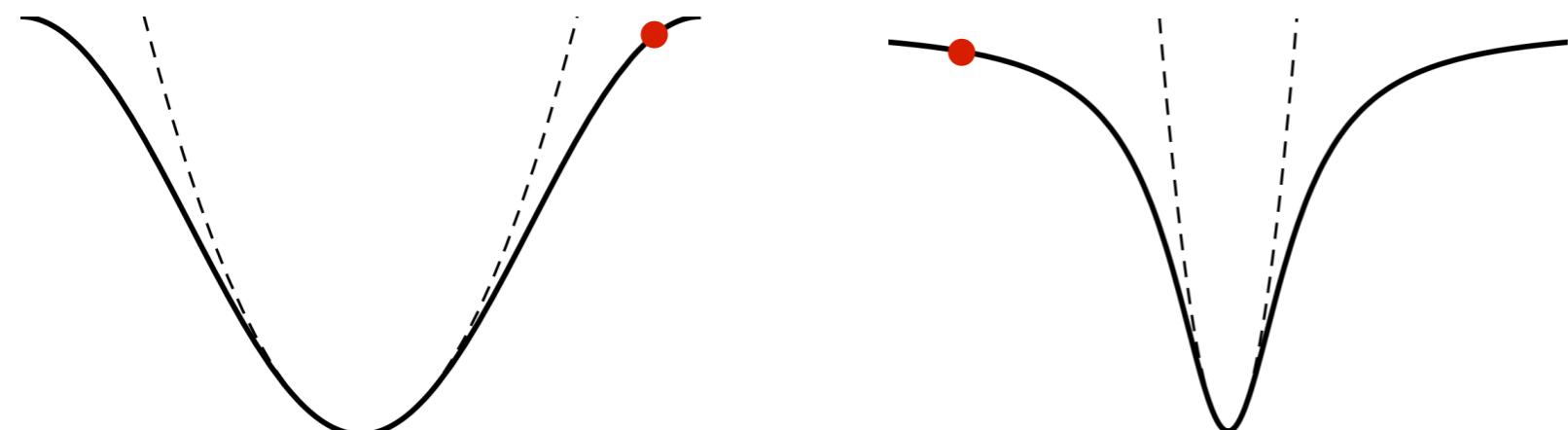
$$V = -m^2 f^2 \cos \frac{\phi}{f}$$

modulus

$$V = \frac{m^2 f^2}{2} \frac{\phi^2}{f^2 + \phi^2}$$

QCD axion

$$V = -V_{\pi}^2 f_{\pi}^2 \sqrt{m_a \left(\frac{4 m_u m_d}{m_u + m_d} \right)^2 \cos^2 \frac{a}{2 f_a}}$$



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$$\text{if } |\Theta_0| > \frac{\pi}{2} : \quad \text{for } \frac{k}{a} \sim m \sim H_{\text{osc}}$$

$$\mathcal{B} \equiv \frac{\rho_s}{\rho_s^{\text{CDM}}} \sim \exp \left\{ \frac{m}{H_{\text{osc}}} \right\} \quad M_s^* \sim \frac{\rho_{\text{DM}}^0}{(k_*)^3} \sim 5 \times 10^9 M_\odot \left[\frac{10^{-22} \text{ eV}}{m} \right]^{3/2}$$

Large Misalignment Mechanism

$$\frac{\phi}{f} = \Theta(t) + \sum_{\mathbf{k}} \theta_{\mathbf{k}}(t) e^{i\mathbf{k}\cdot\mathbf{x}}$$

$$\tilde{k}^2 \equiv \frac{k^2/a^2}{2mH}$$

3 ways to understand enhancement of structure formation:

1. negative quartic \rightarrow attractive self-interaction $V = m^2 f^2 [1 - \cos \theta] \simeq m^2 f^2 \left[\frac{\theta^2}{2} - \frac{\theta^4}{24} + \dots \right]$

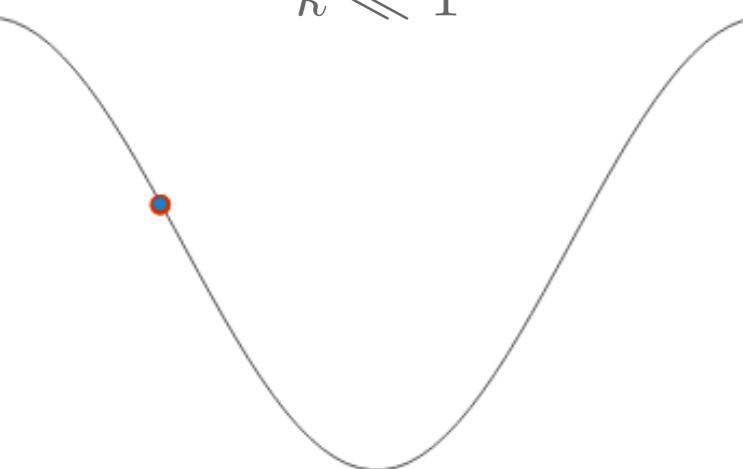
2. density fluctuations have negative sound speed $c_s^2 \simeq \frac{\mathbf{k}^2/a^2}{4m^2} - \frac{\rho}{8m^2 f^2}$

$$\delta_{\mathbf{k}} = 2 \frac{\dot{\Theta} \dot{\theta}_{\mathbf{k}} + m^2 \Theta \theta_{\mathbf{k}}}{\dot{\Theta}^2 + m^2 \Theta^2} \quad \ddot{\delta}_{\mathbf{k}} + 2H\dot{\delta}_{\mathbf{k}} - \left[4\pi G \rho - \frac{c_s^2 \mathbf{k}^2}{a^2} \right] \delta_{\mathbf{k}} = 0$$

3. parametric resonance for field fluctuations

nonrelativistic mode

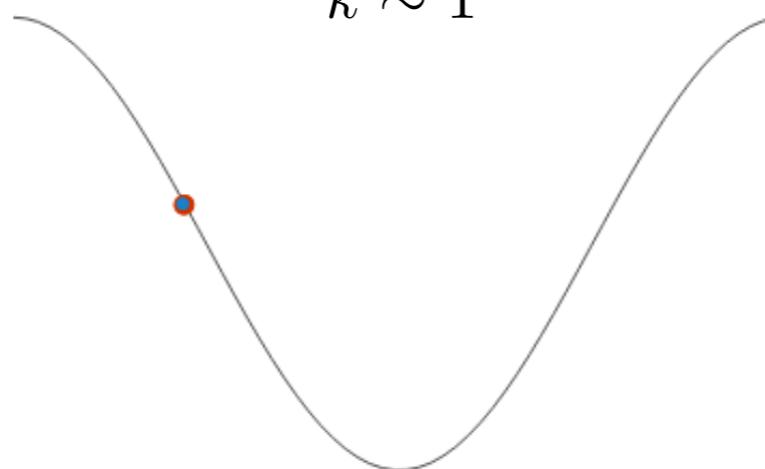
$$\tilde{k} \ll 1$$



enters horizon when
nonlinearities are small

semi-relativistic mode

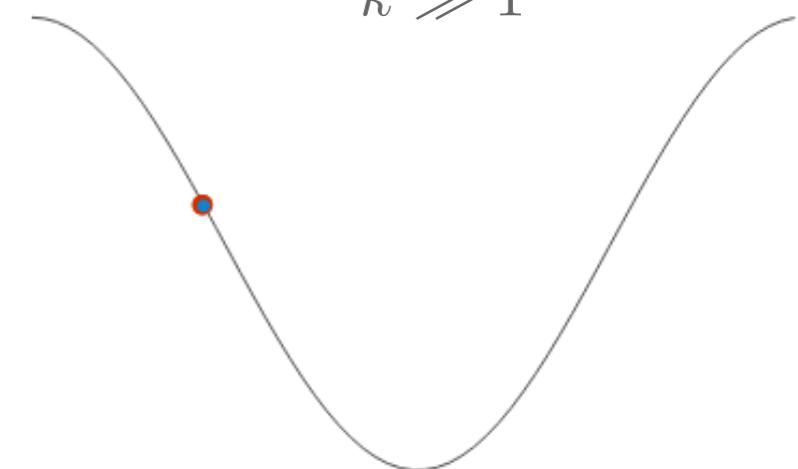
$$\tilde{k} \sim 1$$



frequency match;
nonlinearity > friction

ultra-relativistic mode

$$\tilde{k} \gg 1$$



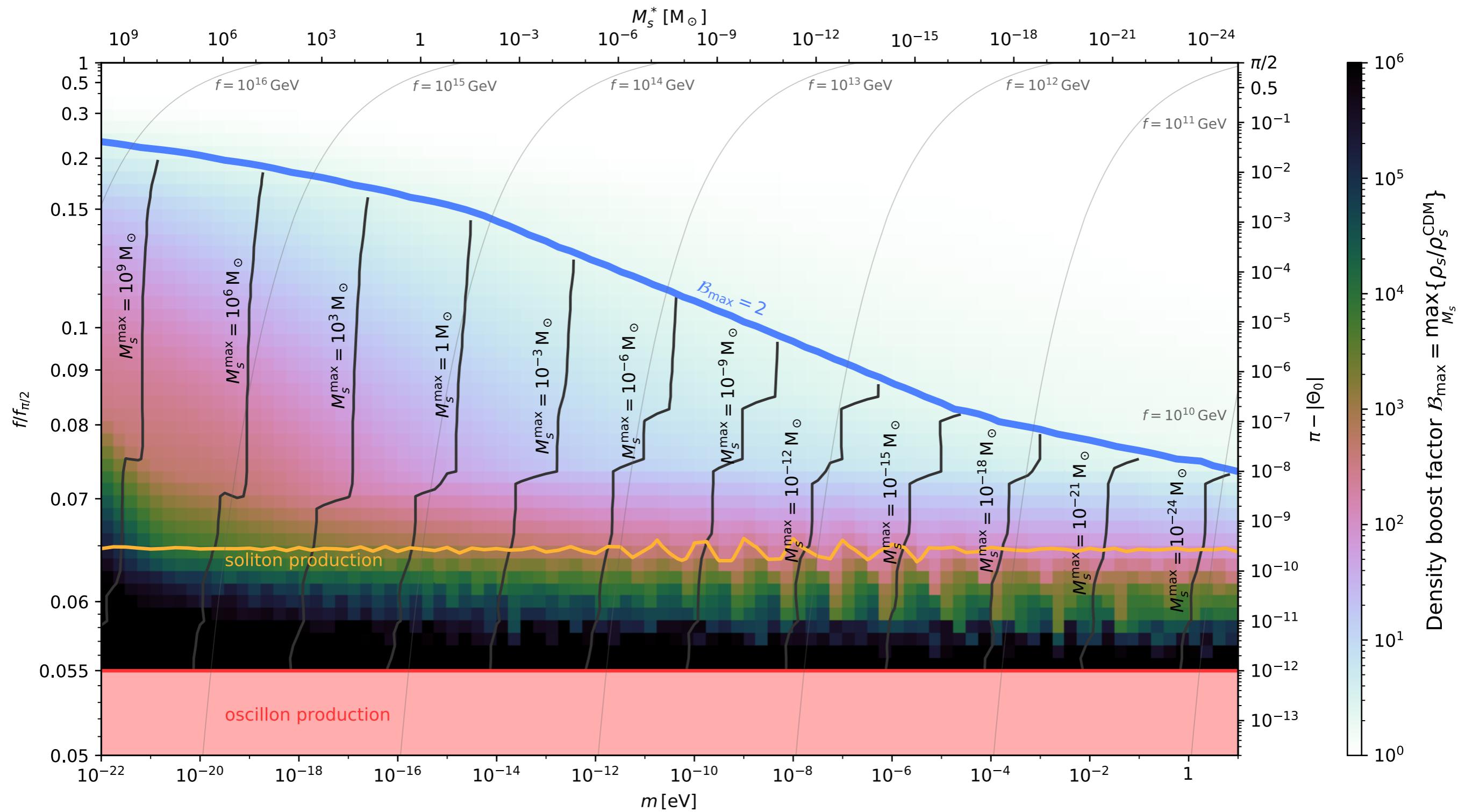
frequency mismatch;
curvature fluctuation damped

