Dark Matter Halos from Parametric Resonance and their Signatures

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Perimeter Institute

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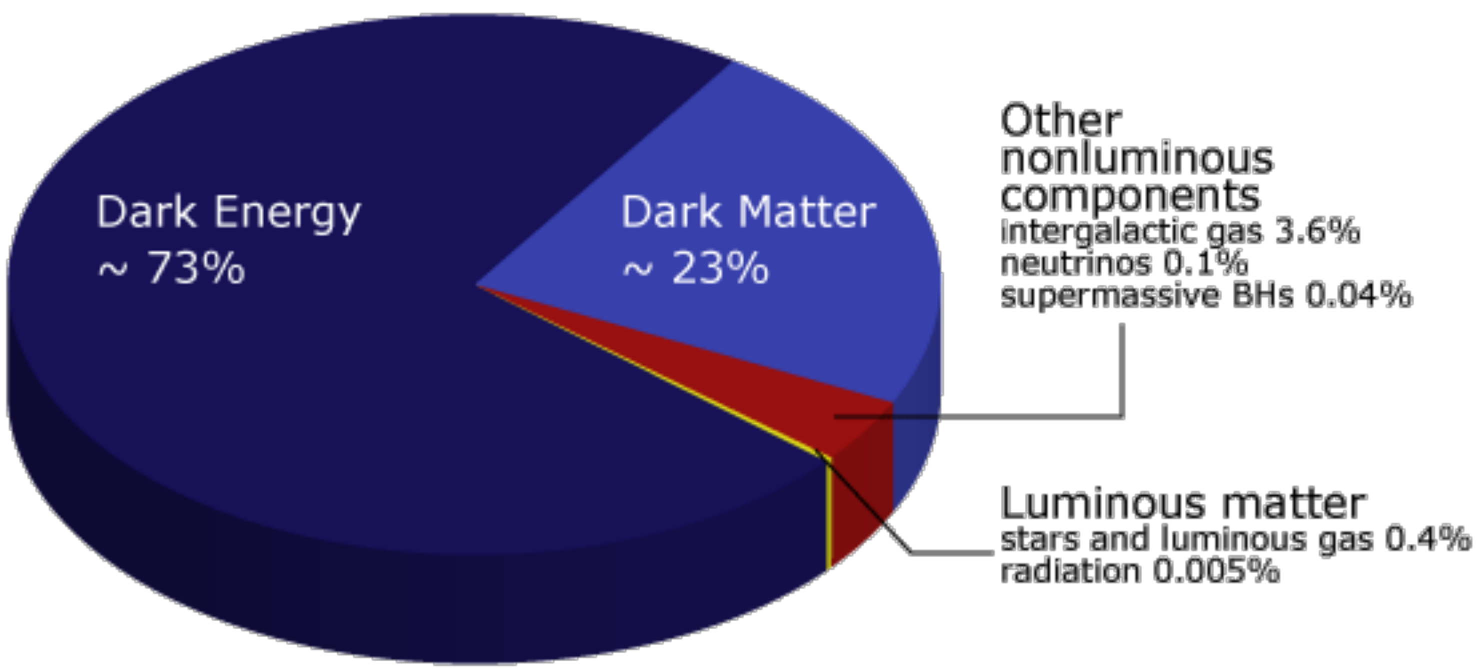
The Mystery of Dark Matter

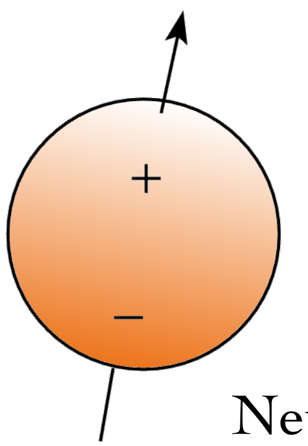


Models of Dark Matter

- What is it made out of?
- How is it produced?
- Does it have interactions other than gravitational?

