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

Ken Van Tilburg (KITP)

A. Arvanitaki, S. Dimopoulos, M. Galanis, L. Lehner, J. Thompson, KVT:
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University of Michigan, Feb 12, 2020

“Problems” in particle physics

Standard Model of particle physics accurately describes every known experiment and observation to the measured and calculated precision*

theoretical frontiers:

mathematical structures | parametric curiosities | computational precision

experimental frontiers:

high-energy | cosmic | intensity | precision

*parametrized unknowns:

dark matter | baryon asymmetry | inflation

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[production] *[initial conditions]*

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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

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

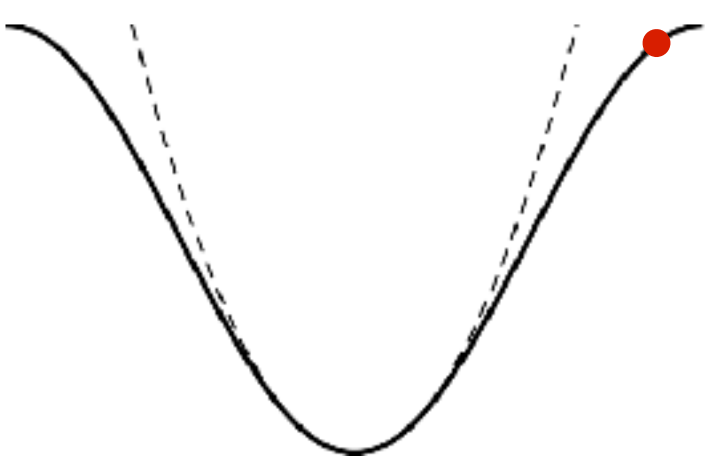
$$V = -m^2 f^2 \cos\frac{\phi}{f}$$

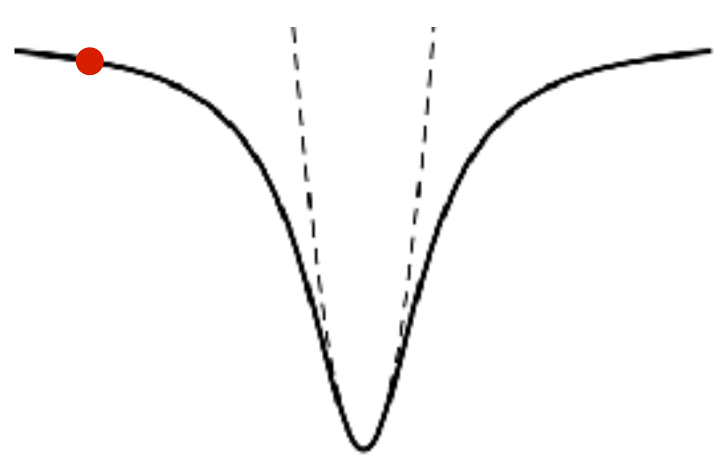
modulus

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

QCD axion

$$V = -m_a(T)^2 f_a^2 \cos\frac{a}{f_a}$$





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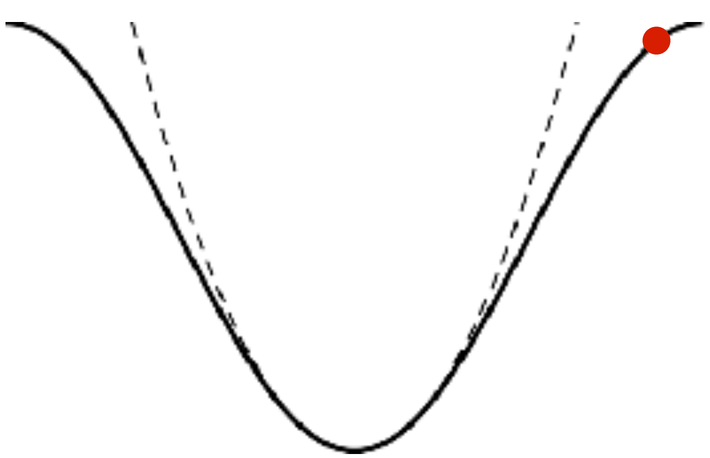

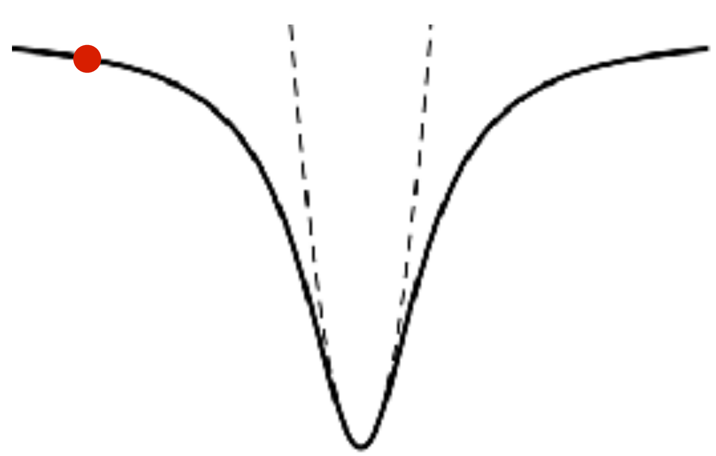

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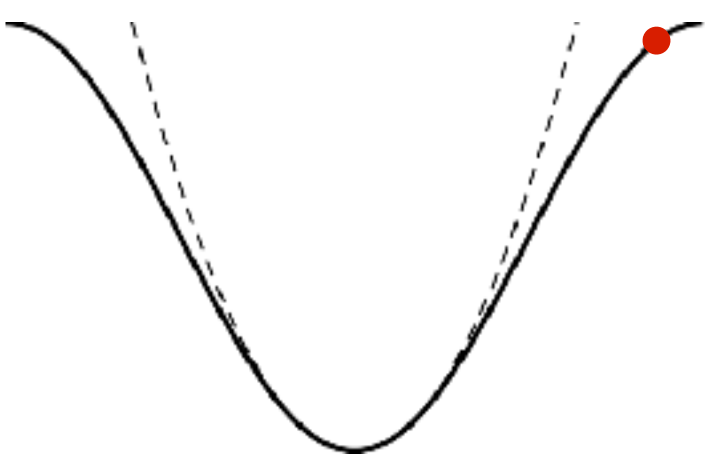

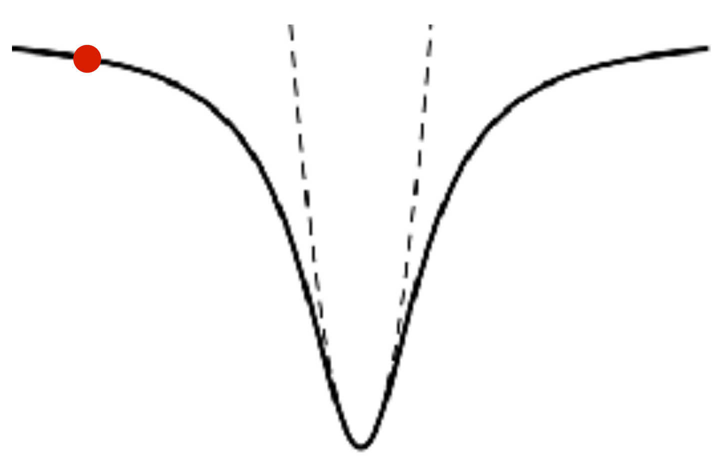

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$$\text{if } |\Theta_0| > \frac{\pi}{2} : \quad \text{for } \frac{k}{a} \sim m \sim H_{\text{osc}}$$

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

Large Misalignment Mechanism

$$\frac{\phi}{f} = \Theta(t) + \sum_{\mathbf{k}} \theta_{\mathbf{k}}(t) e^{i\mathbf{k}\cdot\mathbf{x}} \qquad \tilde{k}^2 \equiv \frac{k^2/a^2}{2mH}$$

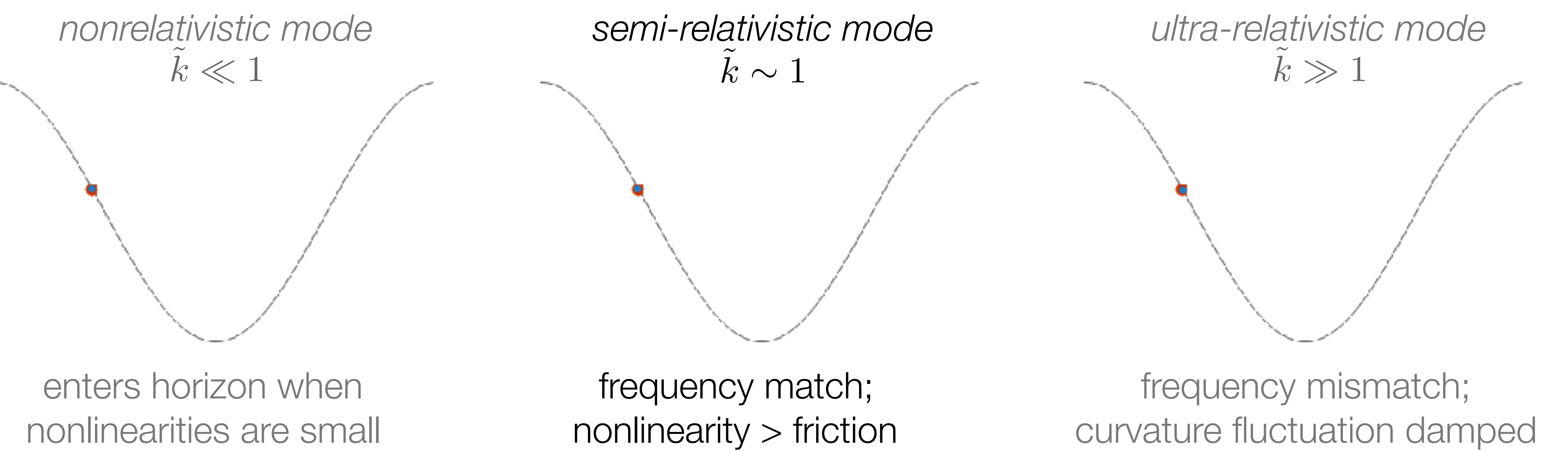
3 ways to understand enhancement of structure formation:

1. negative quartic → 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 $c_s^2 \simeq \frac{\mathbf{k}^2/a^2}{4m^2} - \frac{\rho}{8m^2 f^2}$

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

3. parametric resonance for field fluctuations



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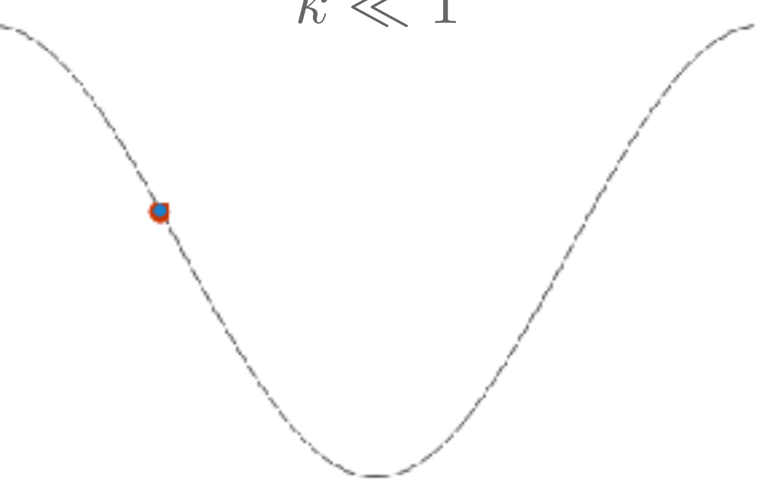
nonrelativistic mode
$\tilde{k} \ll 1$



enters horizon when
nonlinearities are small

semi-relativistic mode
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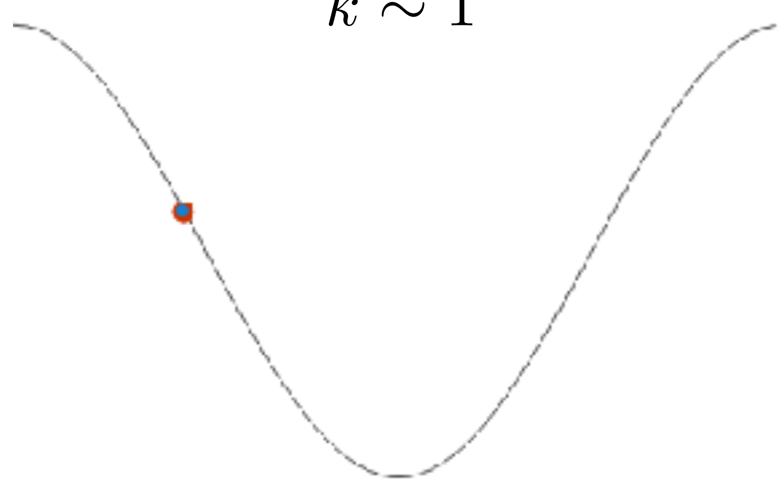

frequency match;
nonlinearity > friction

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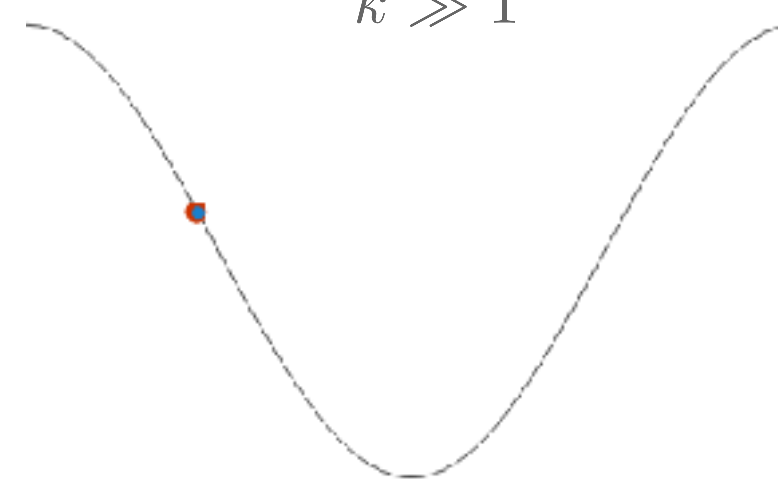