Compact Axion Structures

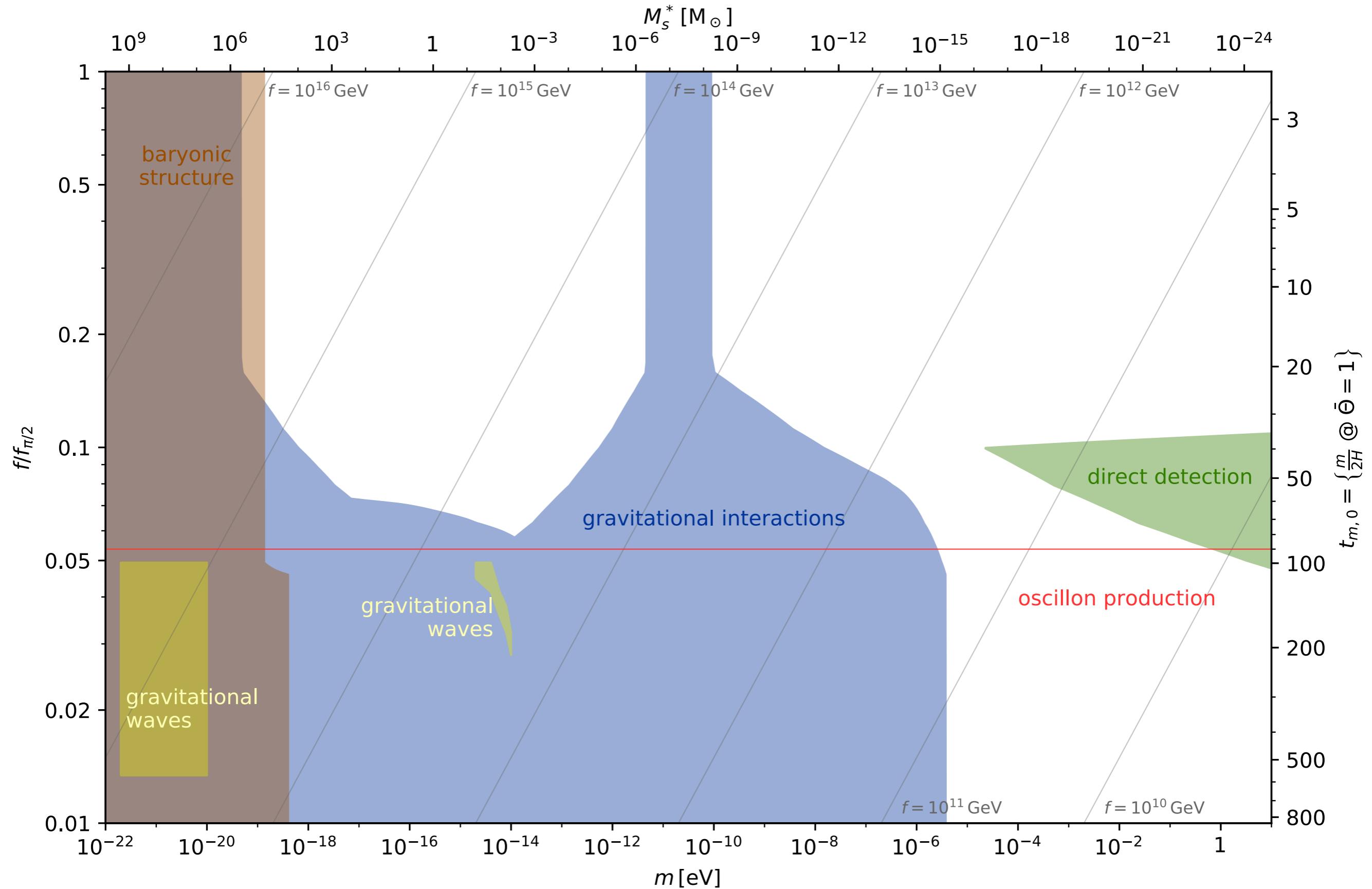
dense axion minihalos

solitons

oscillons

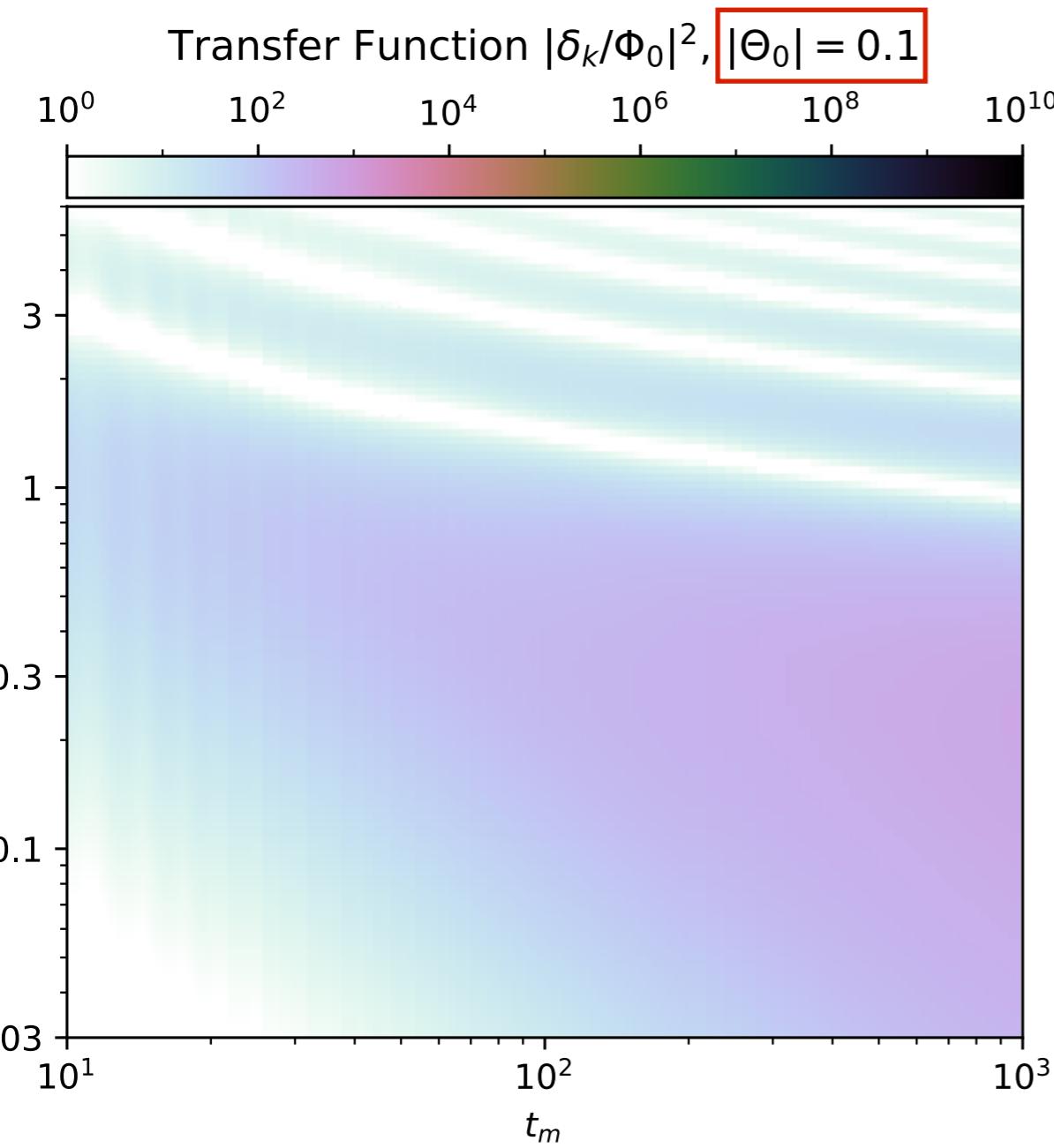


Observable Signatures

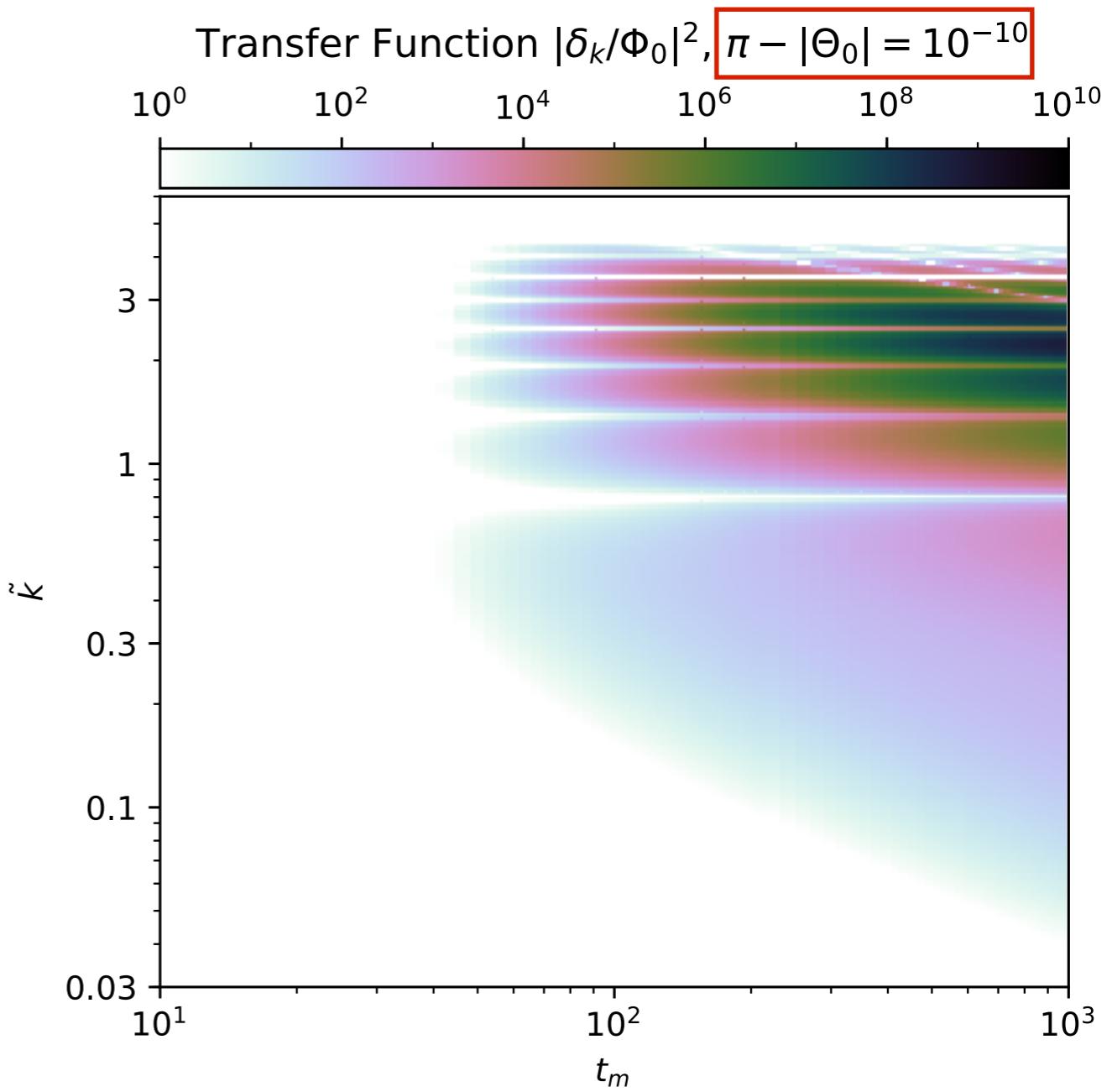