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron
EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

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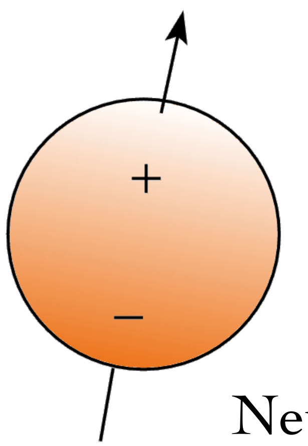

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Experimental bound: $\theta_s < 10^{-10}$

Solution:
$\theta_s \propto a(x,t)$ is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11}\ \mathrm{eV}\ \frac{10^{17}\ \mathrm{GeV}}{f_a} \sim (3\ \mathrm{km})^{-1}\ \frac{10^{17}\ \mathrm{GeV}}{\mathrm{f_a}}$$

f_a : axion decay constant

Elements of String Theory

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

- Extra dimensions

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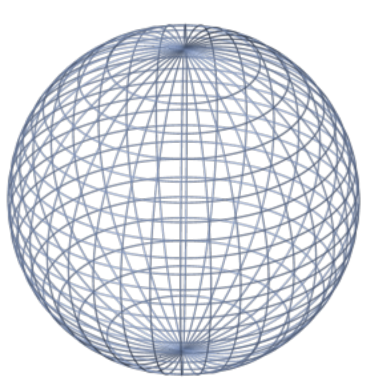

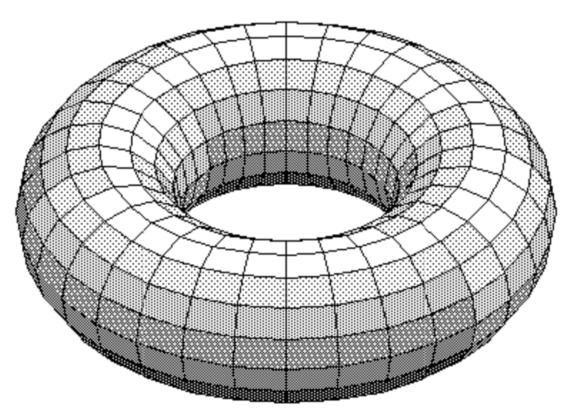

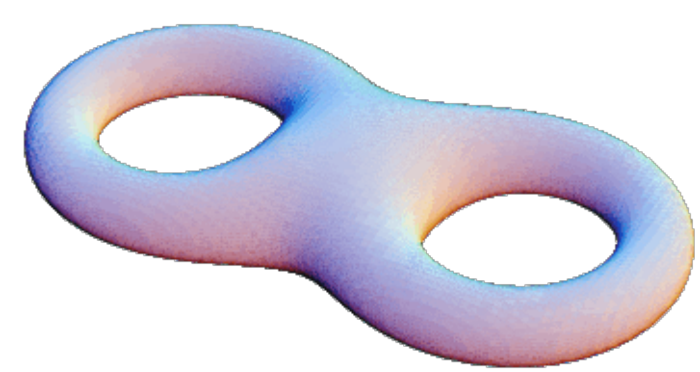

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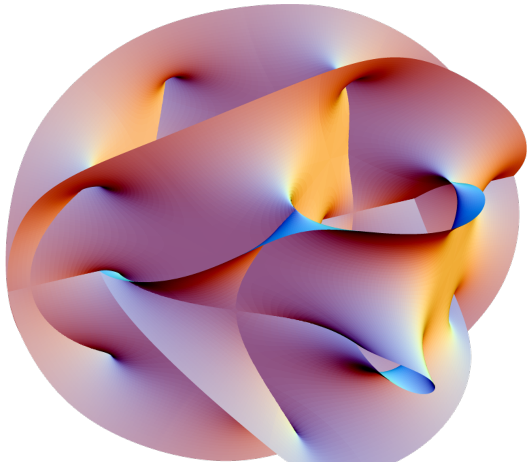