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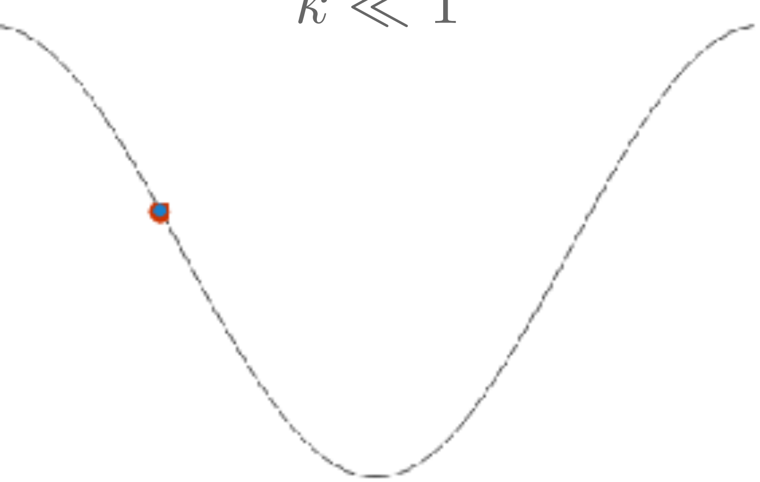

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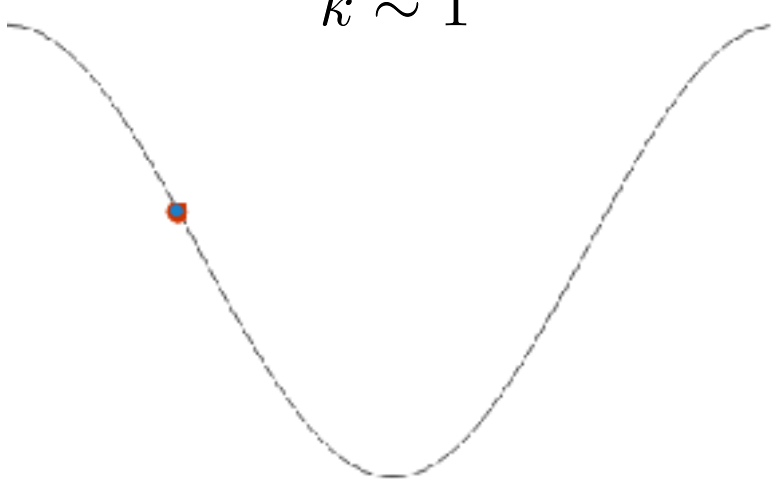

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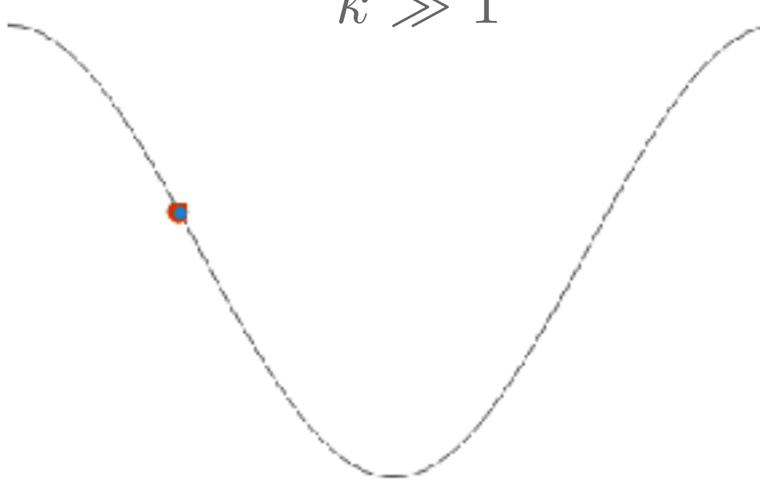

frequency mismatch;
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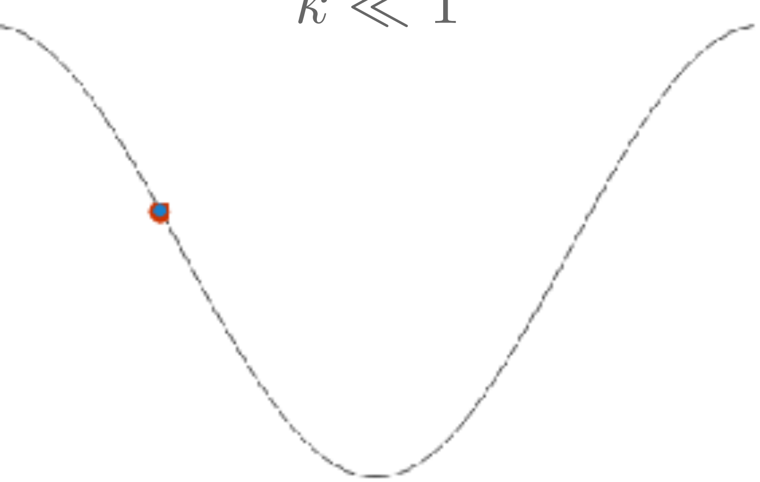

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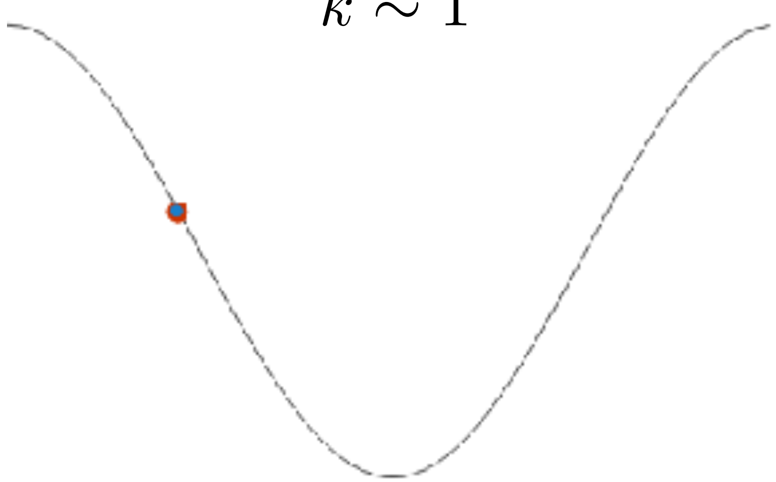

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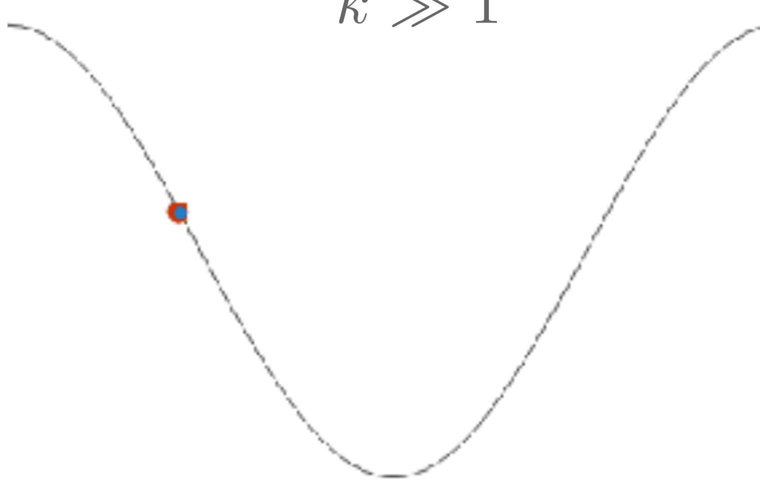


frequency mismatch; curvature fluctuation damped

Compact Axion Structures

$$f_{\pi/2} \sim M_{\rm Pl} \left(\frac{H_{\rm eq}}{m} \right)^{1/4}$$

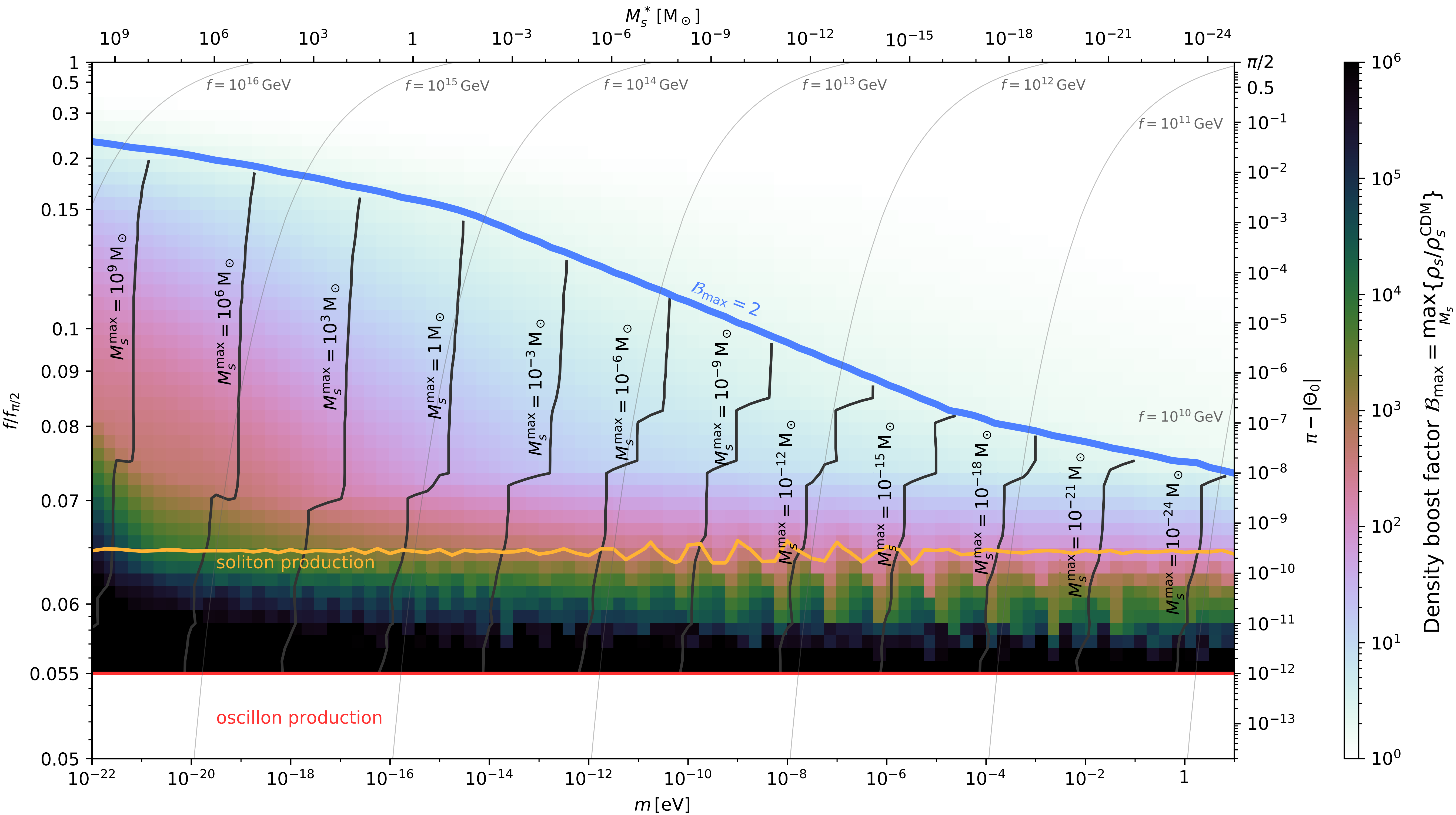
dense axion minihalos

solitons

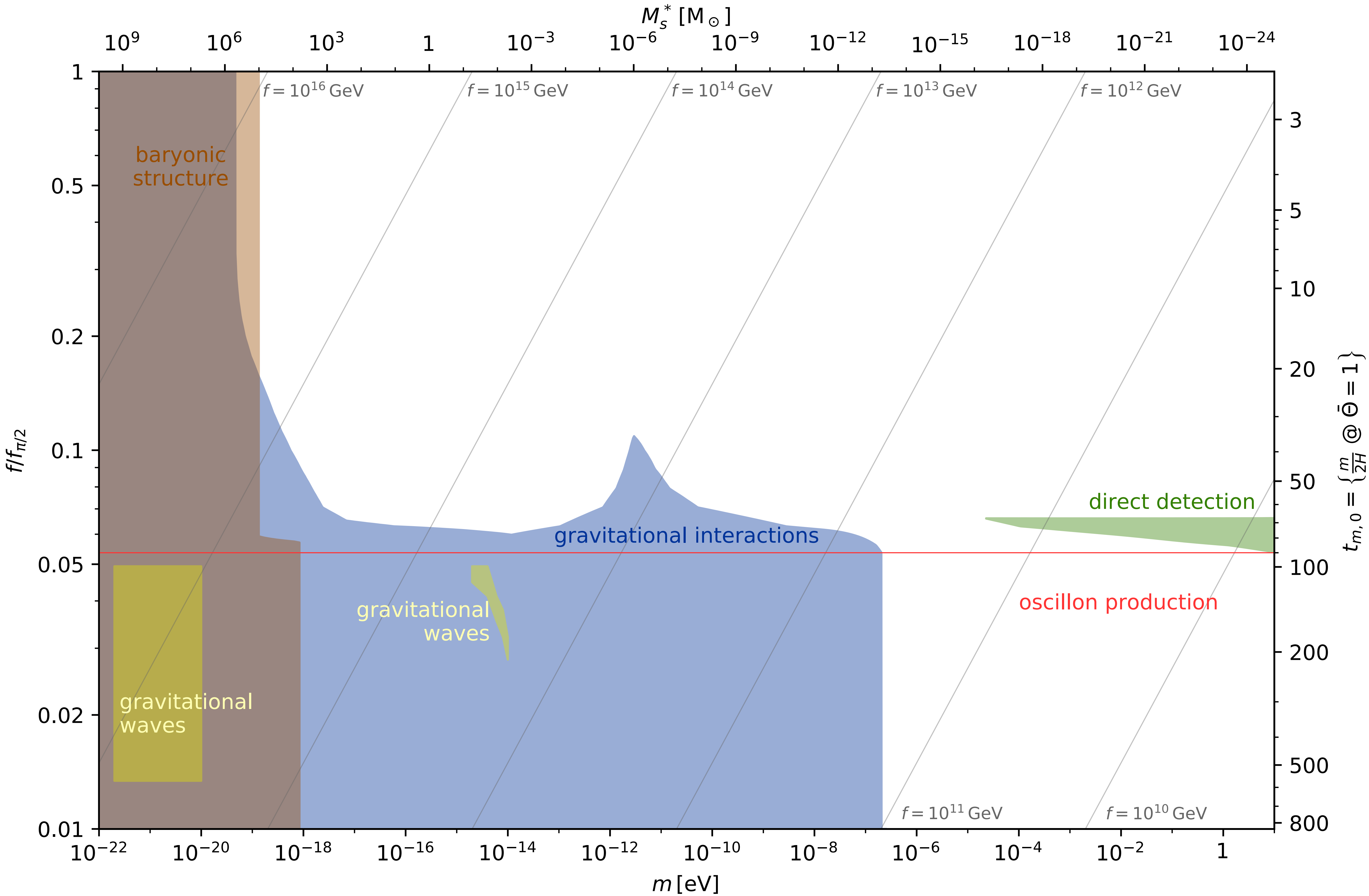
[gravity+kinetic]

oscillons

[self-interactions+kinetic]