Linear Evolution in Time

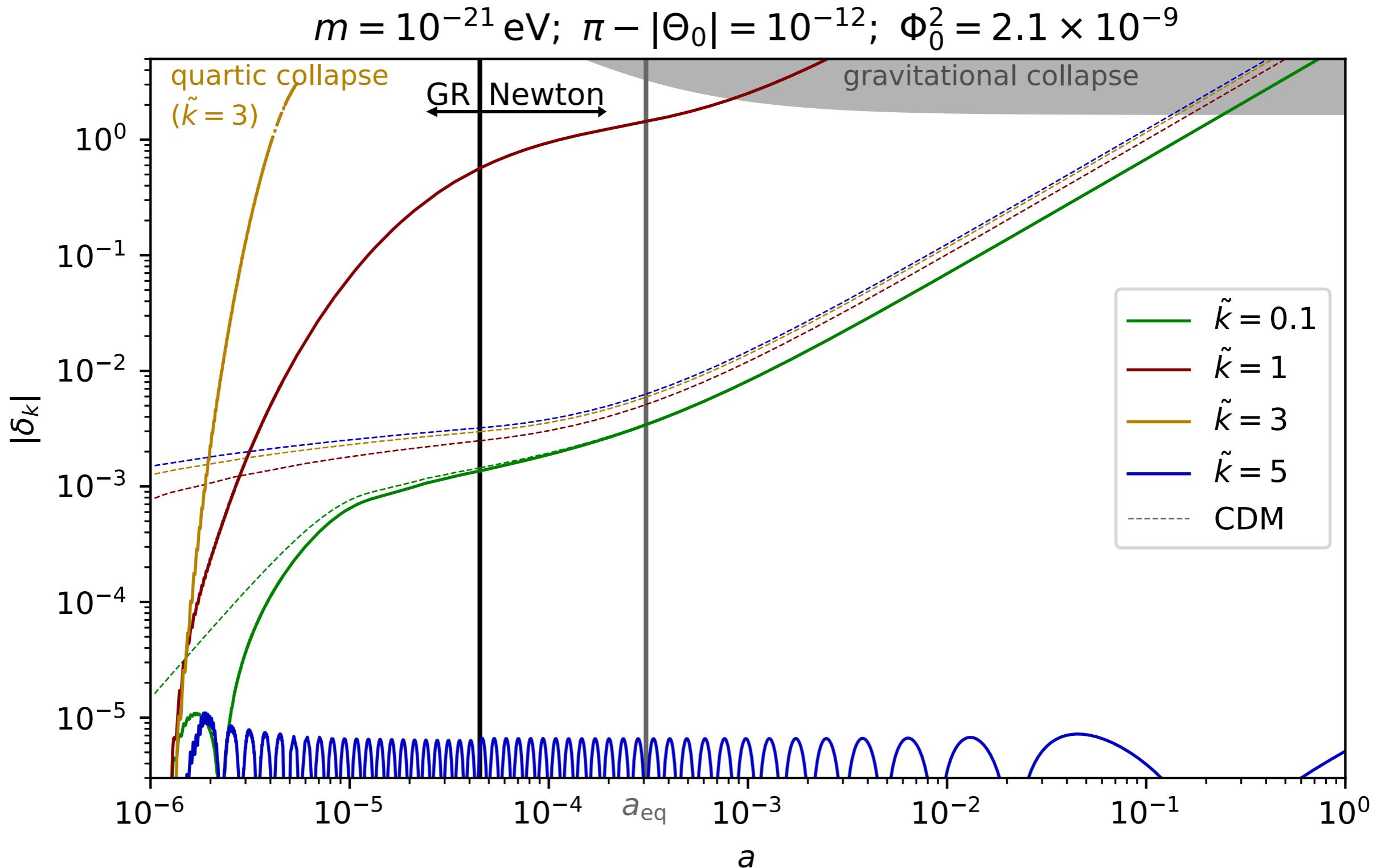
small misalignment



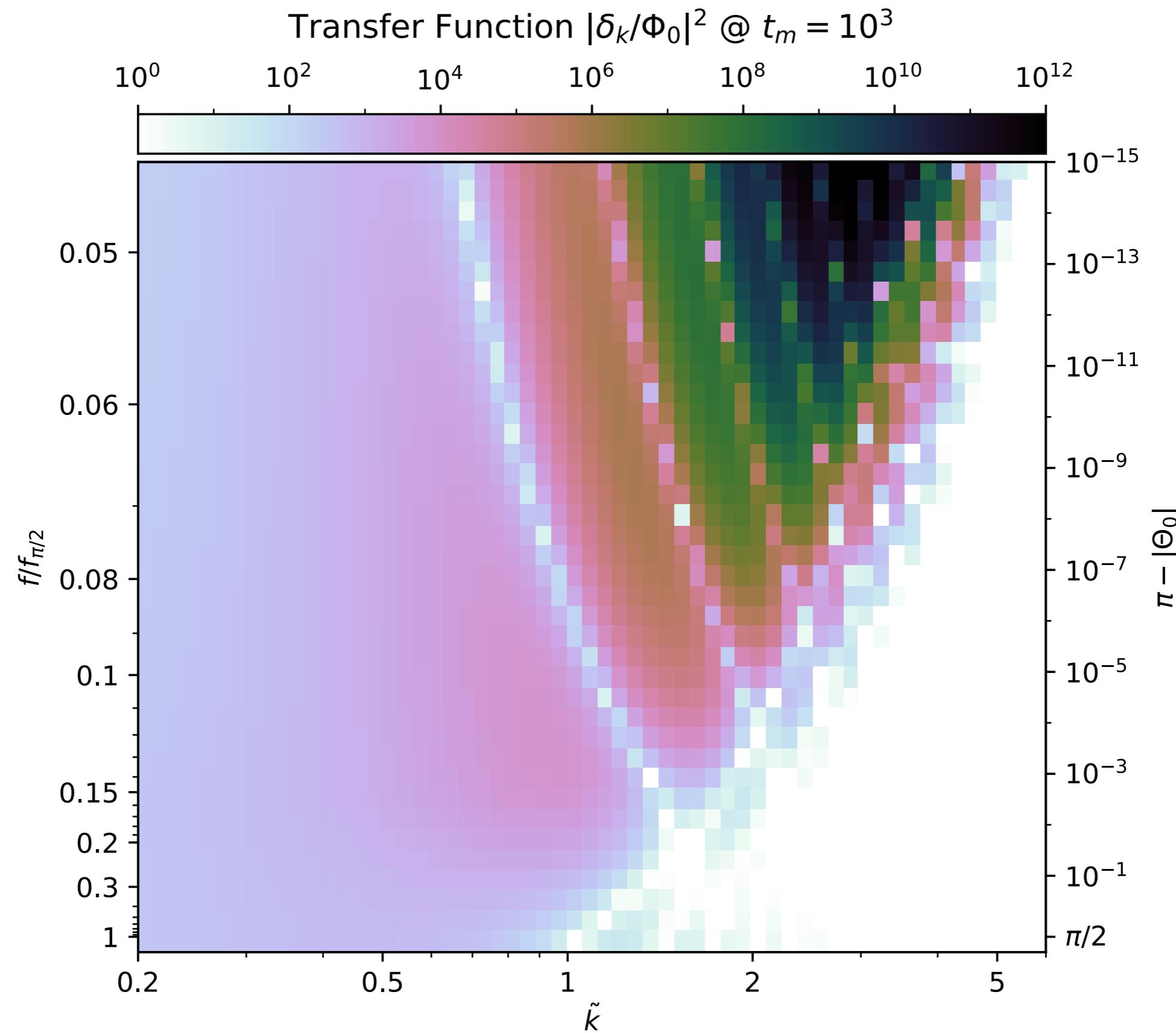
large misalignment



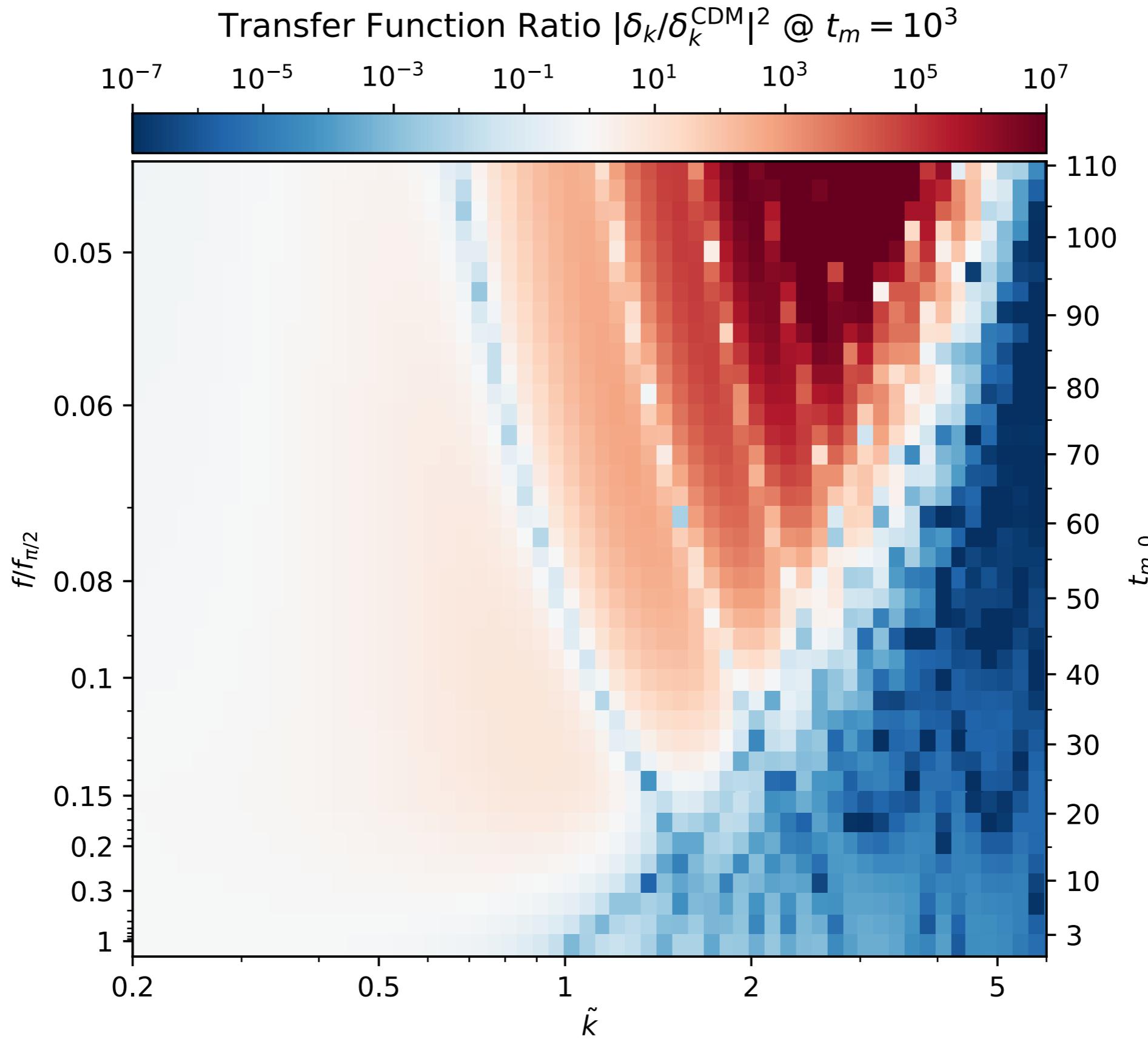
Linear Evolution in Time