Elements of String Theory

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- Extra dimensions

- Gauge fields

- Topology

Give rise to a plenitude of massless particles in our Universe

Non-trivial gauge configurations

The Aharonov-Bohm Effect

Solenoid

Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

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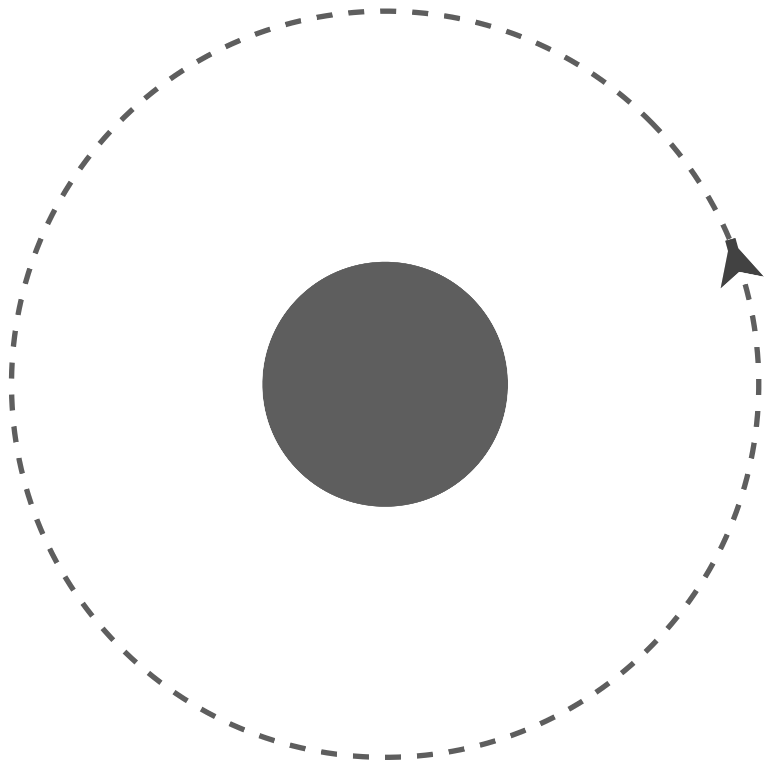

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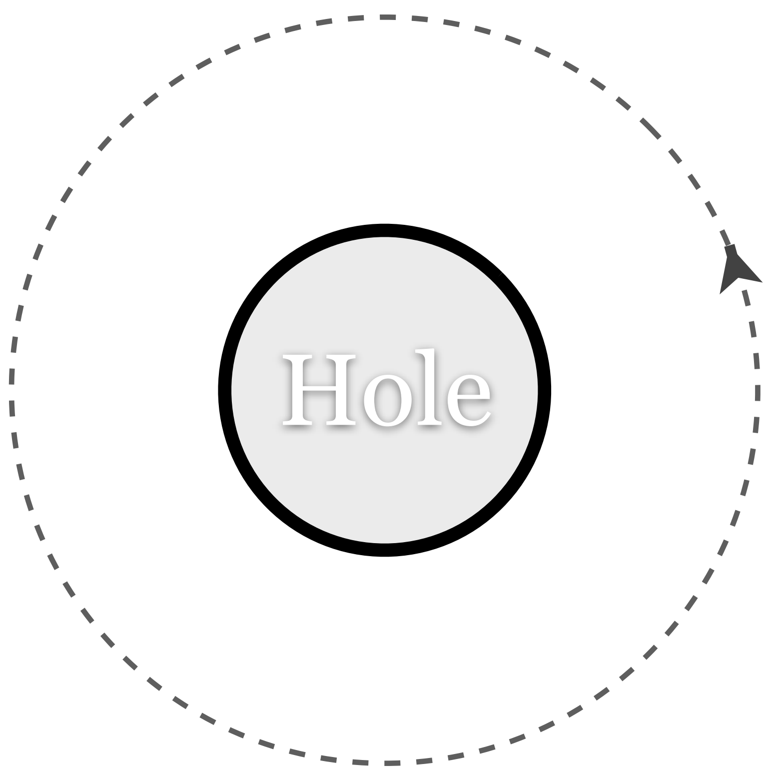