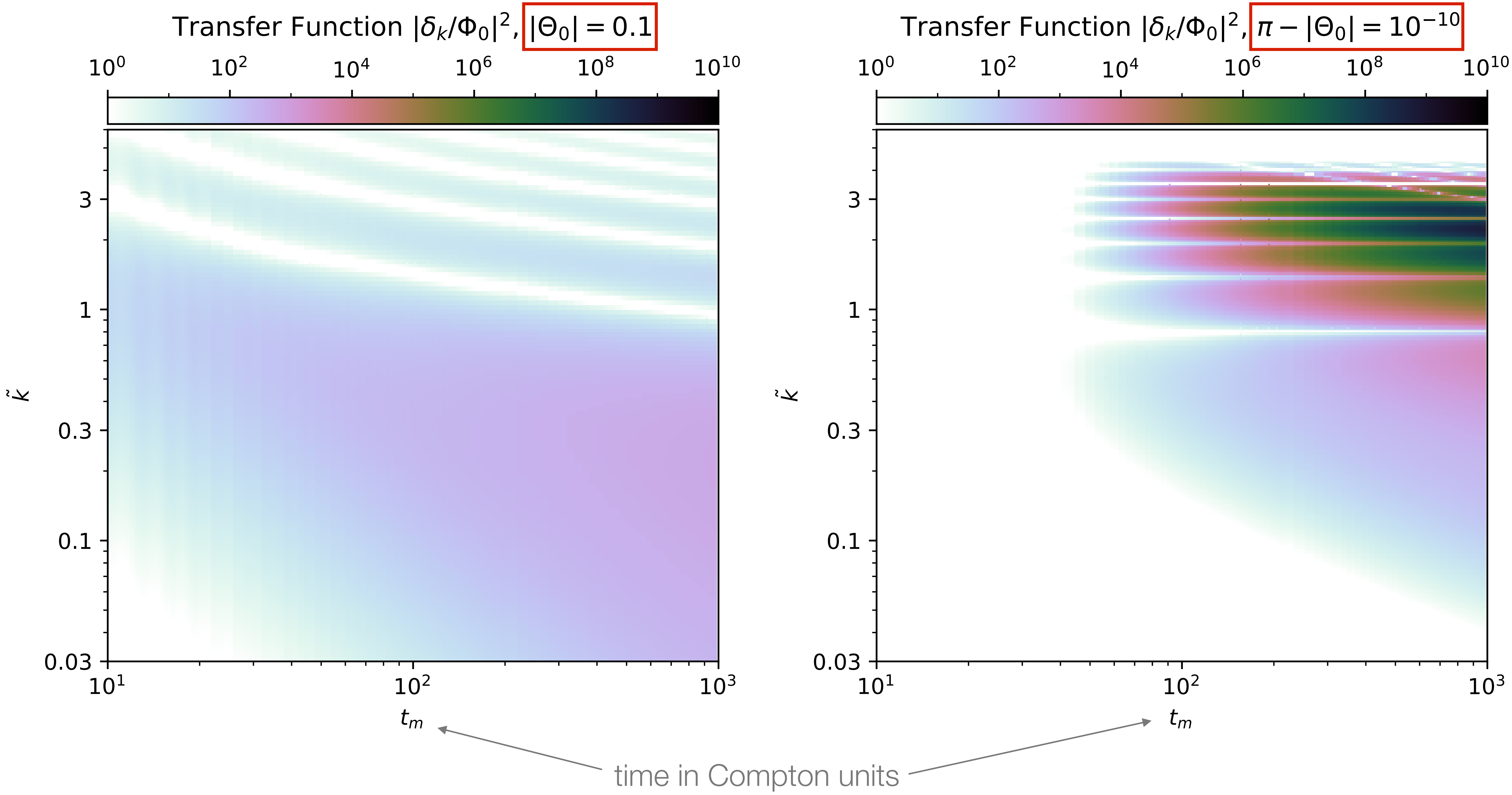
Observable Signatures



Linear Evolution in Time

small misalignment

large misalignment



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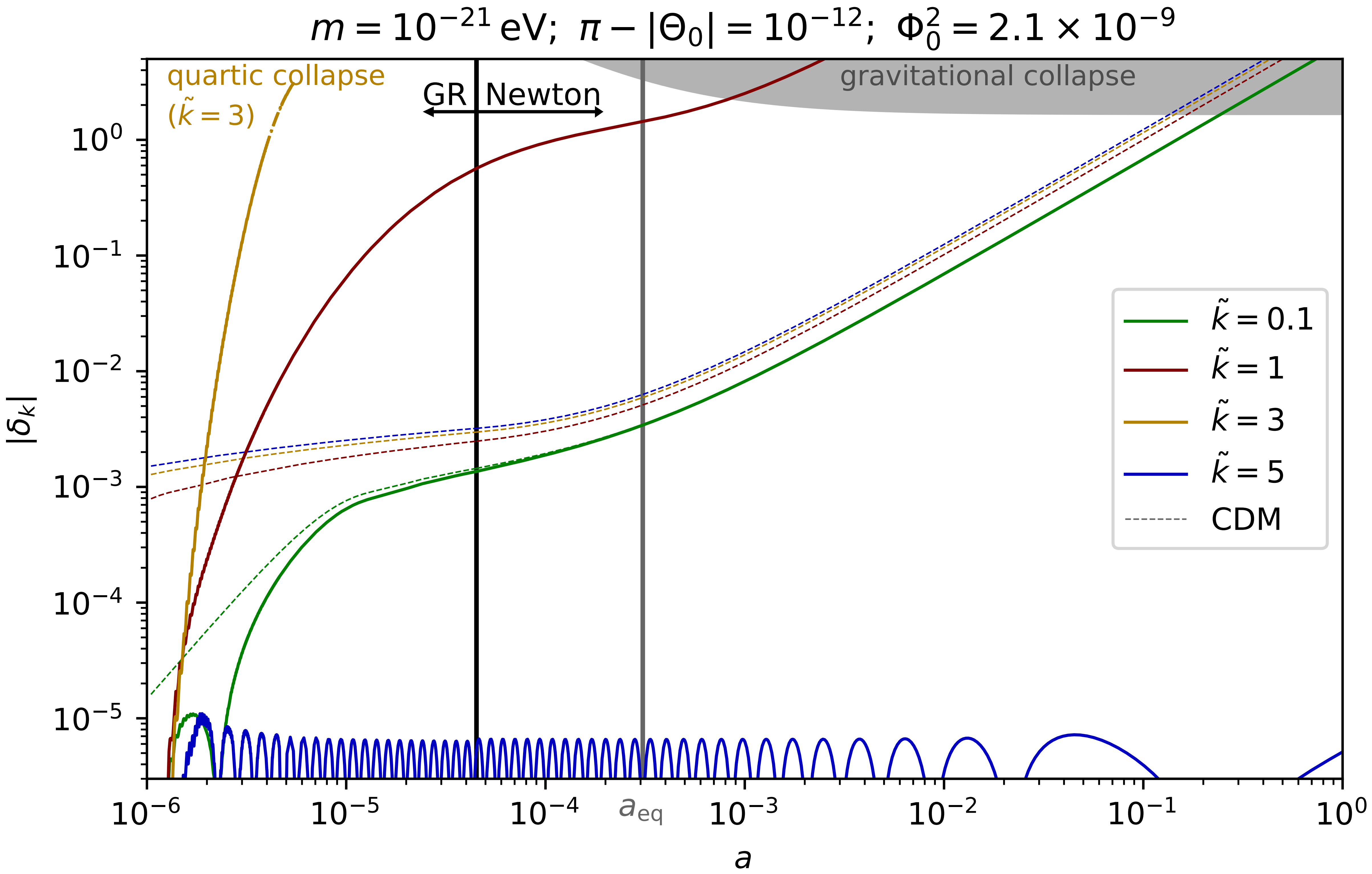
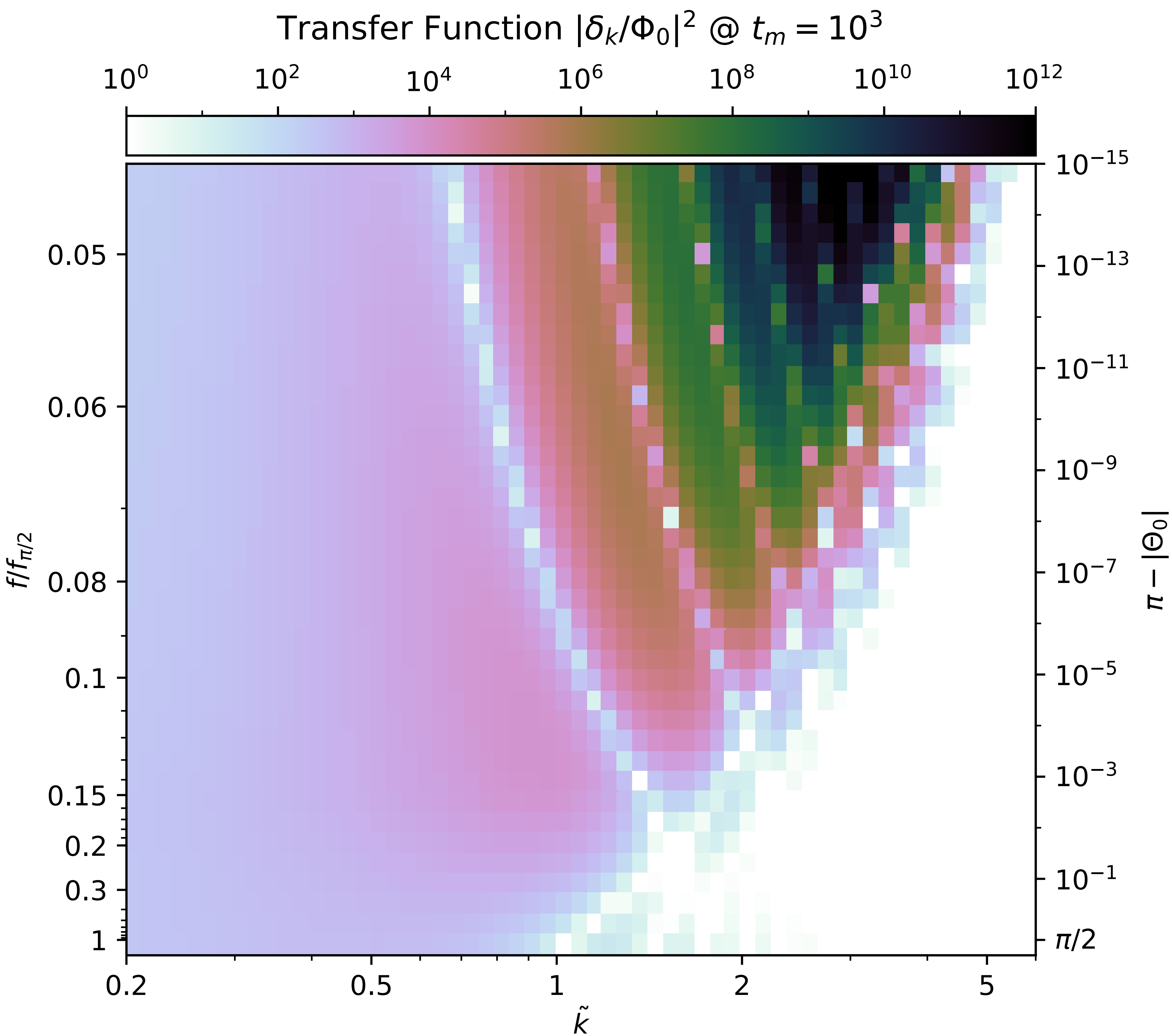