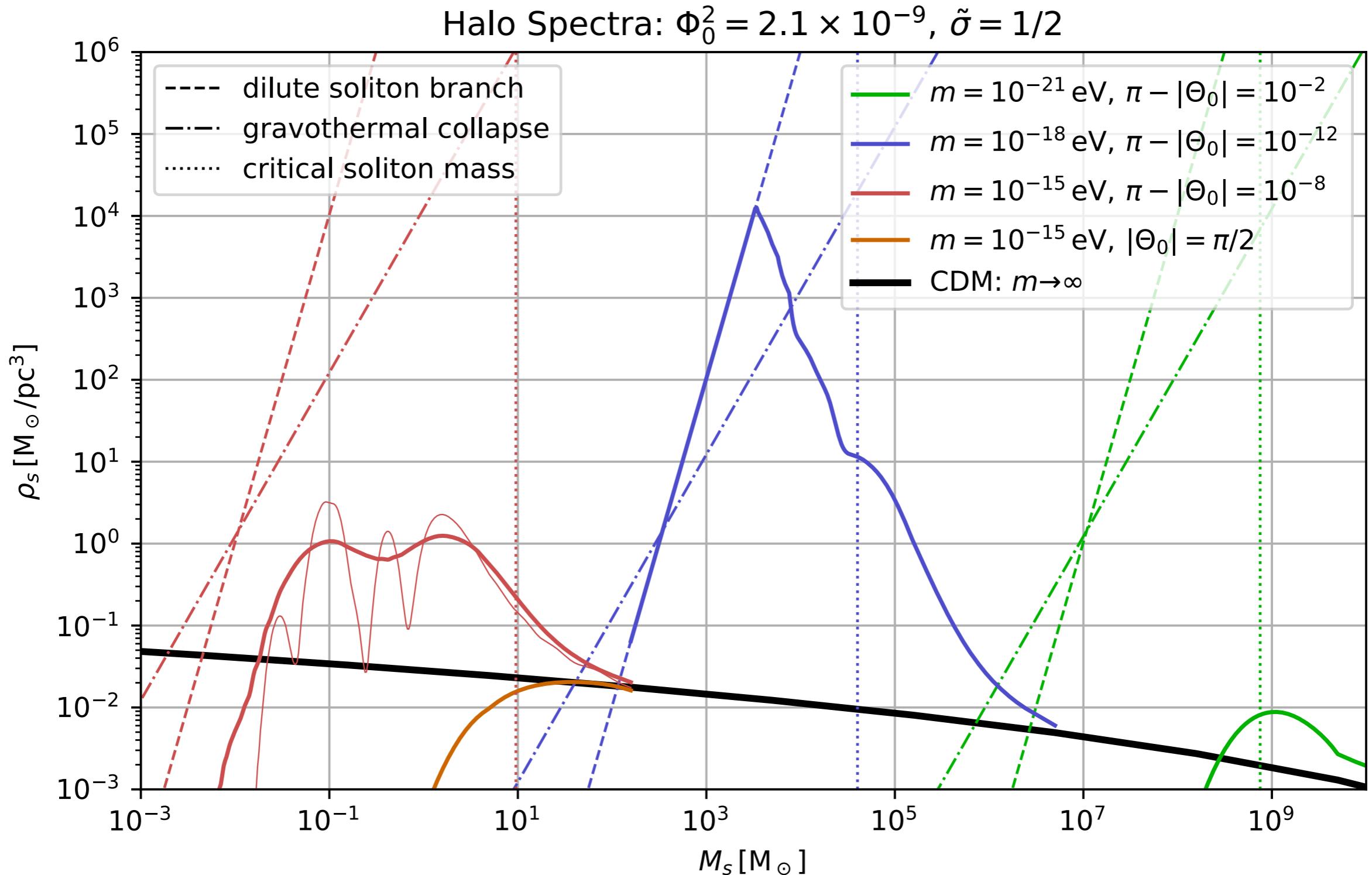
Linear Evolution versus Misalignment



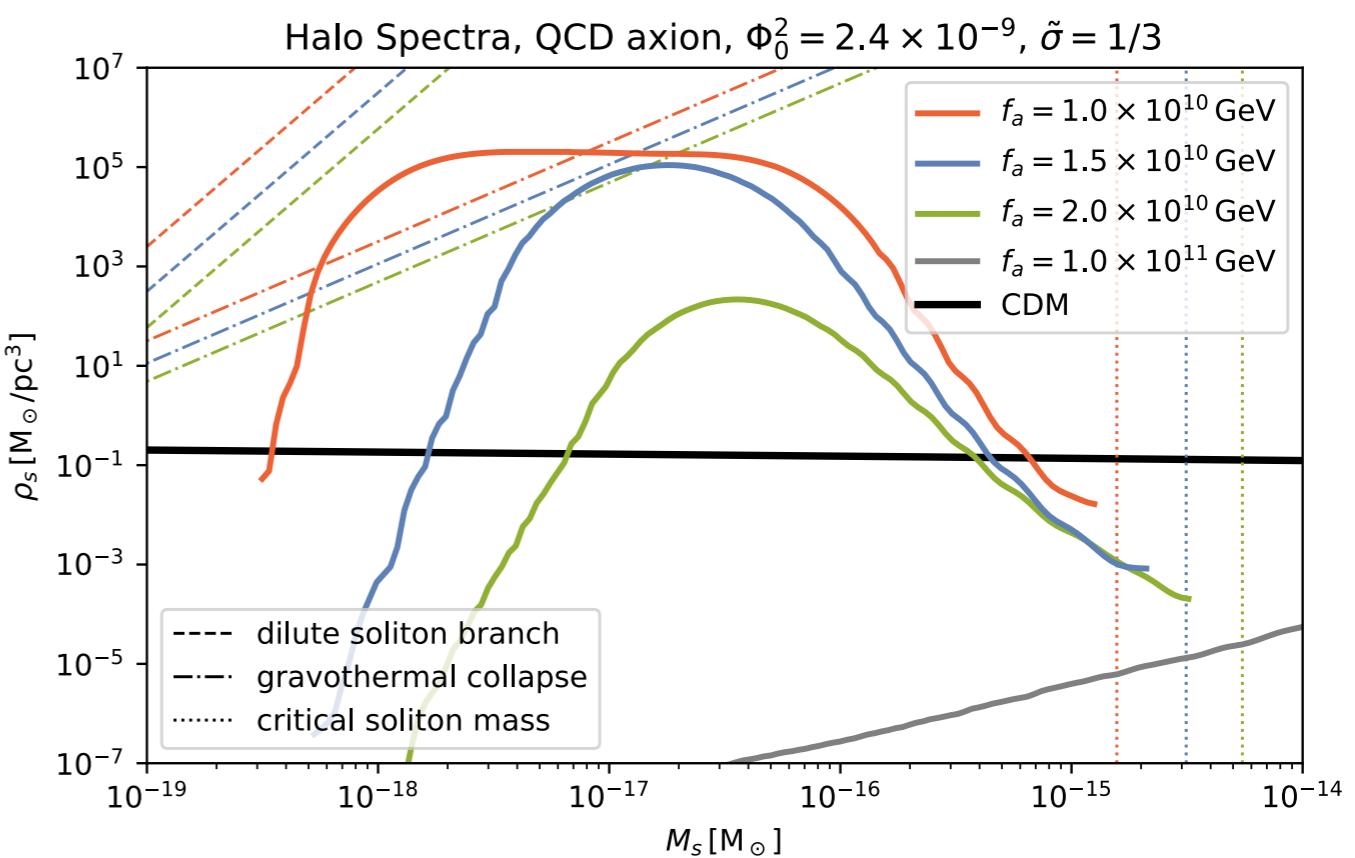
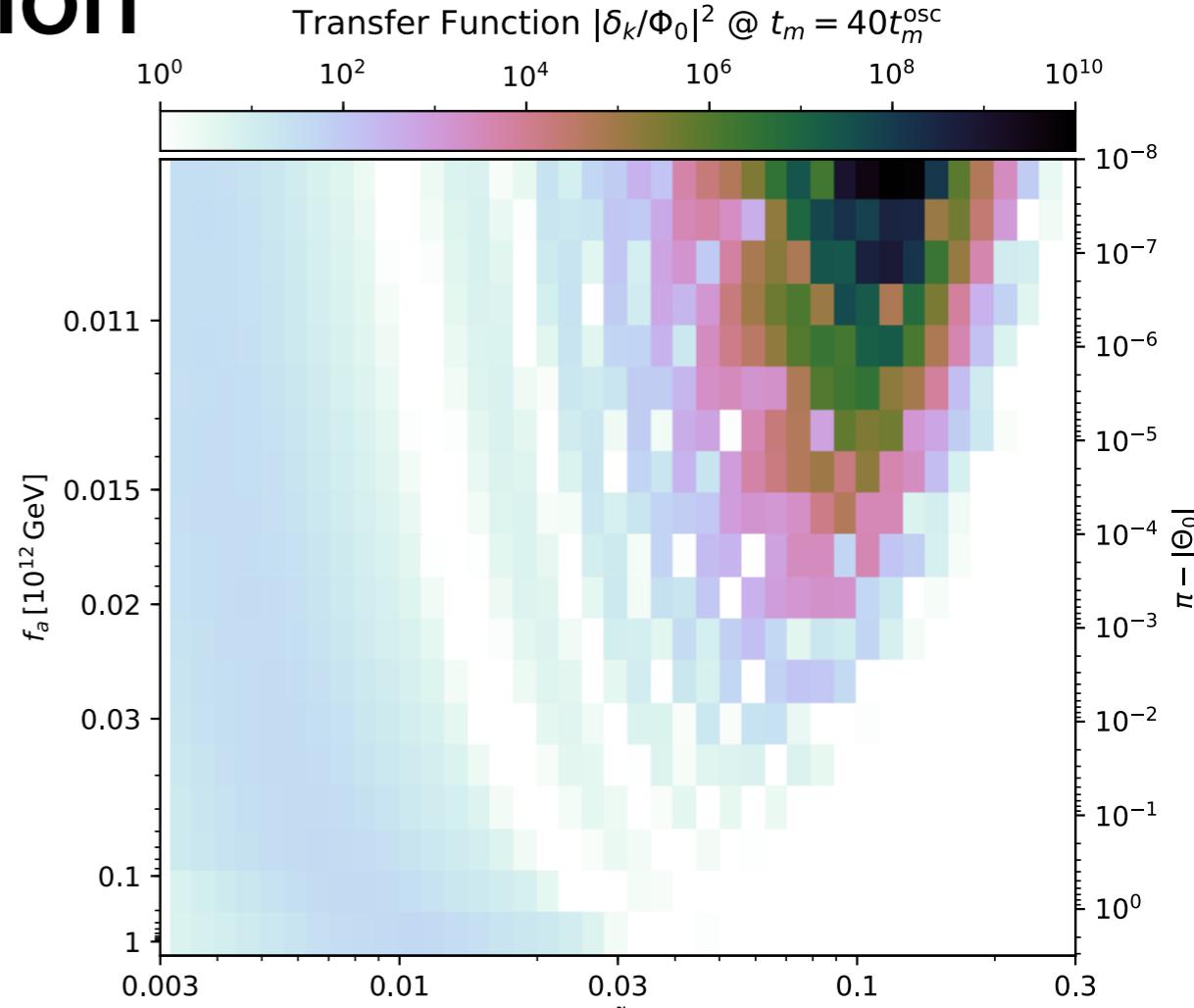
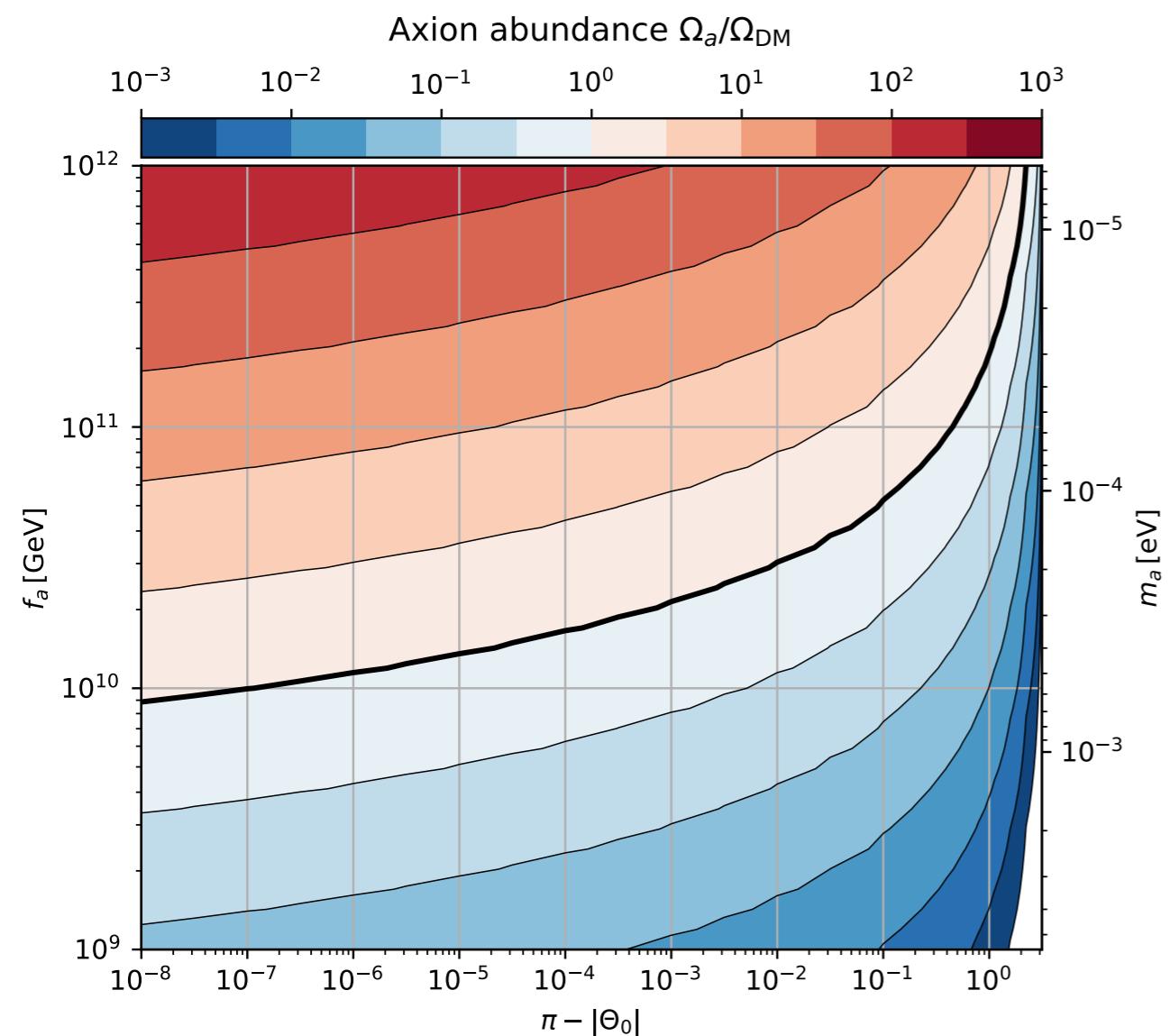
Linear Evolution versus Misalignment