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Non-trivial topology:
“Blocking out” the core still leaves a non-trivial gauge, but no mass

A Plenitude of (Almost) Massless Particles

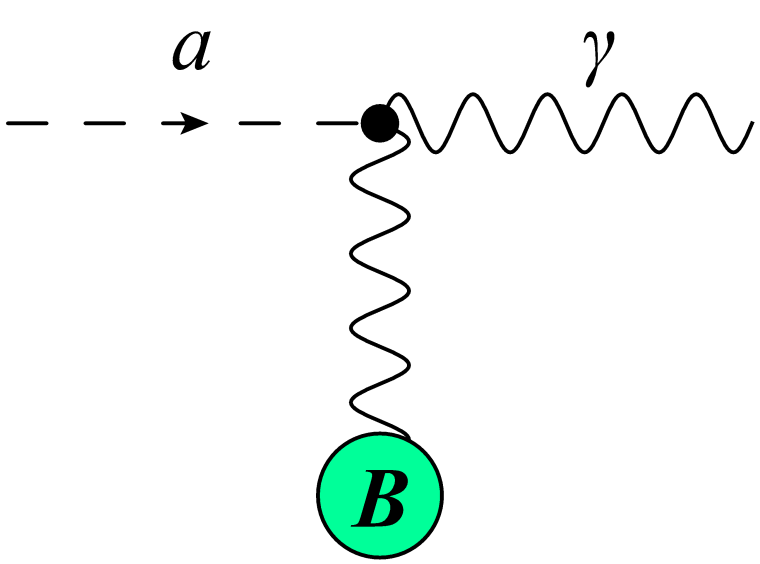
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

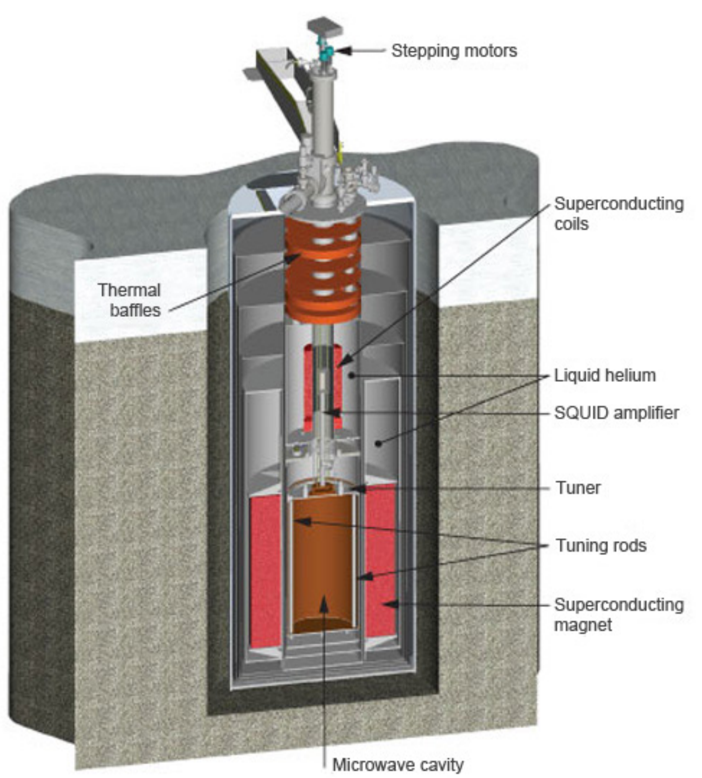
Axion Dark Matter

Some examples

- Axion-to-photon conversion in EM cavities (ex. ADMX)