Linear Evolution versus Misalignment



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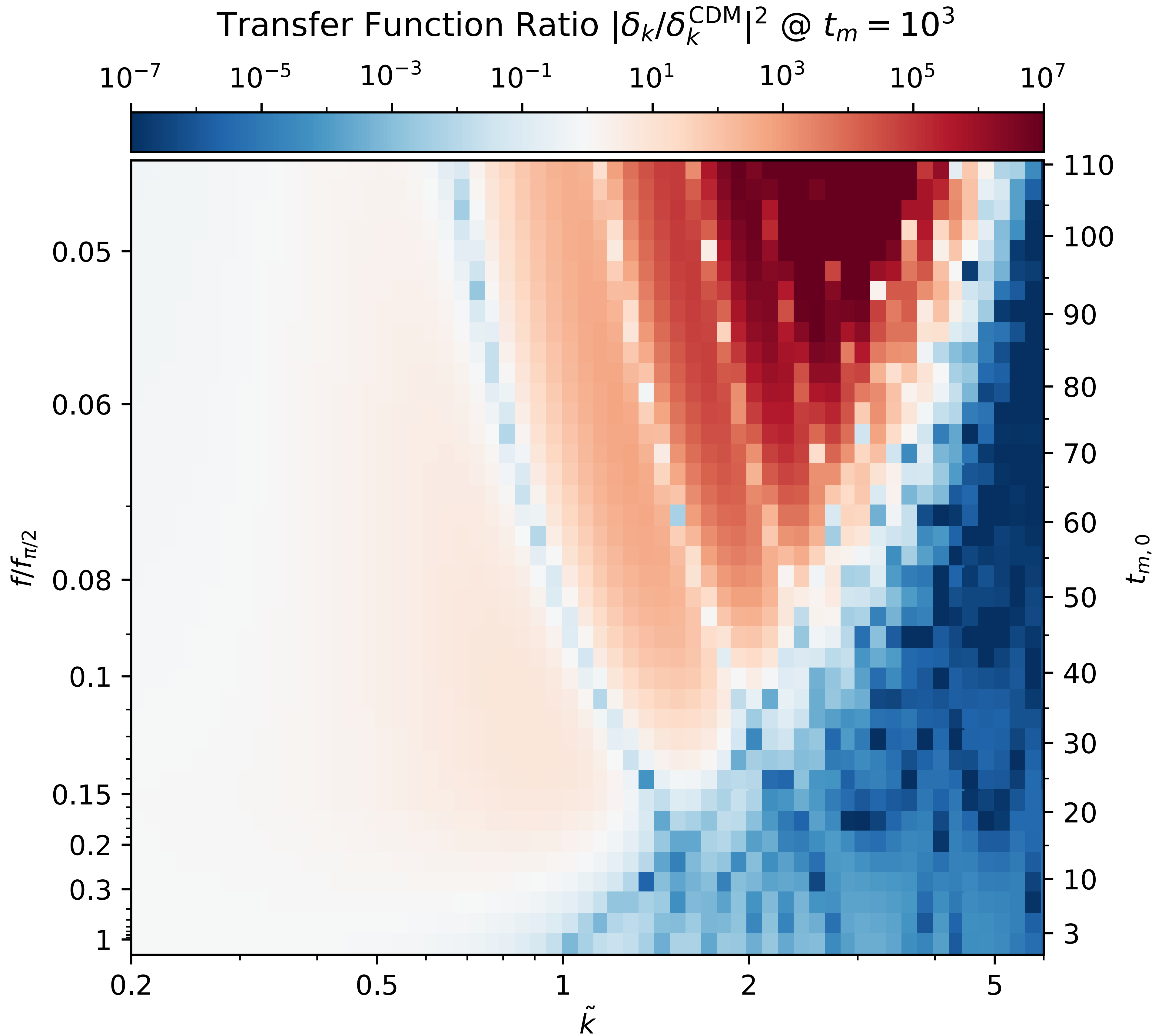
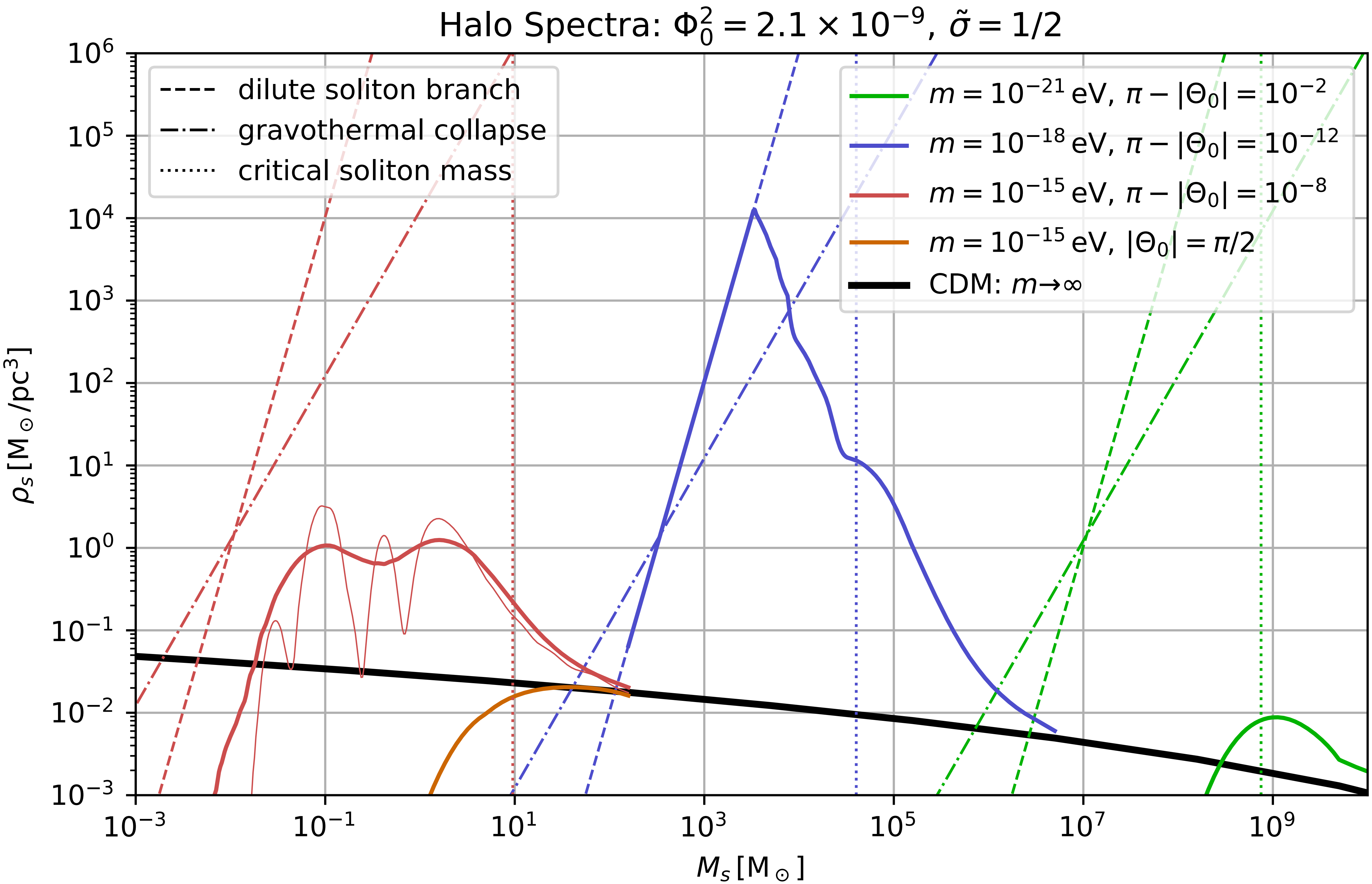
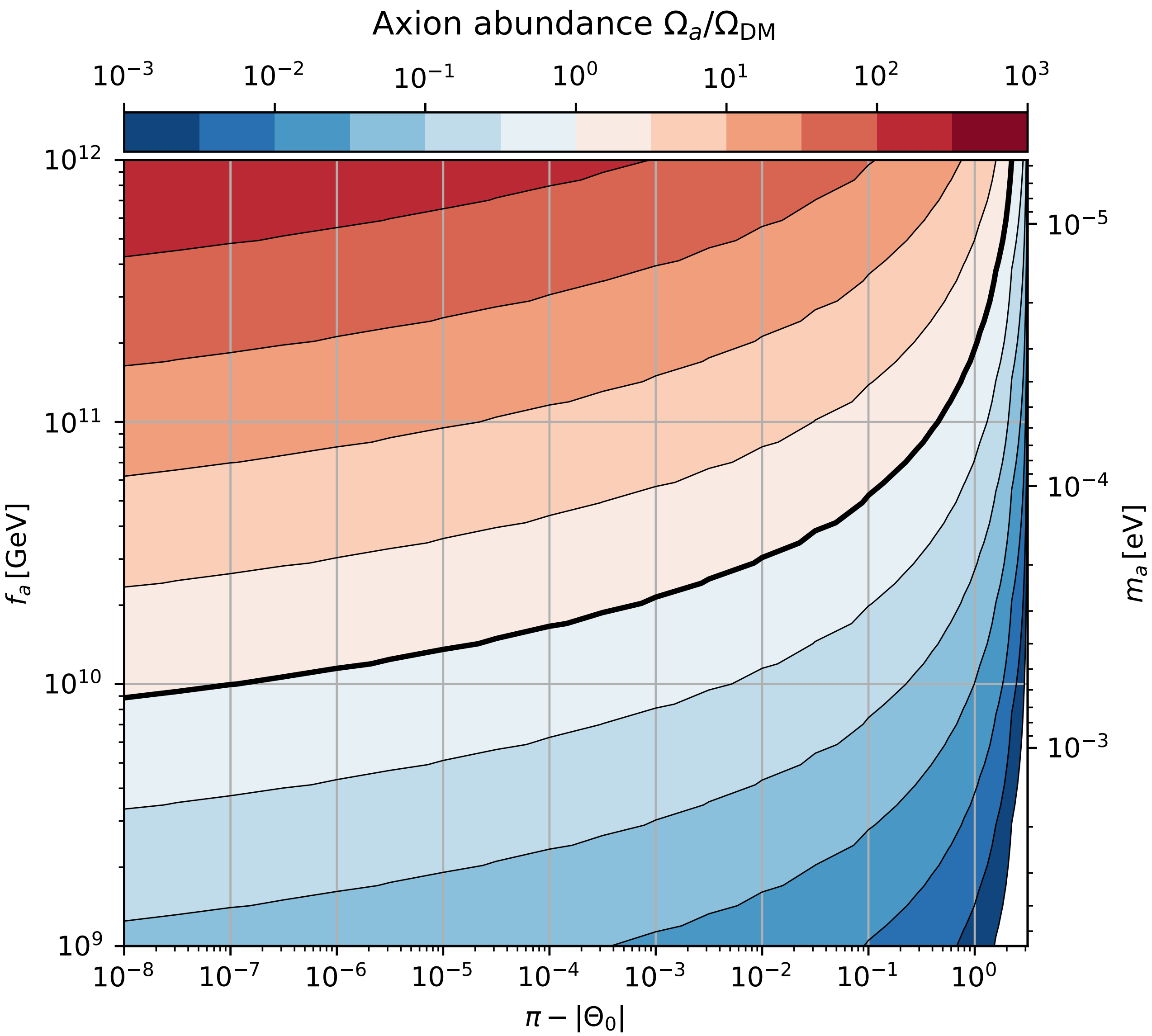
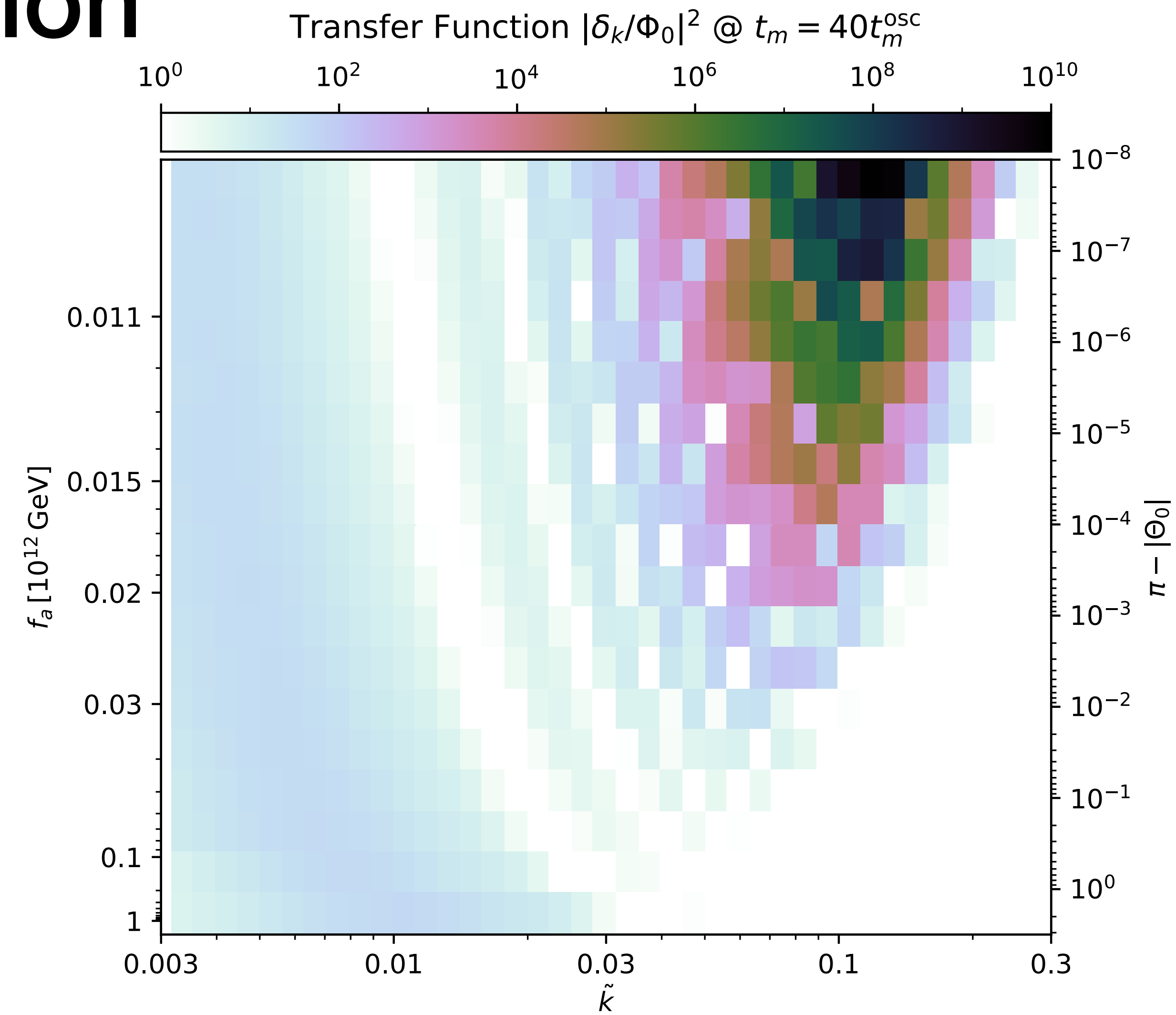