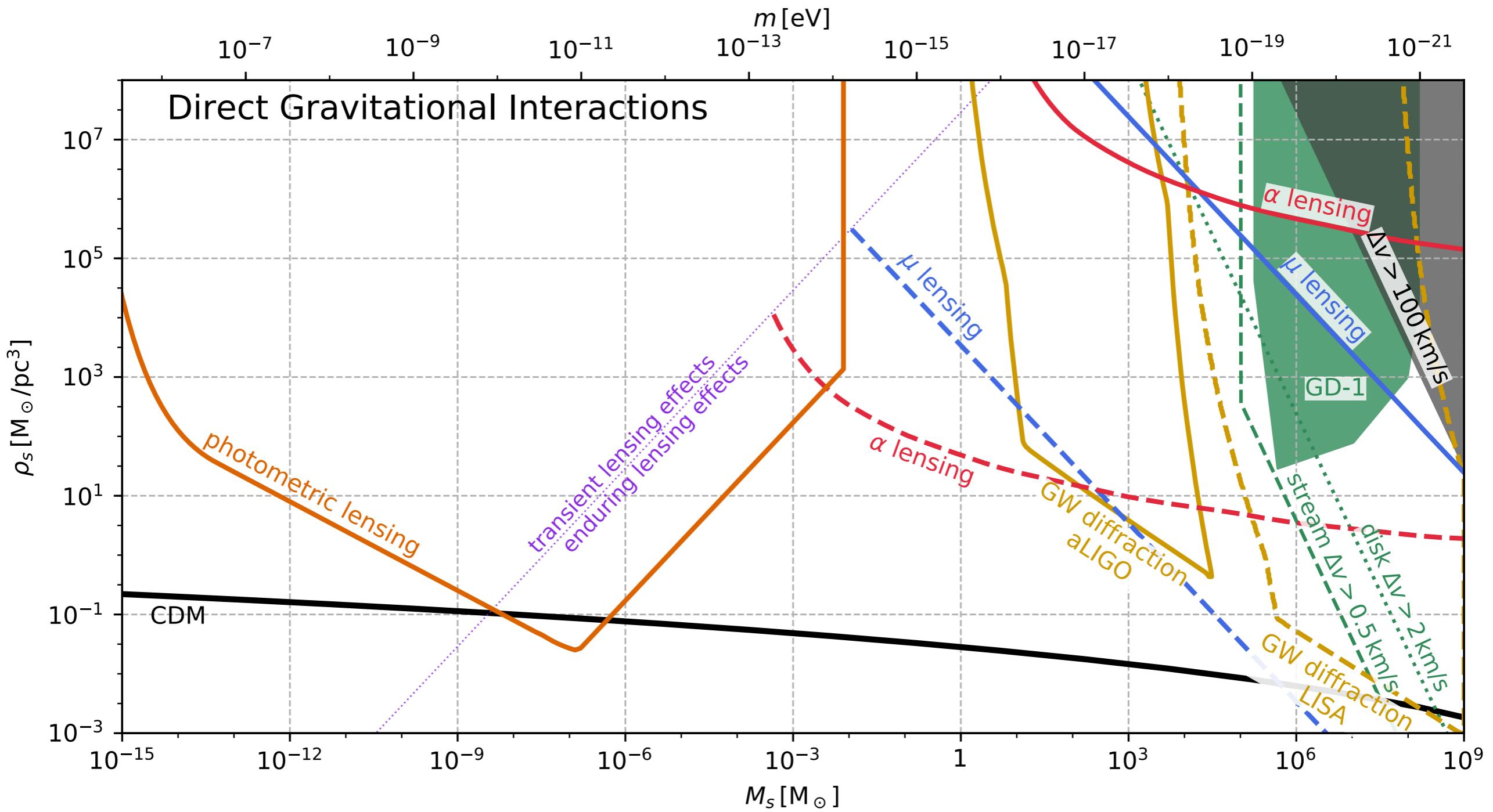
Dense Axion Halos & Solitons



QCD Axion



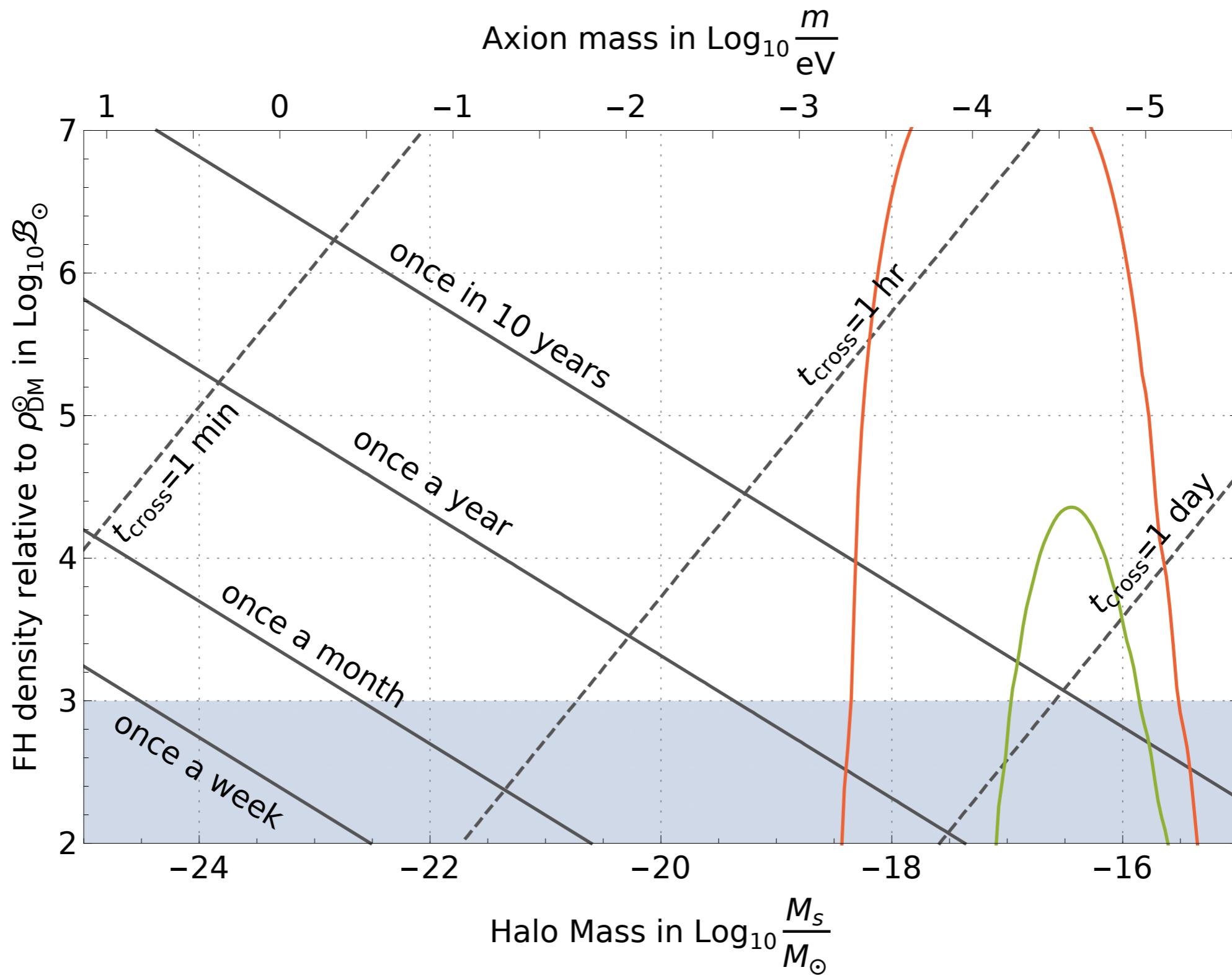
Gravitational Interactions



Direct Detection

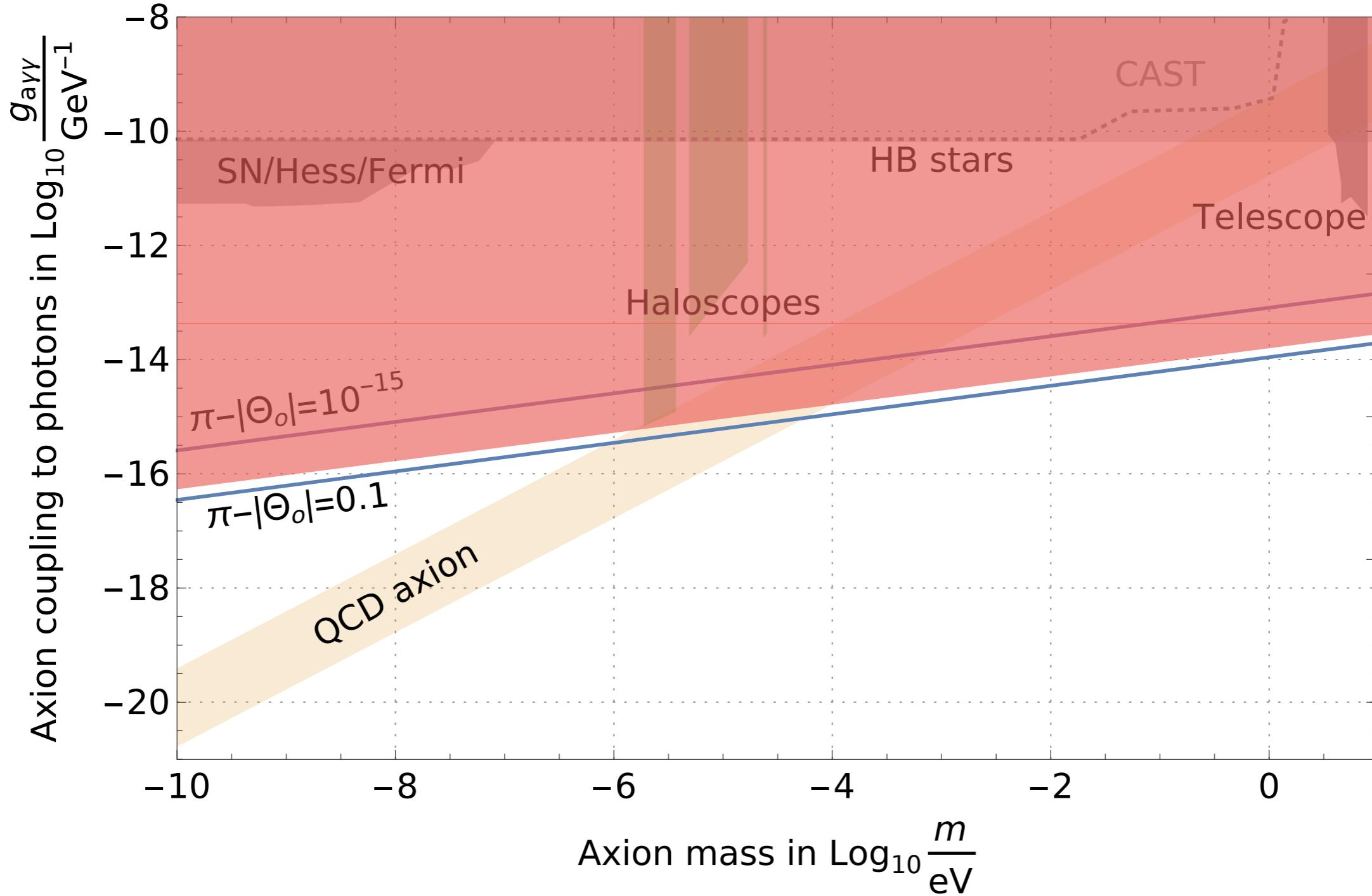
intermittent, highly coherent signals