$$g_{a\gamma\gamma}a(x)\vec{E}\cdot\vec{B}$$



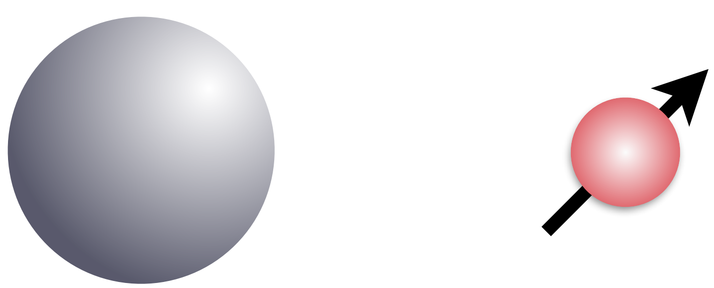


- At large wavelengths, axion detected via LC circuits (ex. ABRACADABRA and DM Radio)

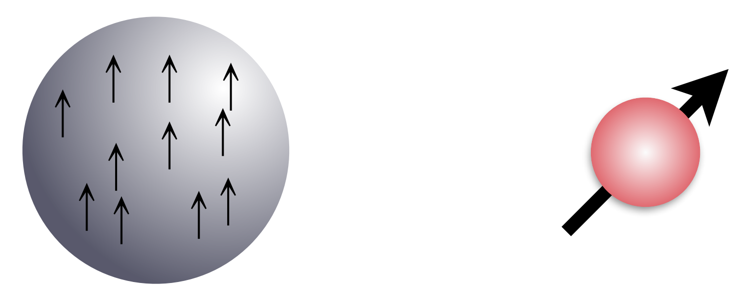
Axion Dark Matter

Some examples

Monopole-Dipole Interaction



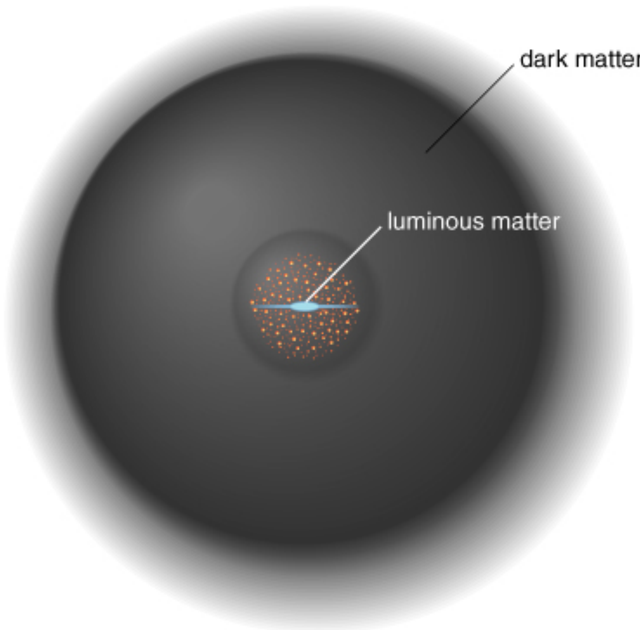
Dipole-Dipole Interaction



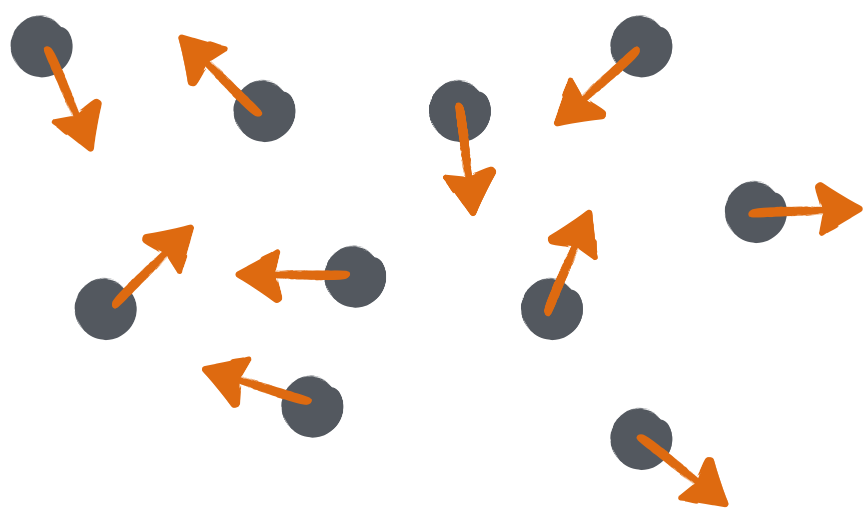
- Axion Force experiments (ex. ARIADNE) and DM experiments (ex. Casper)