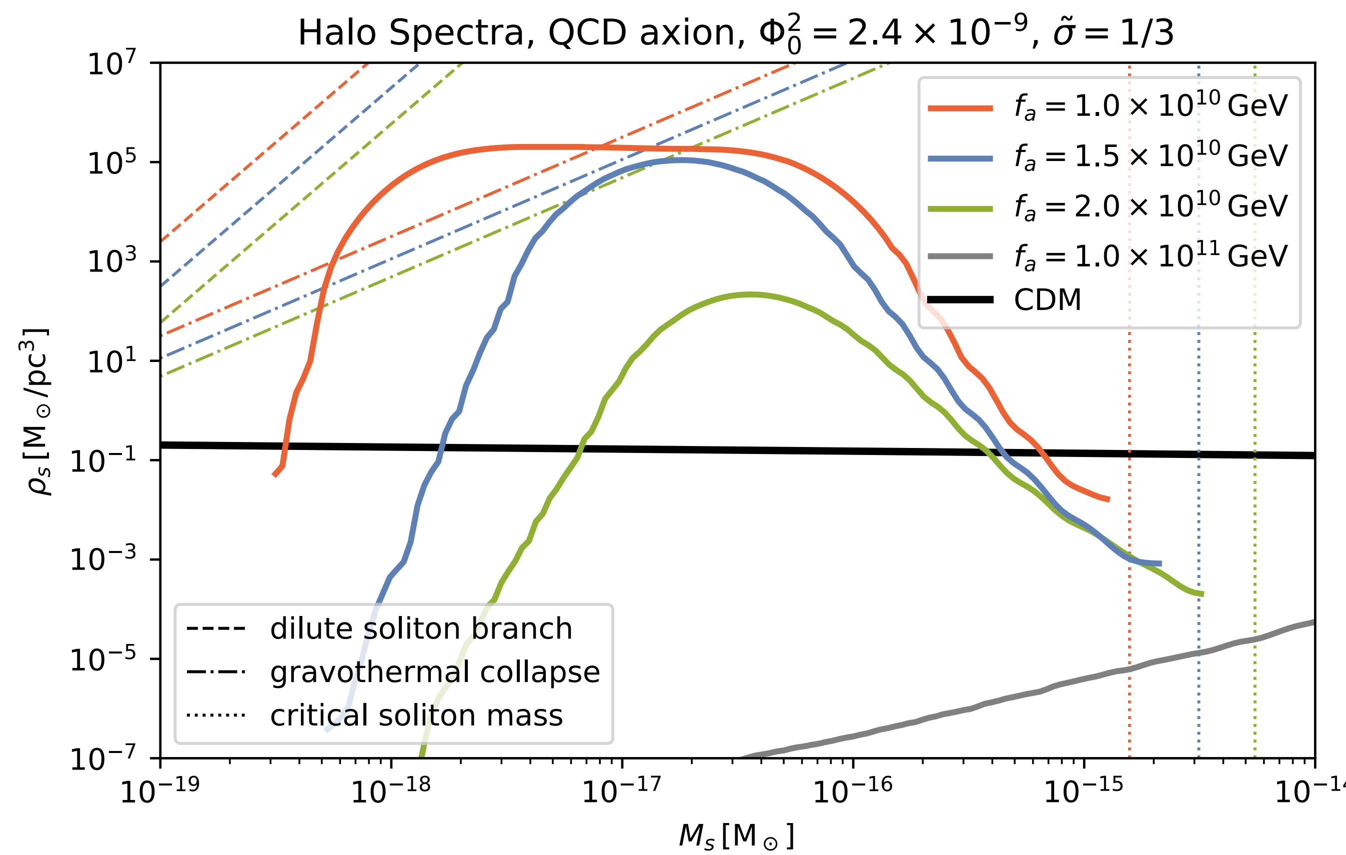
Dense Axion Halos & Solitons



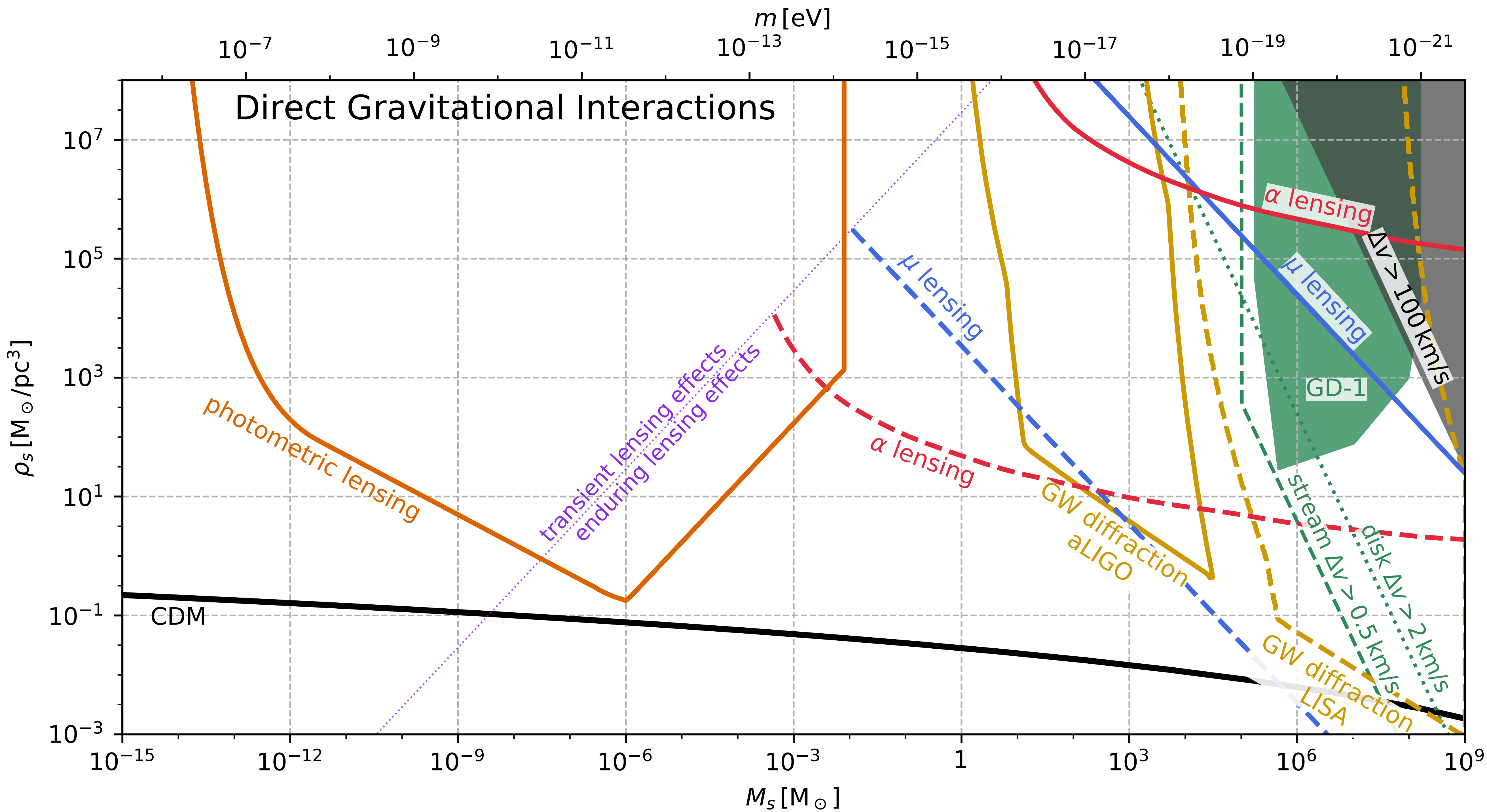
QCD Axion


Axion abundance $\Omega_a/\Omega_{\rm DM}$
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
f_a [GeV]
10^{12} 10^{11} 10^{10} 10^{9}
m_a [eV]
10^{-5} 10^{-4} 10^{-3}
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
$\pi - |\Theta_0|$


Transfer Function $|\delta_k/\Phi_0|^2$ @ $t_m = 40 t_m^{\rm osc}$
10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10}
$f_a\,[10^{12}\,\mathrm{GeV}]$
0.011 0.015 0.02 0.03 0.1 1
$\pi - |\Theta_0|$
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
0.003 0.01 0.03 0.1 0.3
$\tilde{k}$

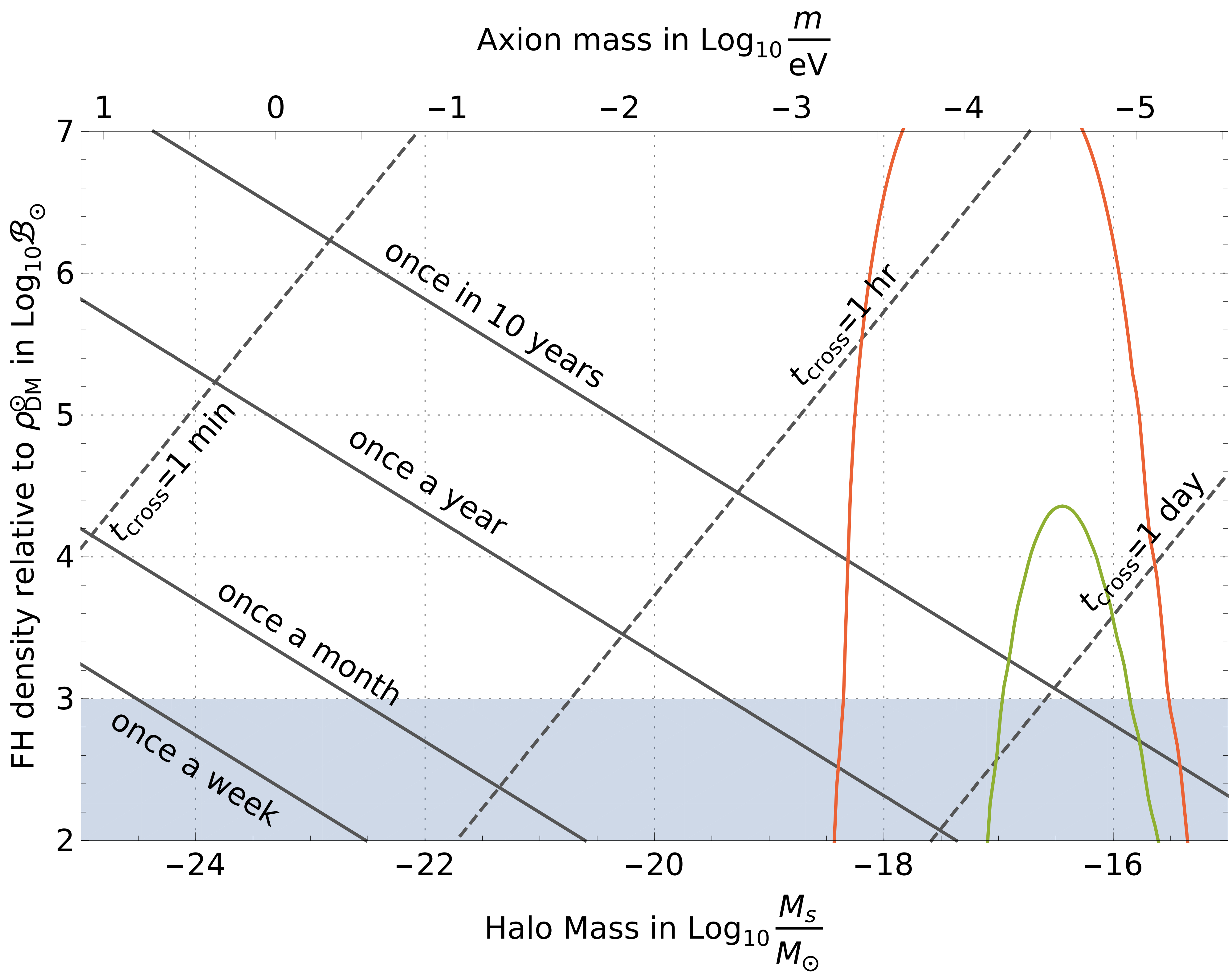

Halo Spectra, QCD axion, $\Phi_0^2 = 2.4 \times 10^{-9}$, $\tilde{\sigma} = 1/3$
$\rho_s\,[\mathrm{M}_\odot/\mathrm{pc}^3]$
10^{7} 10^{5} 10^{3} 10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7}
$f_a = 1.0 \times 10^{10}$ GeV
$f_a = 1.5 \times 10^{10}$ GeV
$f_a = 2.0 \times 10^{10}$ GeV
$f_a = 1.0 \times 10^{11}$ GeV
CDM
dilute soliton branch
gravothermal collapse
critical soliton mass
10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14}
$M_s\,[\mathrm{M}_\odot]$

Gravitational Interactions



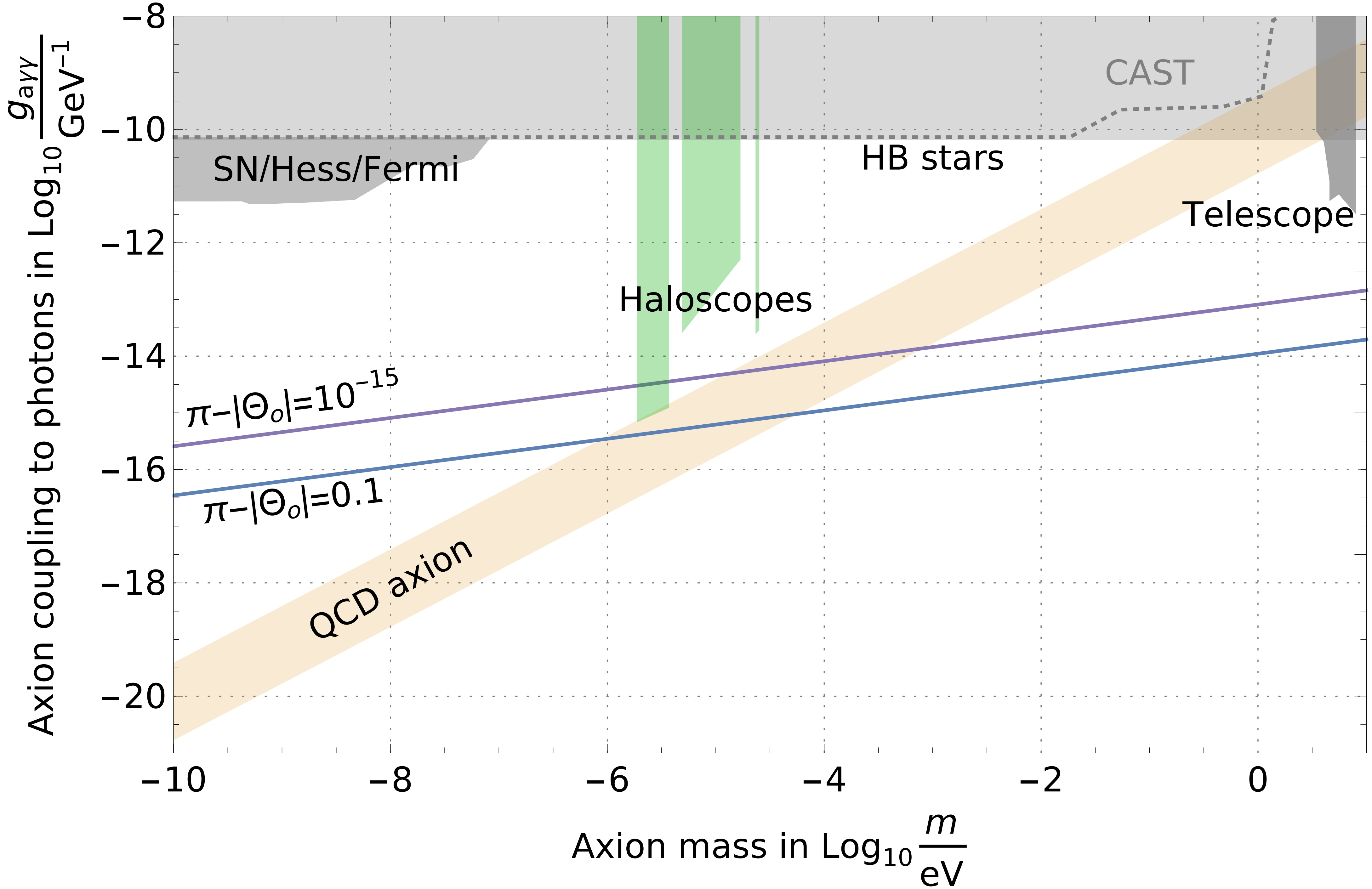
Direct Detection

intermittent, highly coherent signals → broadband data recording, matched filters



Direct Detection

re-evaluate constraints and optimize high-frequency axion searches



[Michael's talk]