broadband data recording
matched filters



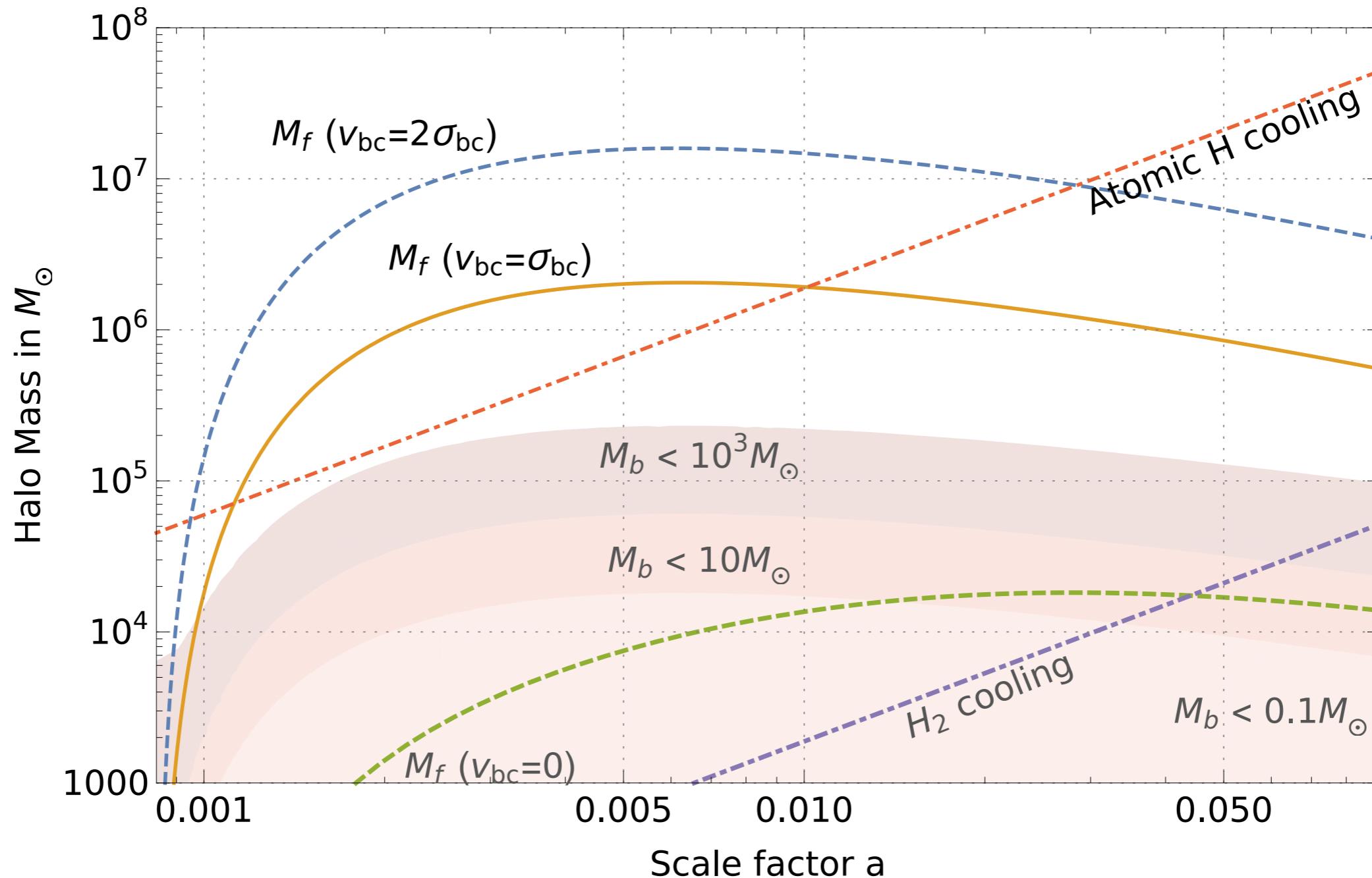
Direct Detection

re-evaluate constraints and optimize high-frequency axion searches

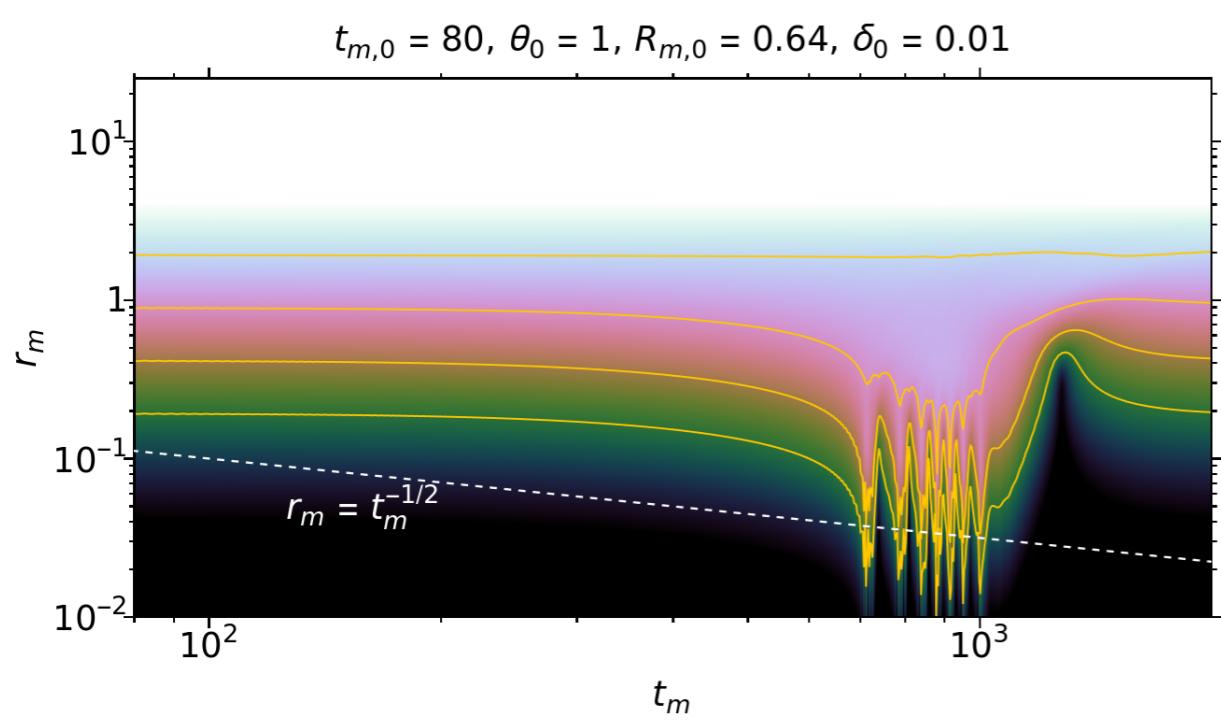
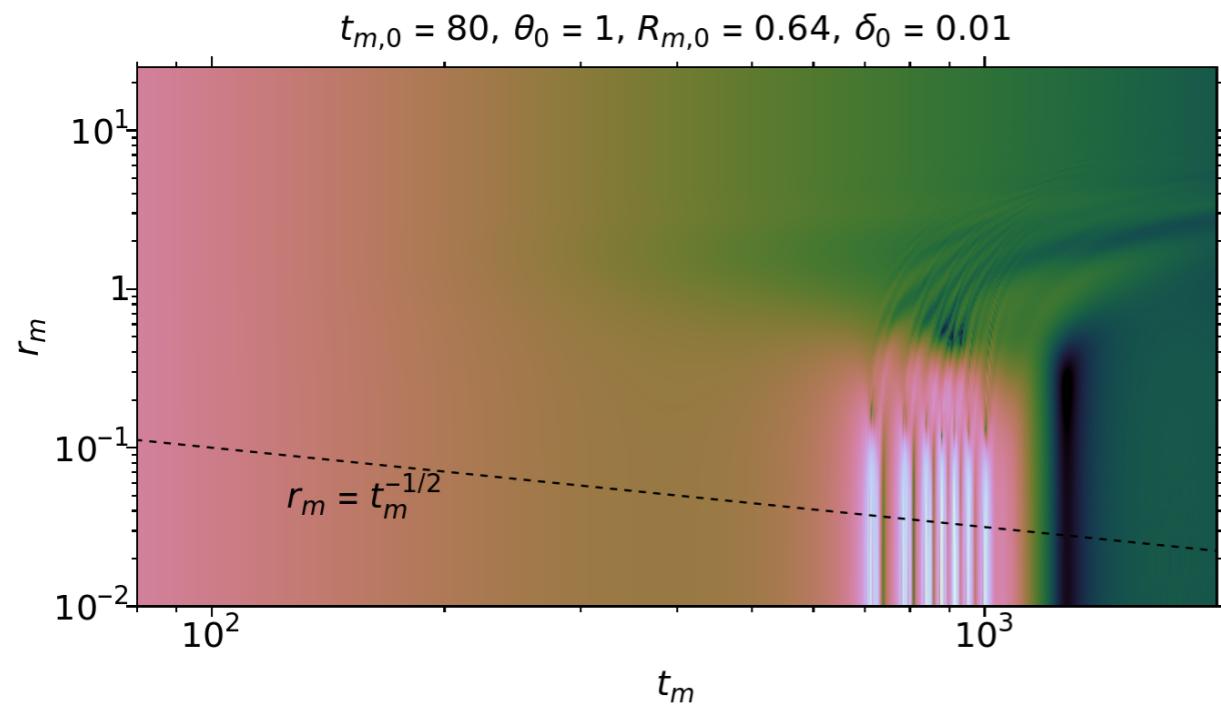


[Michael's talk]