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Usually we think of …



like a WIMP

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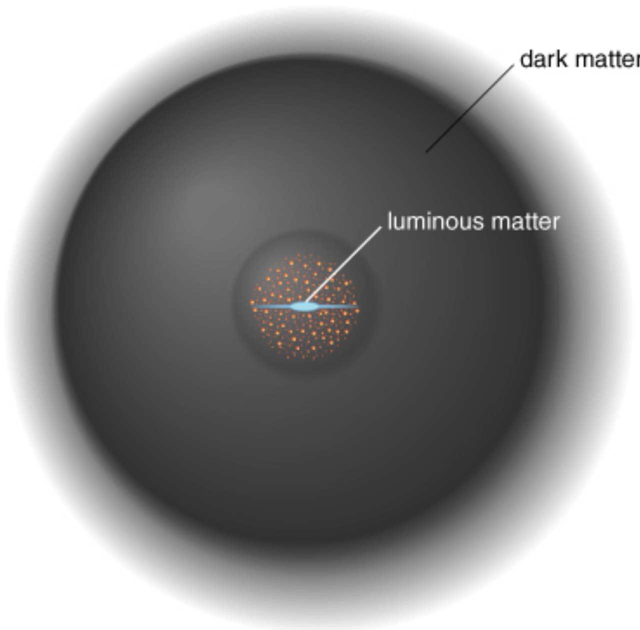

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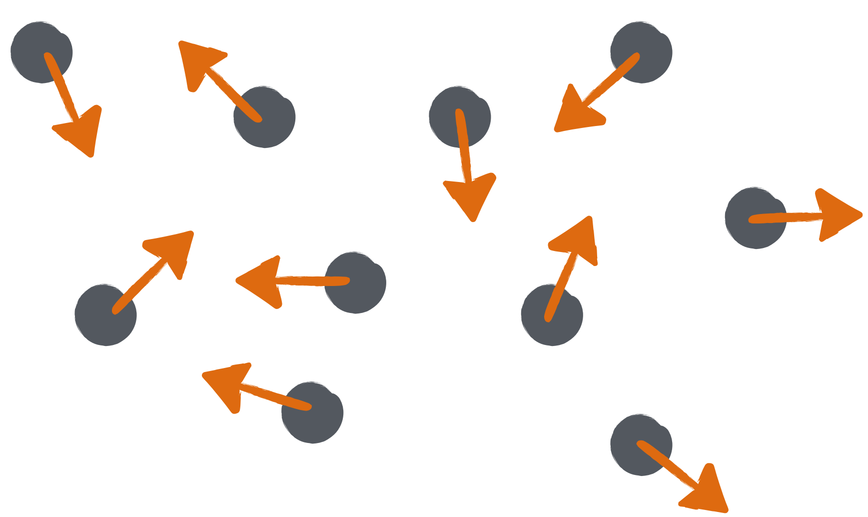
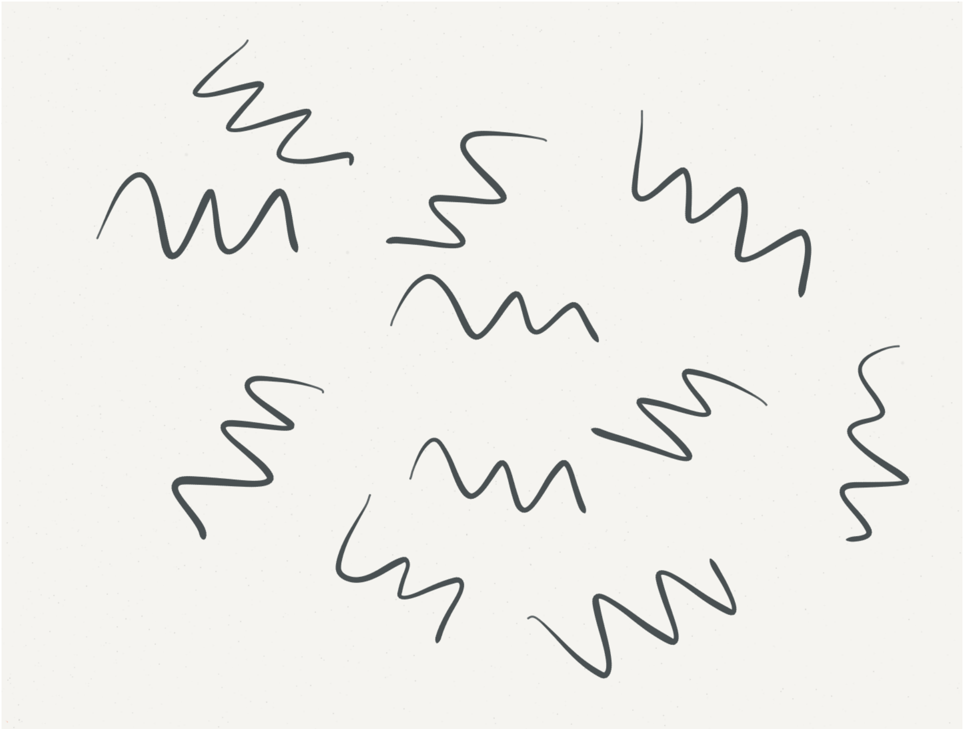