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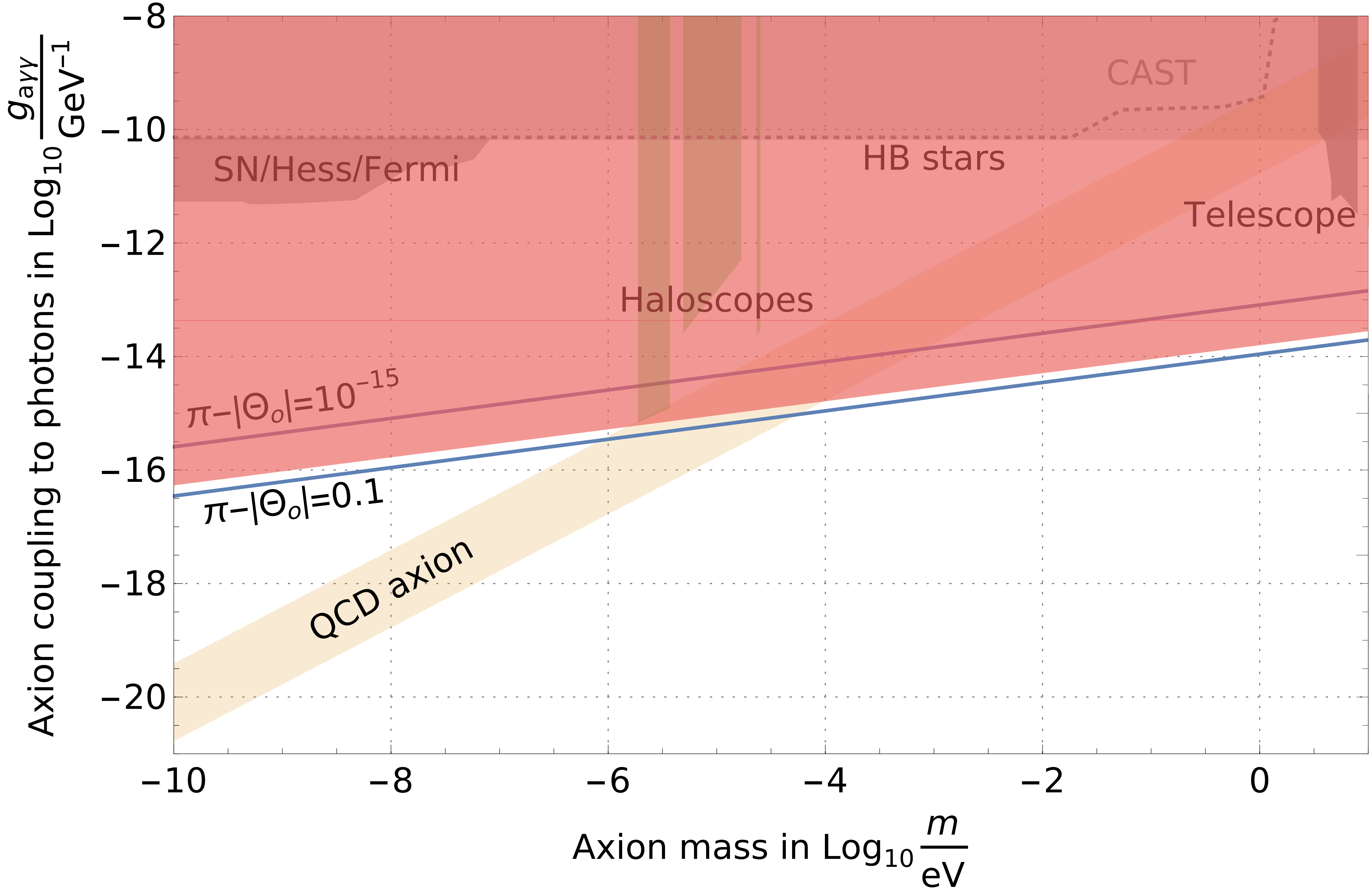
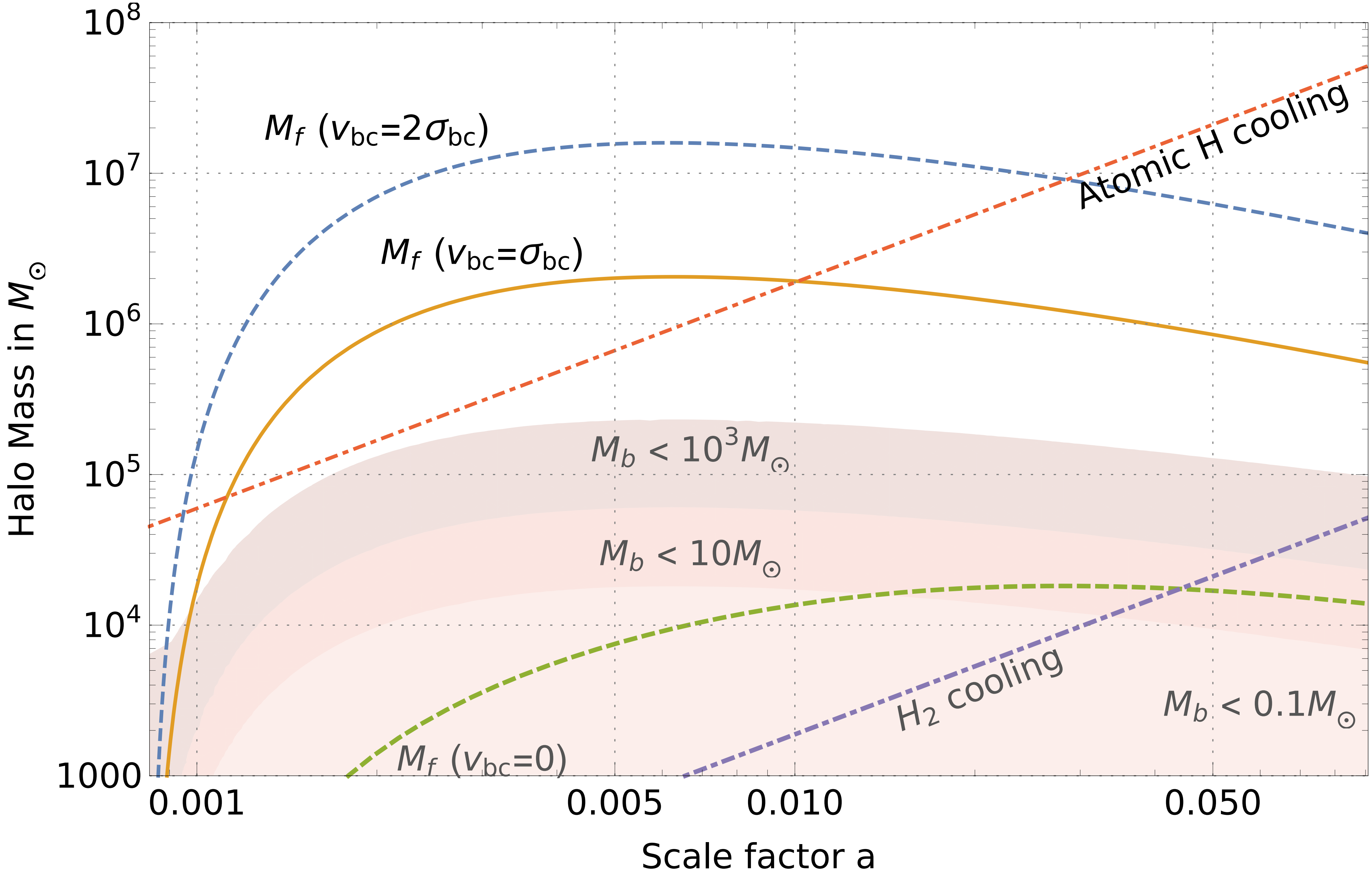
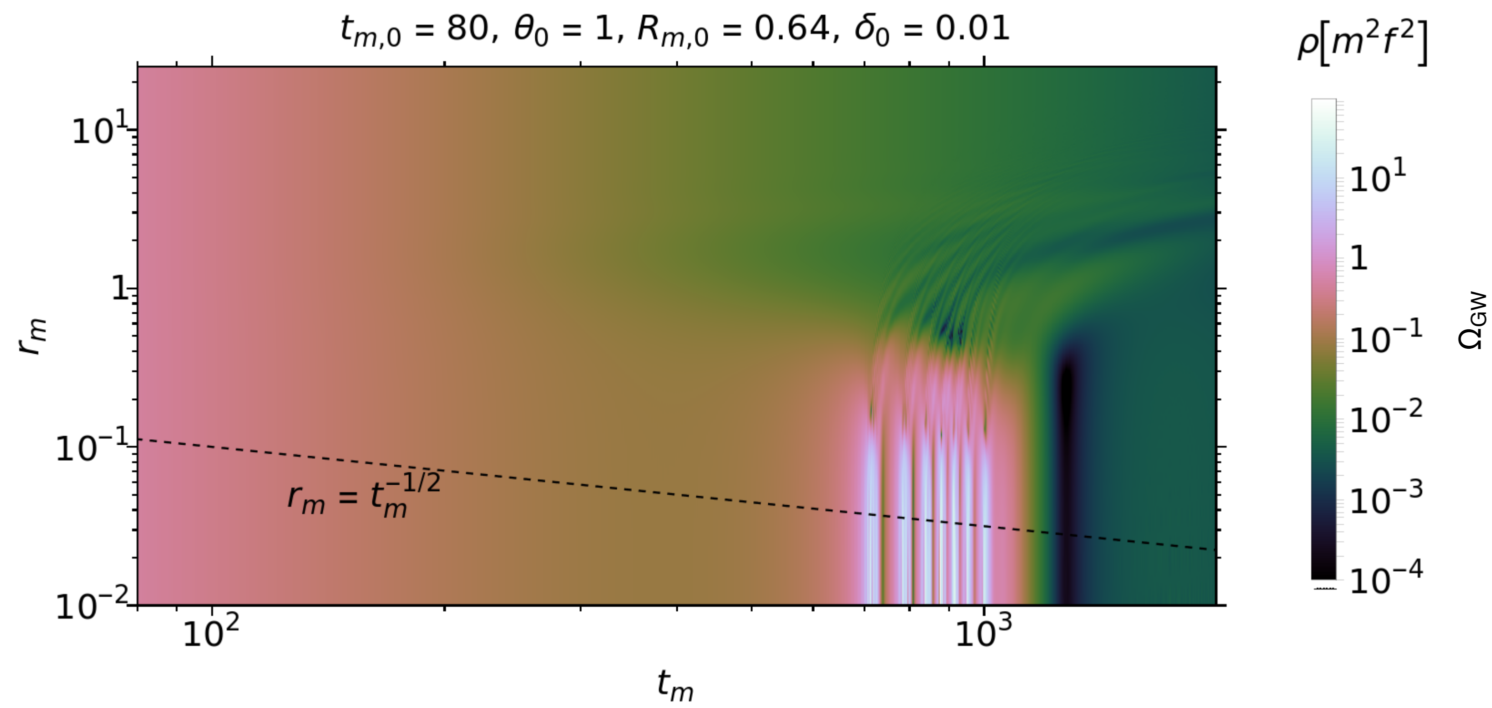


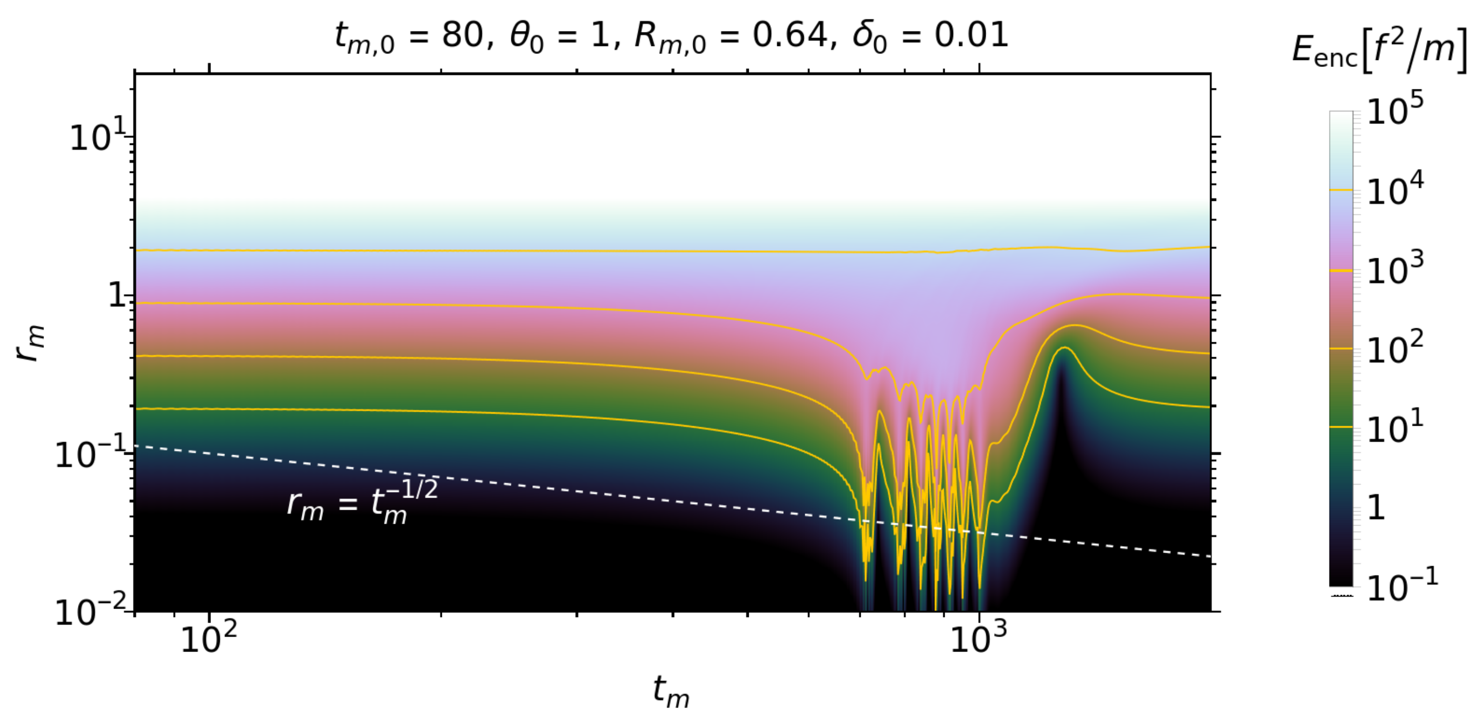
[Michael's talk]