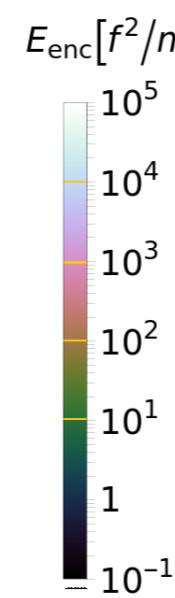
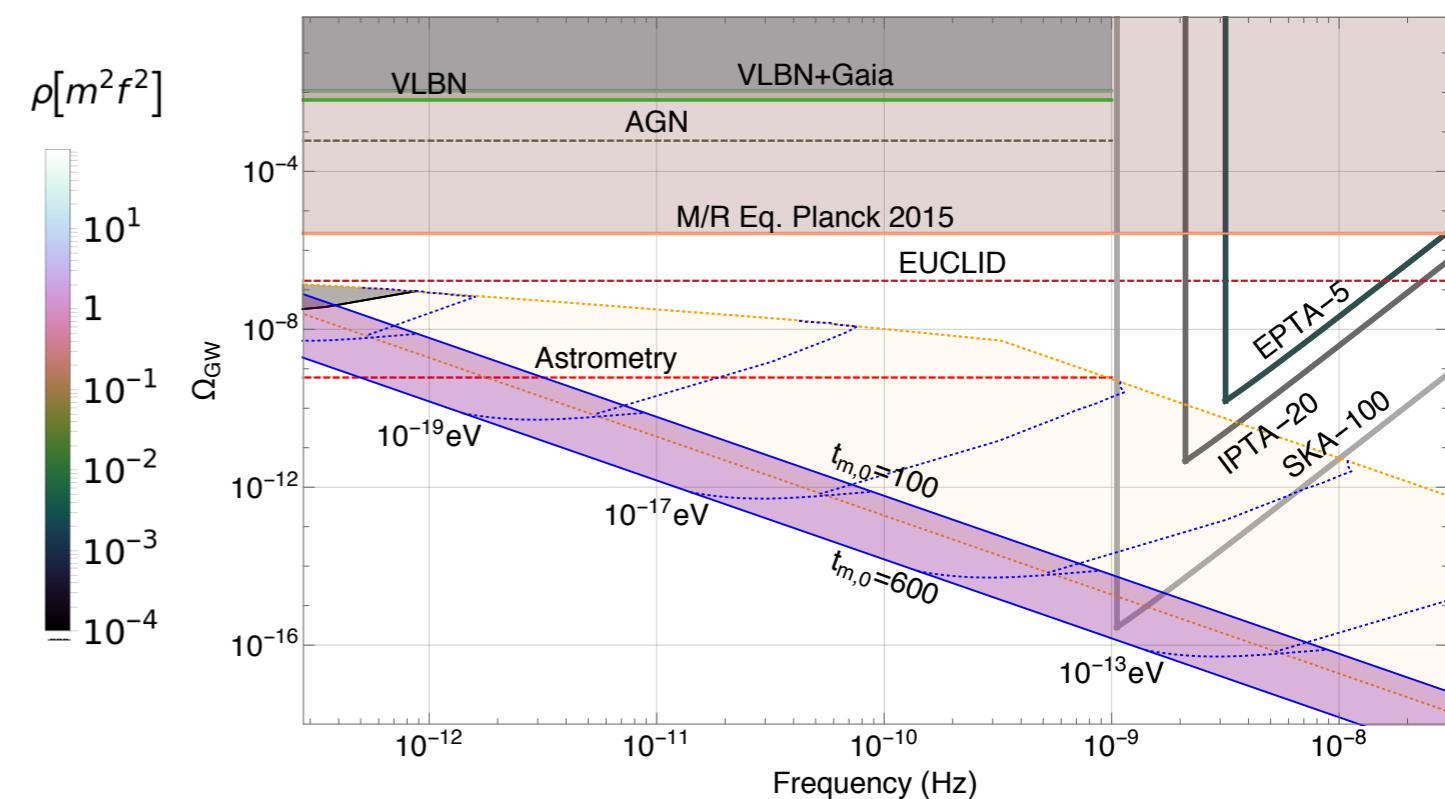
Baryonic Structure & Star Formation



Oscillon Production



Gravitational Waves

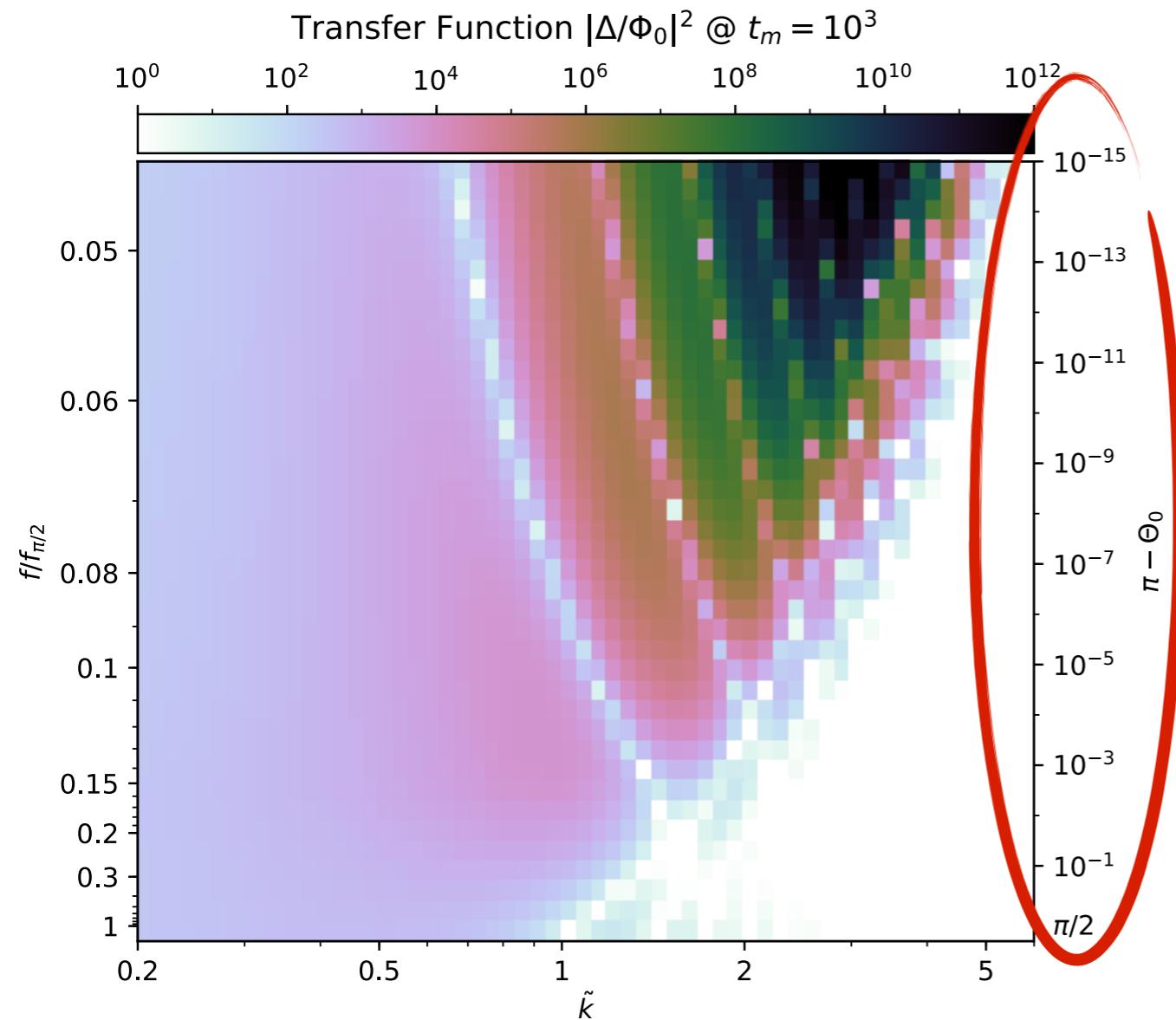


Initial Conditions

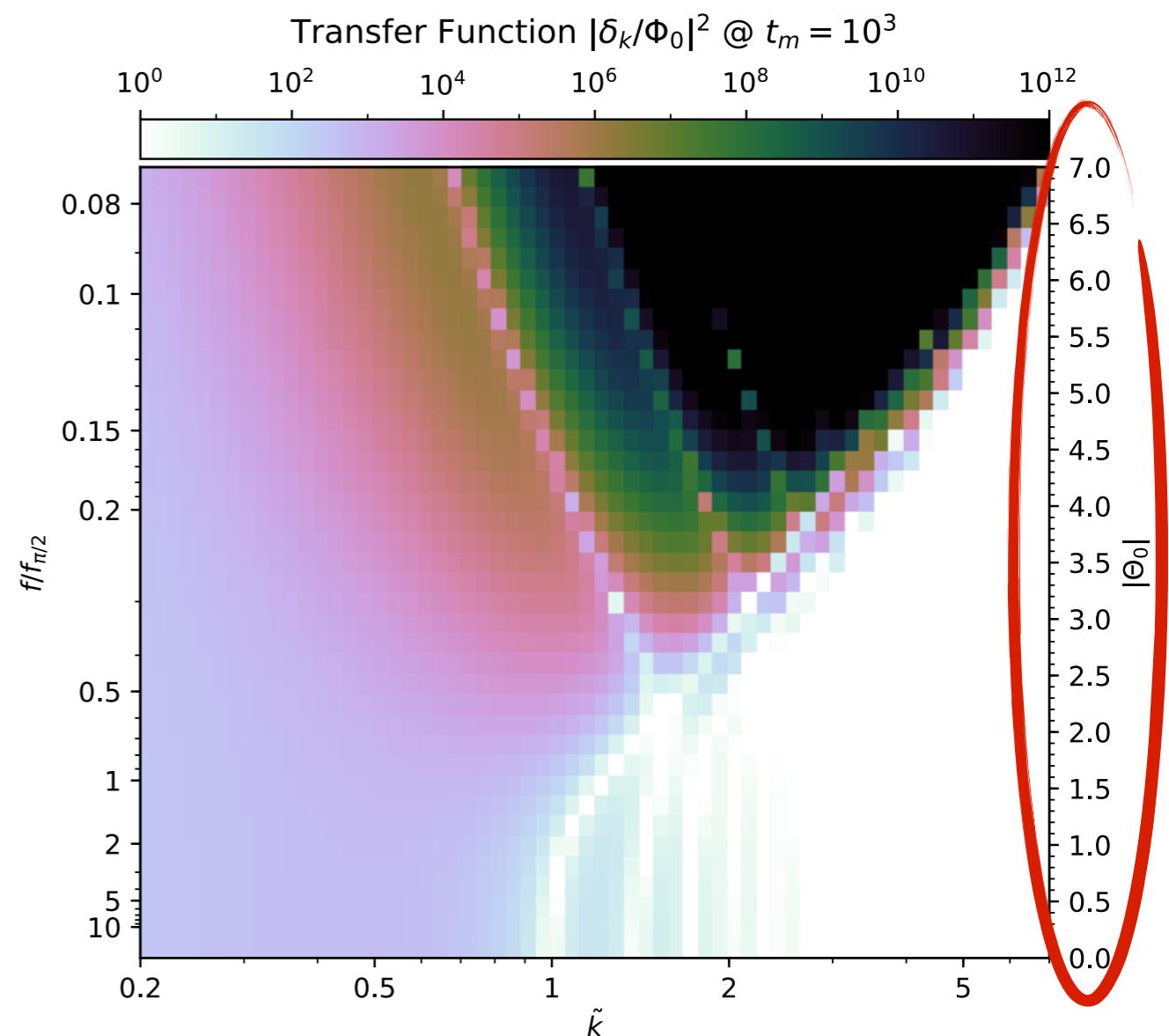
1. inflationary dynamics for $|\Theta_0| \simeq \pi$