like a WIMP

instead of…



$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

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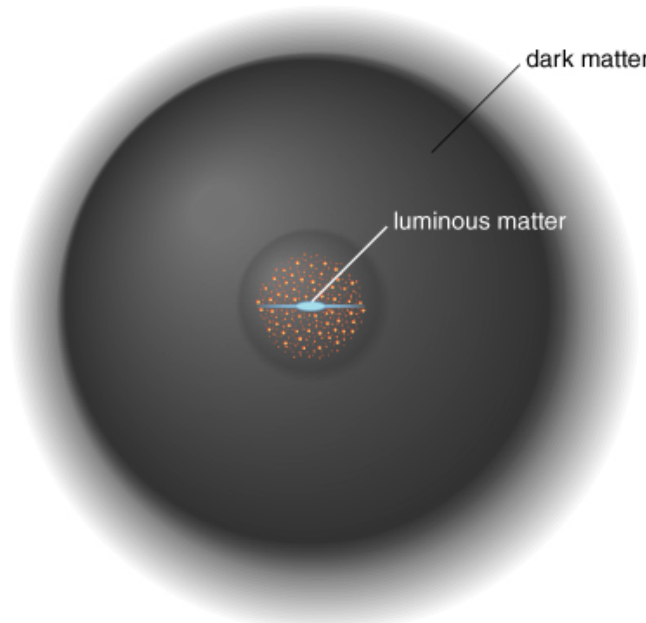