Baryonic Structure & Star Formation

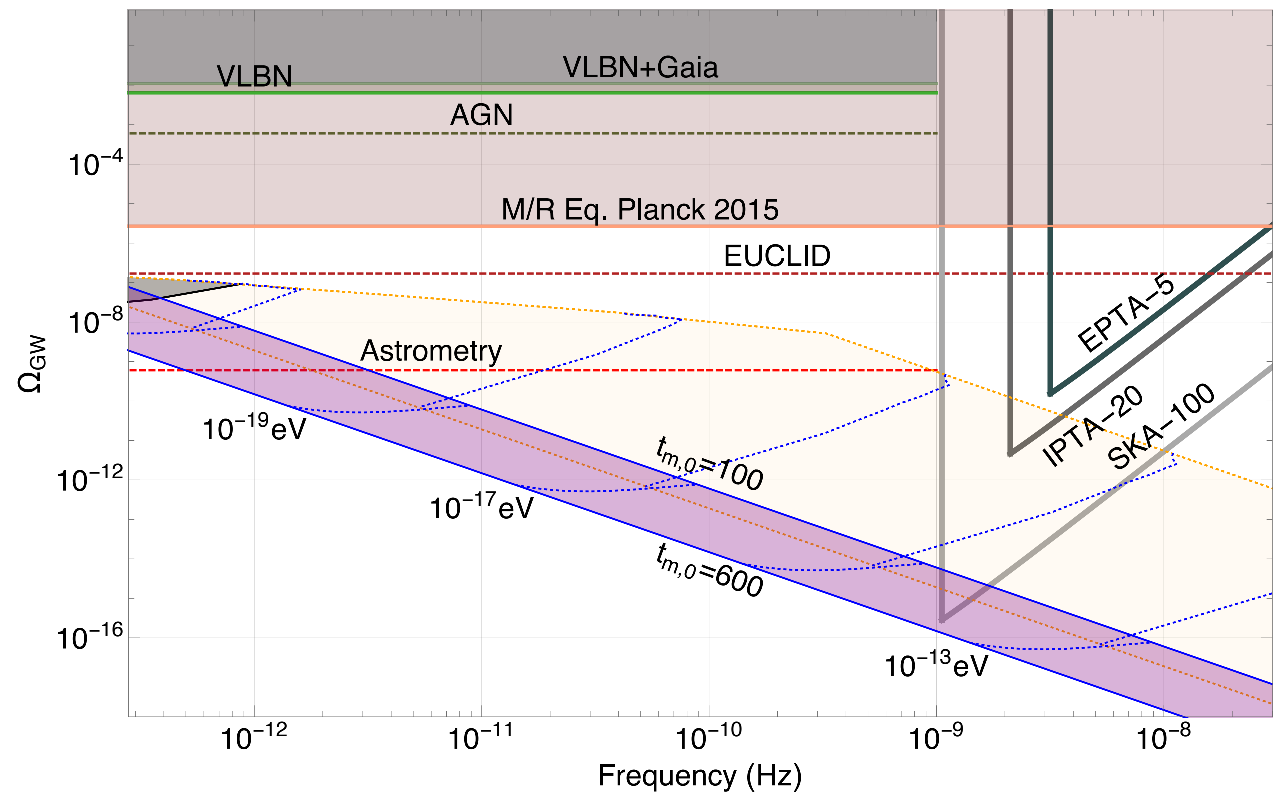


Oscillon Production





Gravitational Waves

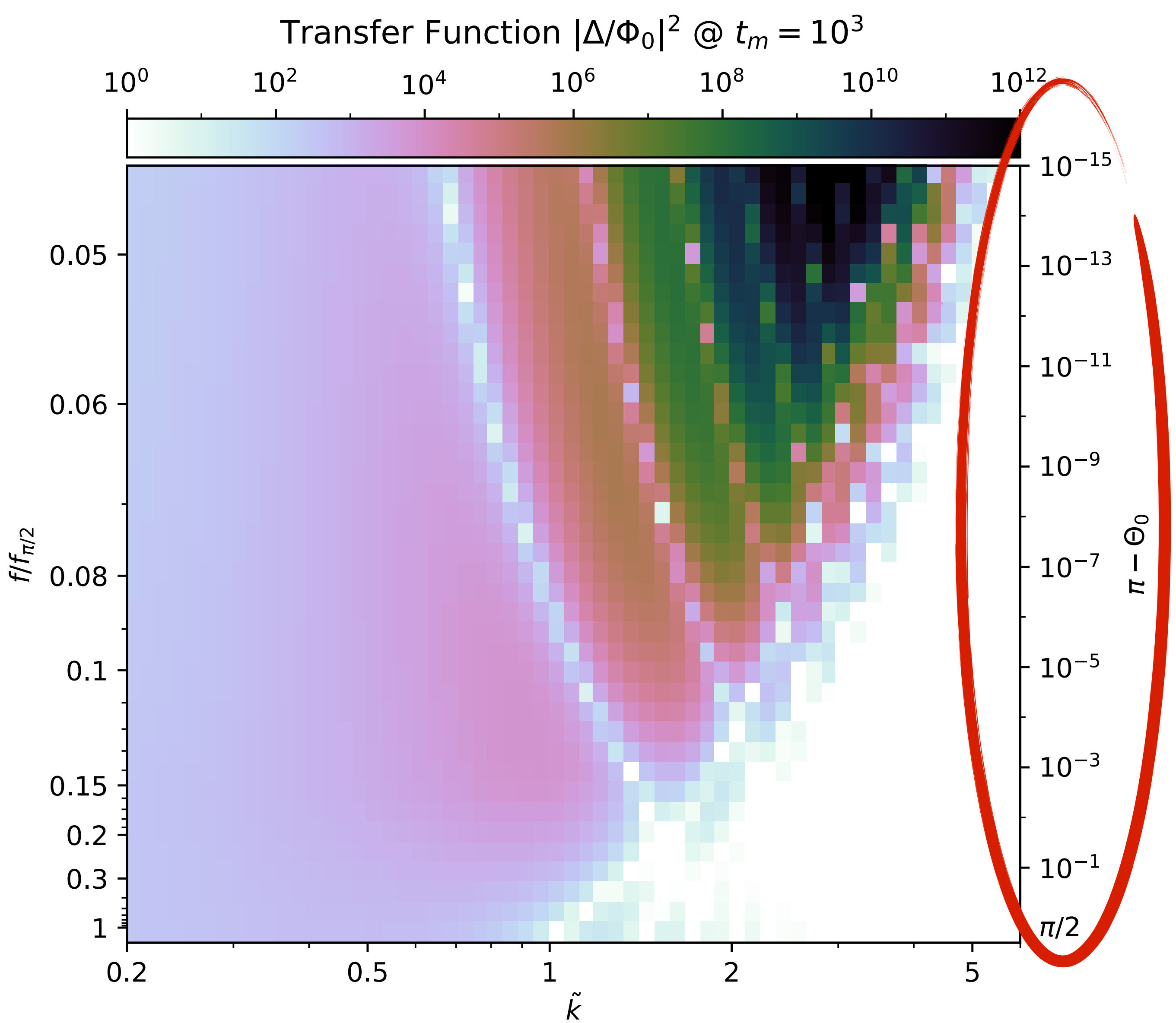


Initial Conditions

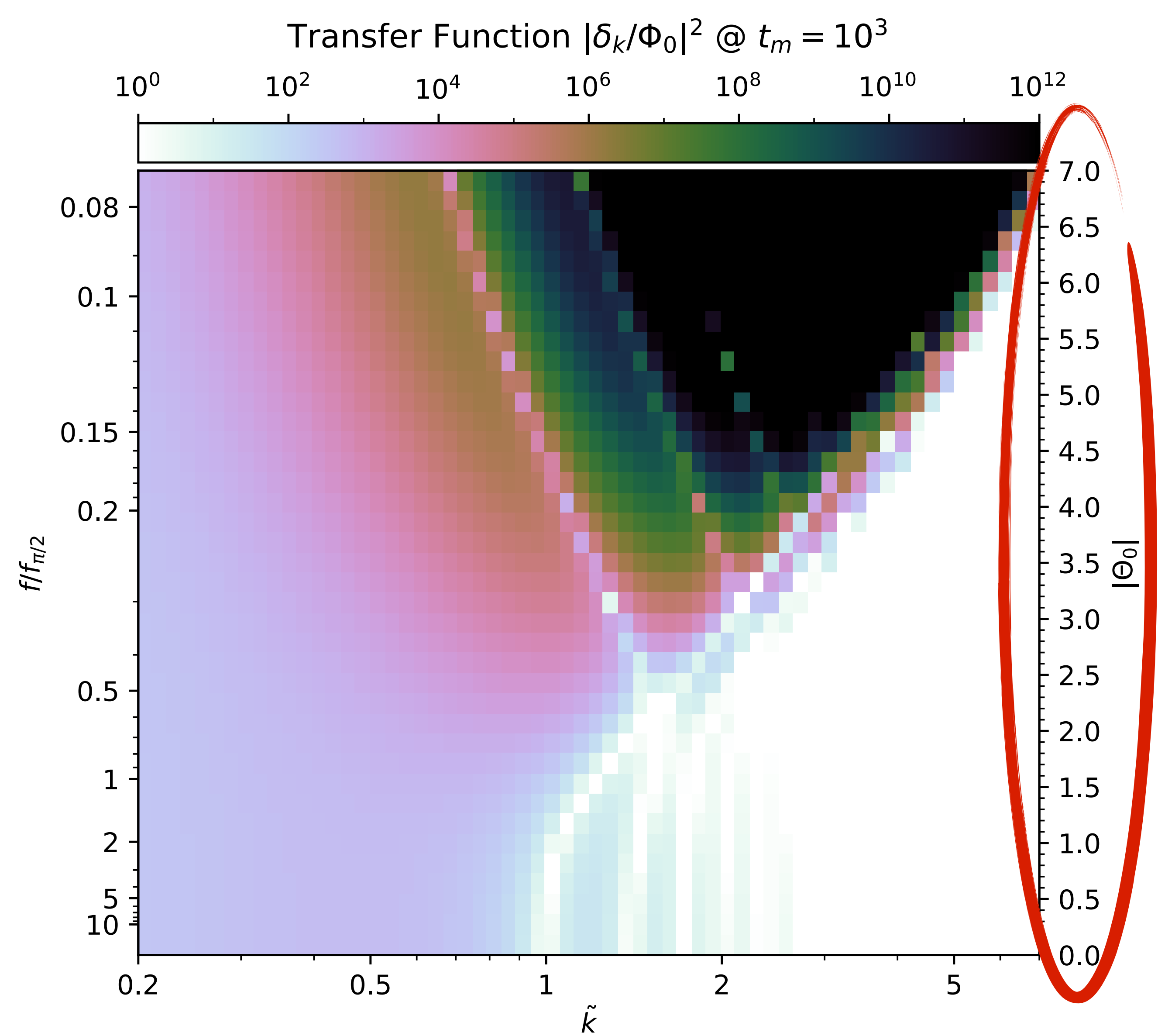
1. inflationary dynamics for $|\Theta_0| \simeq \pi$

2. environmental selection on DM abundance

3. large misalignment in other potentials:



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



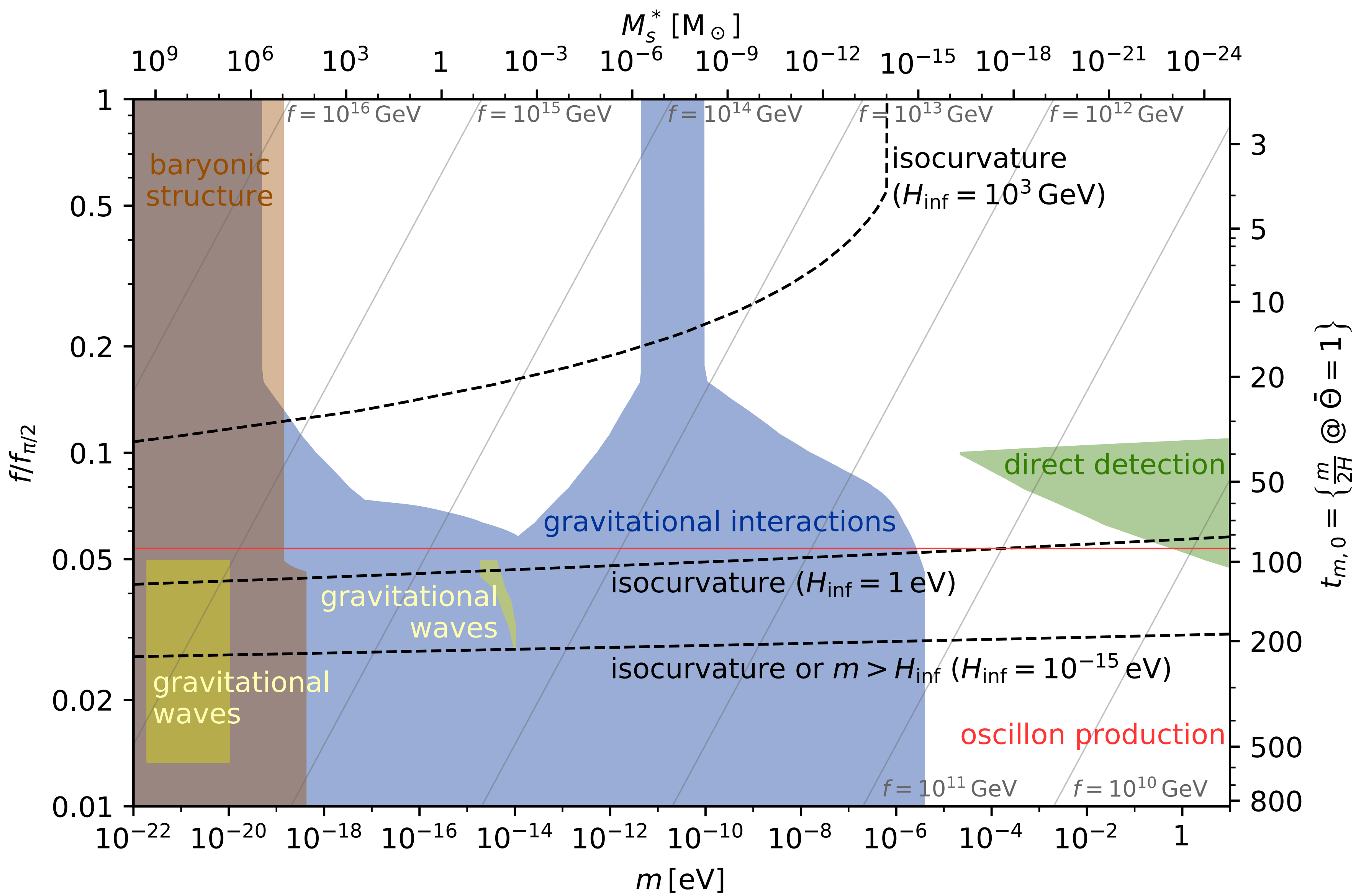
$$V(\Theta) \propto \frac{\Theta^2}{2 + \Theta^2}$$

Summary

If the onset of axion oscillations is delayed such that

nonlinearities > Hubble friction, 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