2. environmental selection on DM abundance

3. large misalignment in other potentials:



$$V(\Theta) \propto (1 - \cos(\Theta))$$



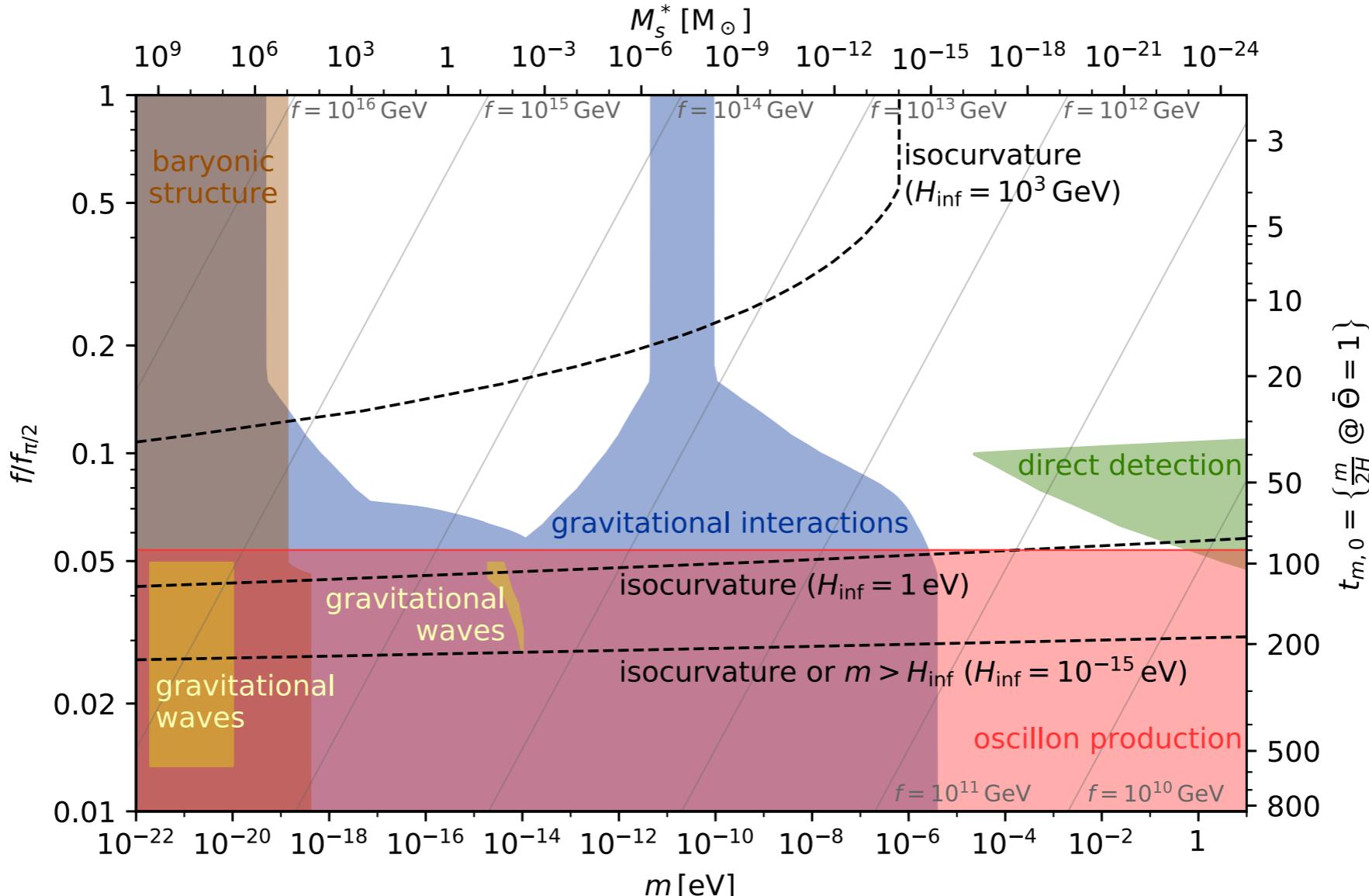
$$V(\Theta) \propto \frac{\Theta^2}{2 + \Theta^2}$$

Summary

If the onset of axion oscillations is delayed such that

$$\text{nonlinearities} > \text{Hubble friction}, \text{ i.e. } \bar{\Theta}^2 \gtrsim \frac{4m}{H},$$

then semi-relativistic fluctuations grow exponentially to form compact axion structures

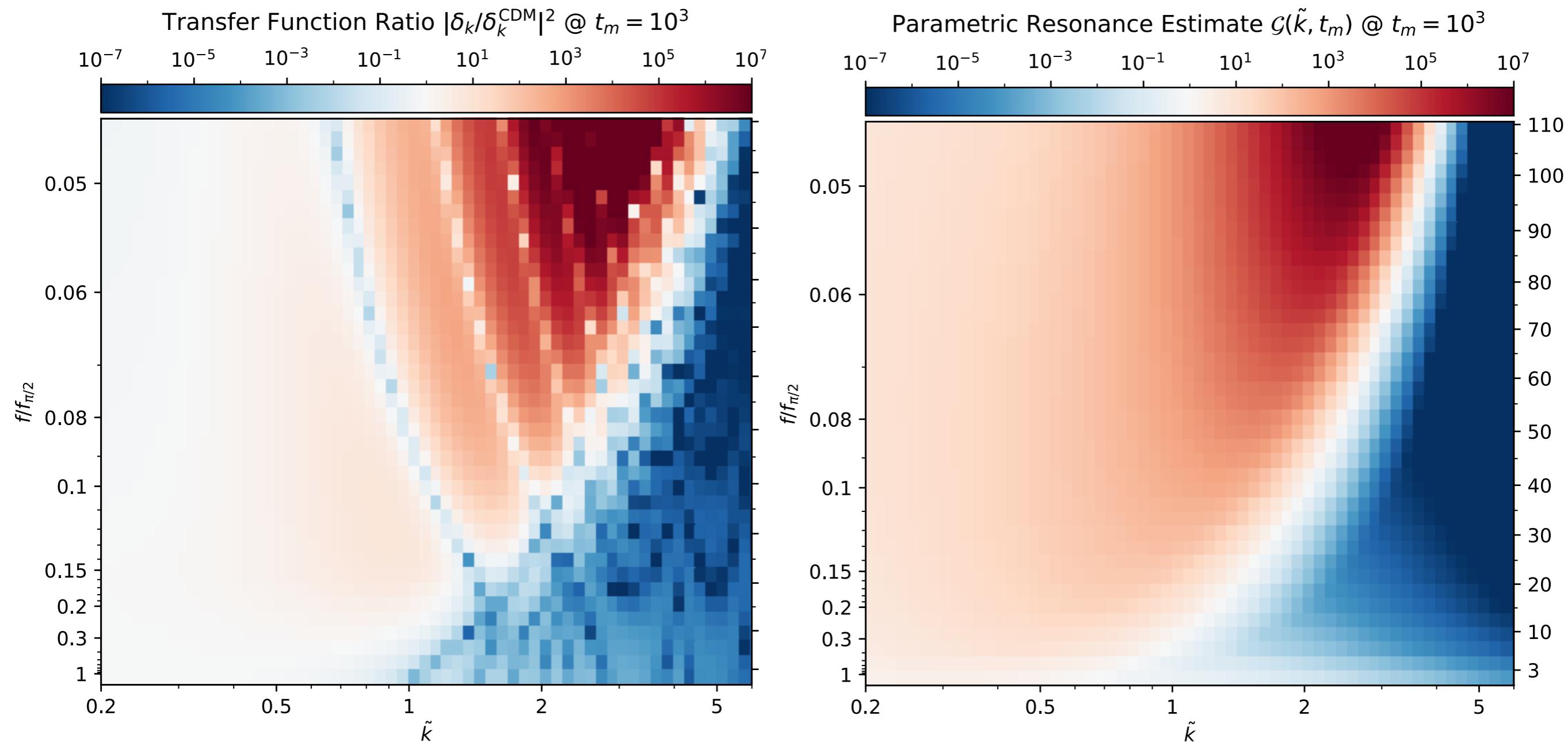


Open Questions:

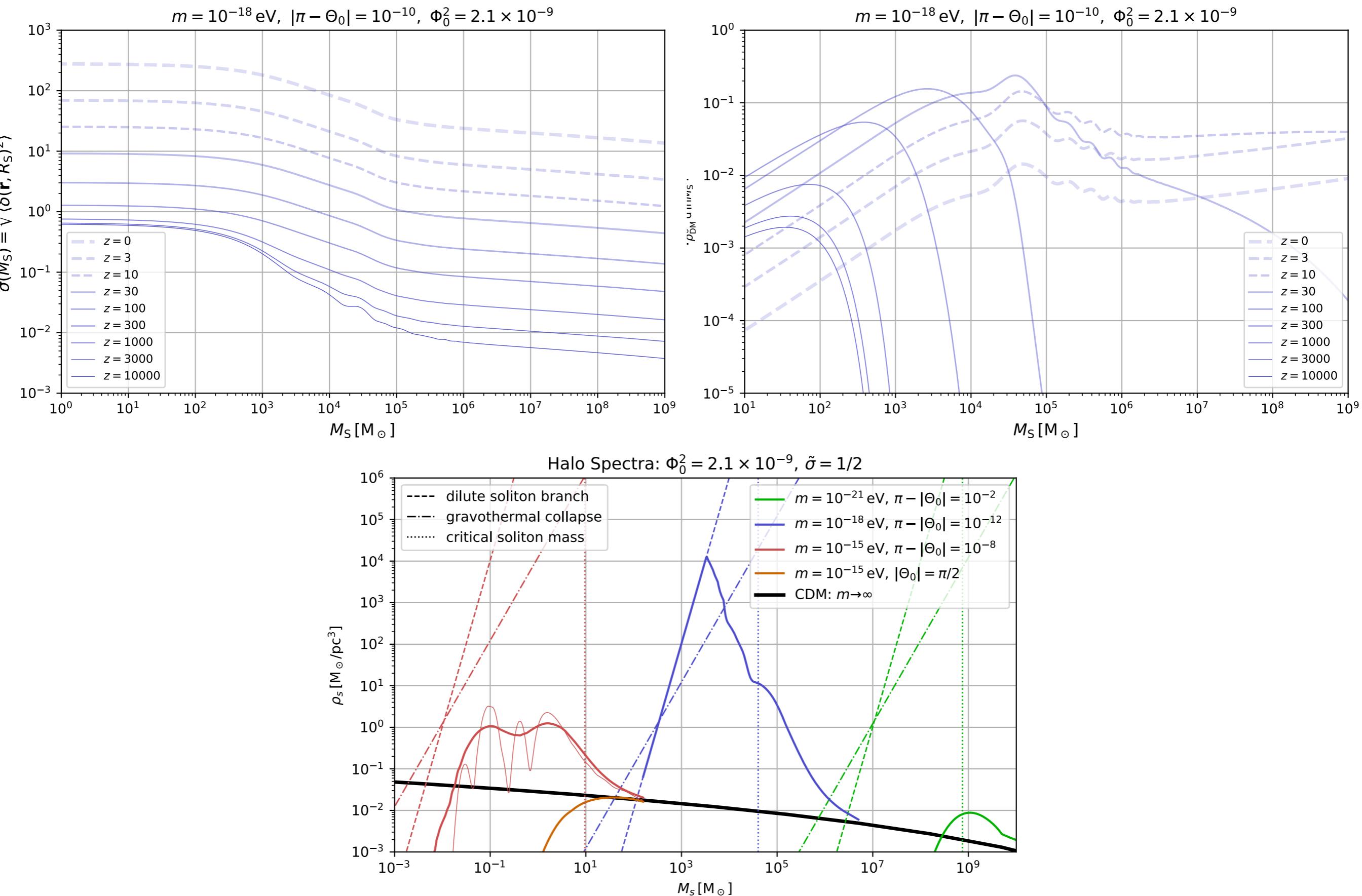
1. Nonlinear simulations:
 - tidal stripping
 - gravitational cooling
 - oscillon dynamics
 - GW production
2. Impact on direct detection
3. Star formation & re-ionization history
4. Analytic estimates of oscillon lifetime

Backup

Parametric resonance



Press-Schechter



Condition for Oscillon Formation