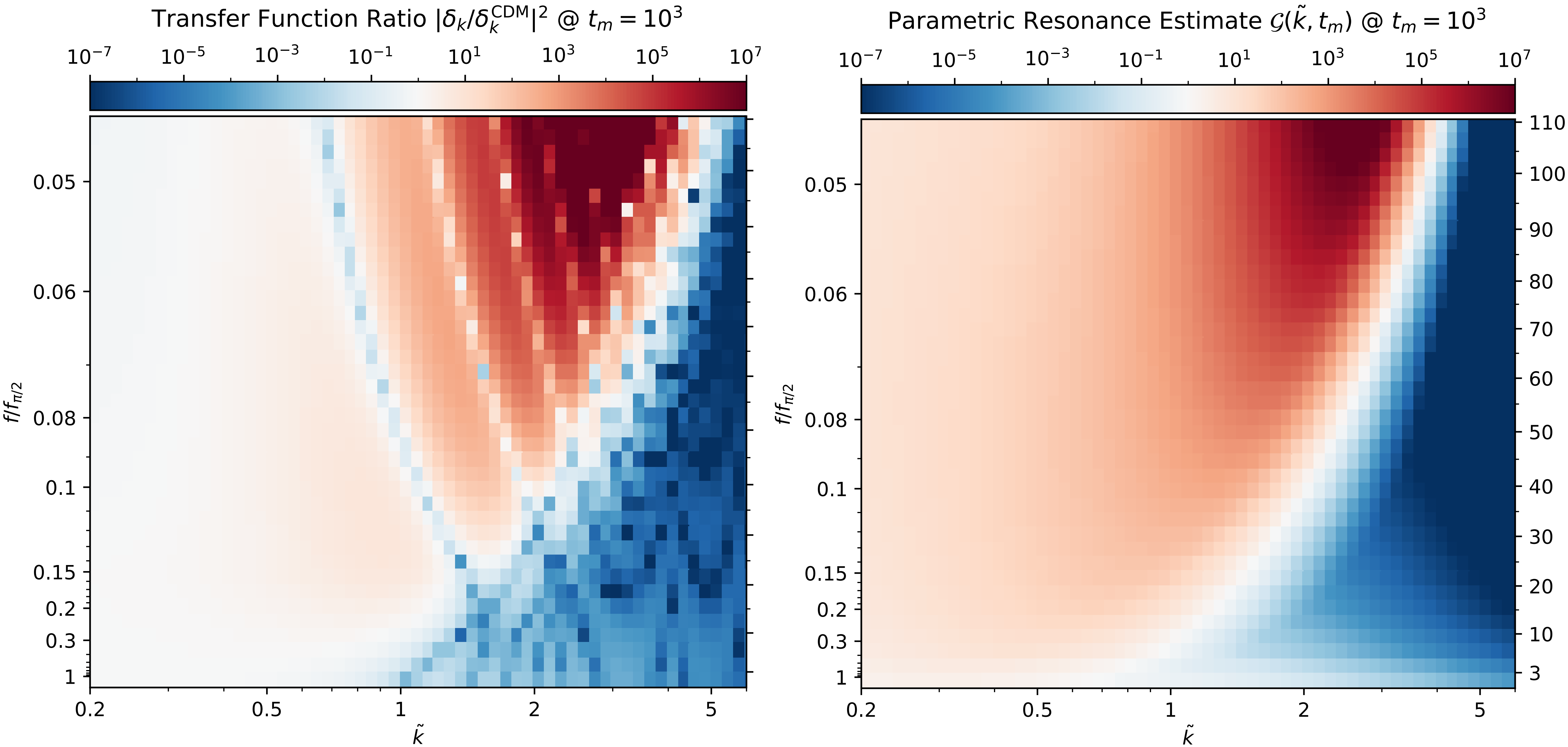
2. Impact on direct detection

3. Star formation & re-ionization history

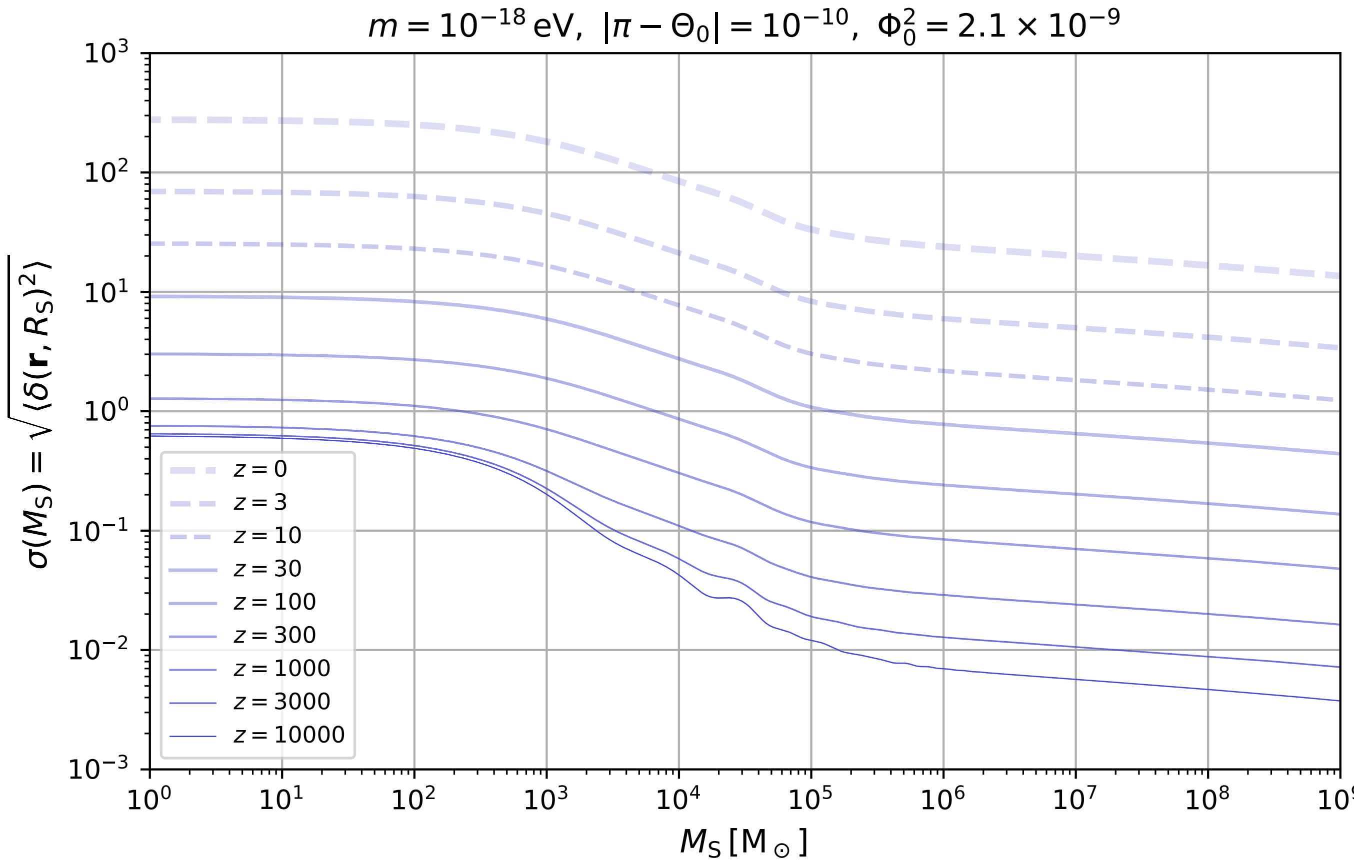
4. Analytic estimates of oscillon lifetime

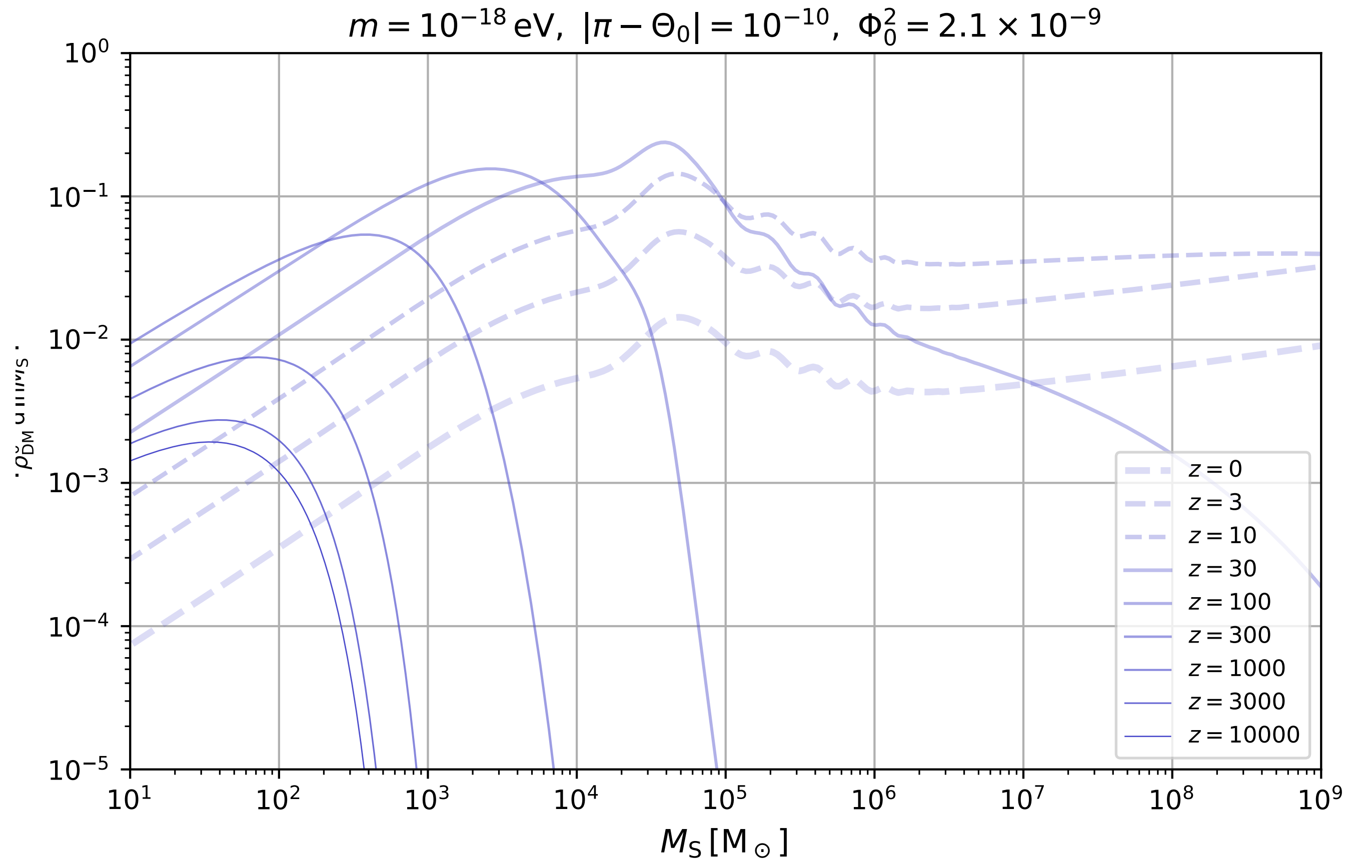
Backup

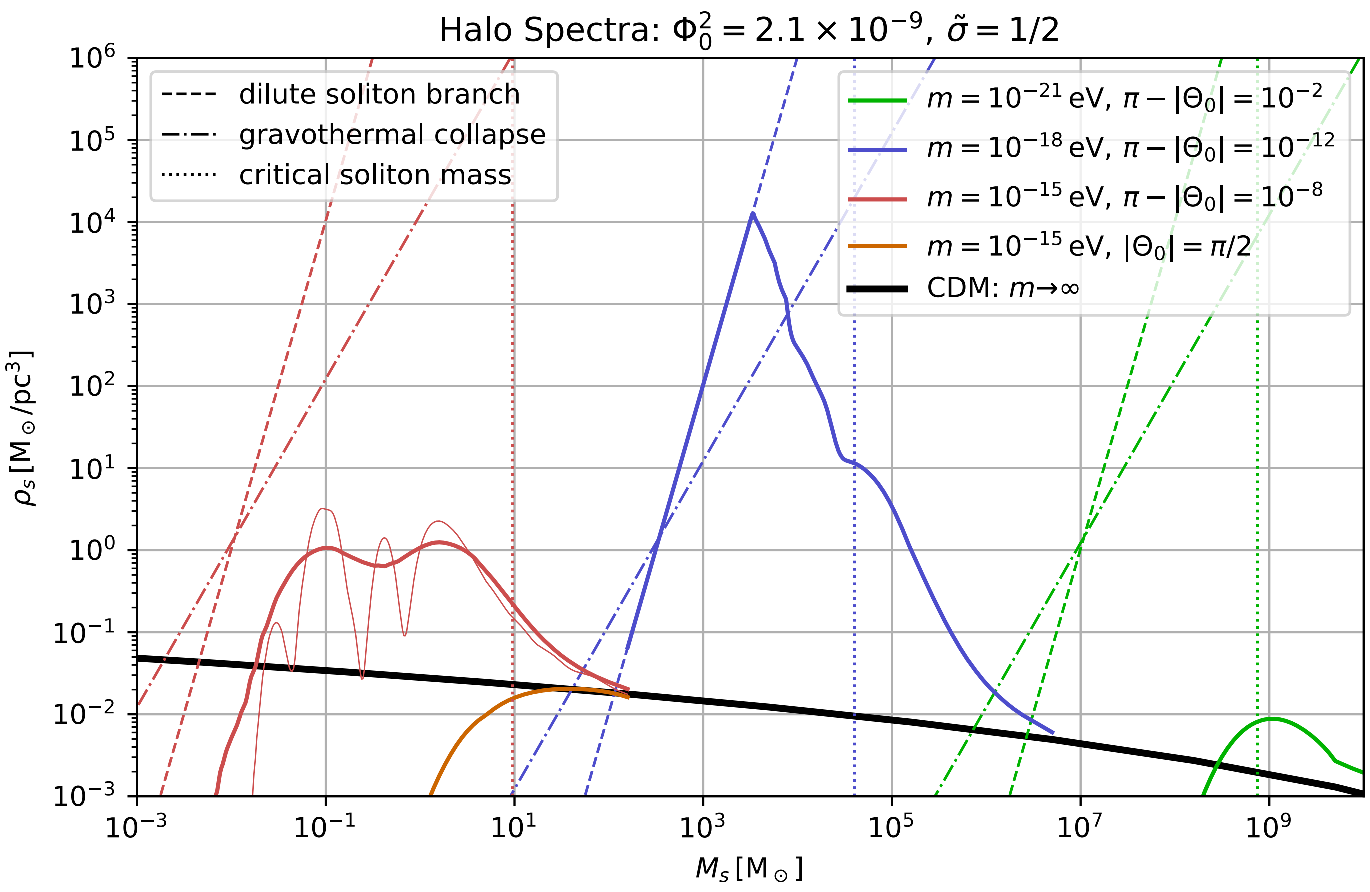
Parametric resonance



Press-Schechter







Condition for Oscillon Formation