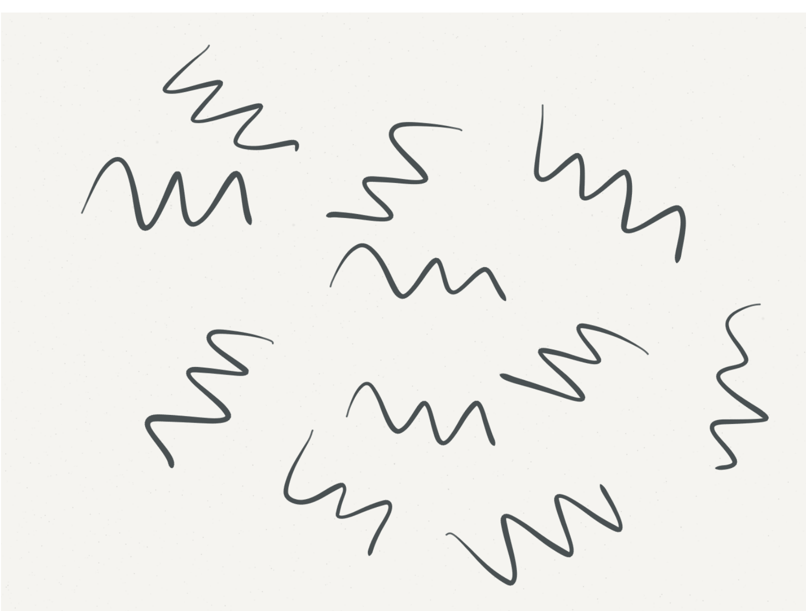

Decreasing DM Mass

What If DM Is a Boson and Very Light?

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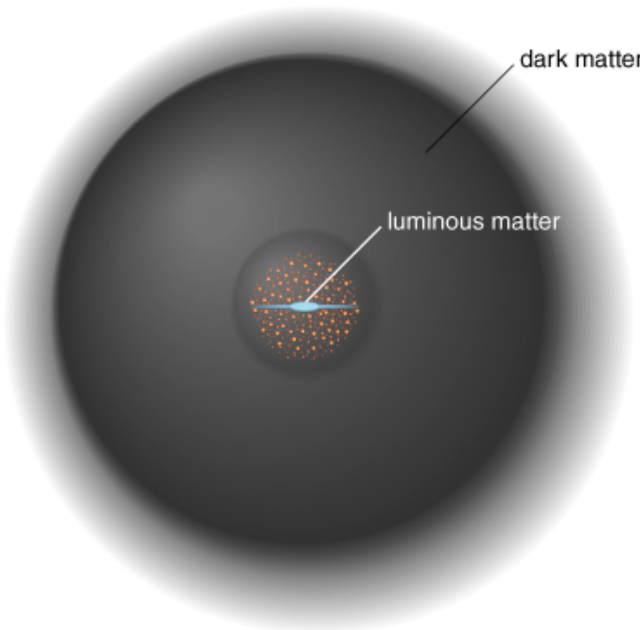

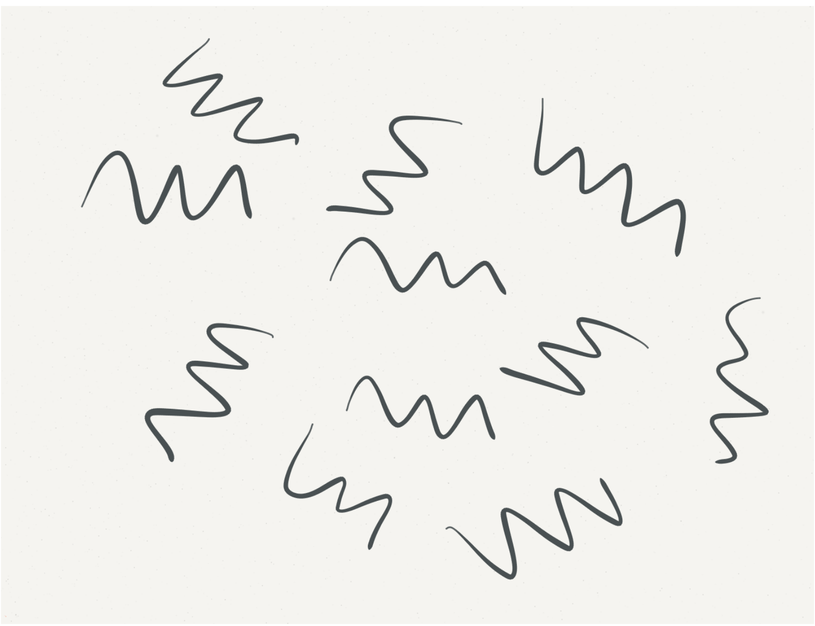

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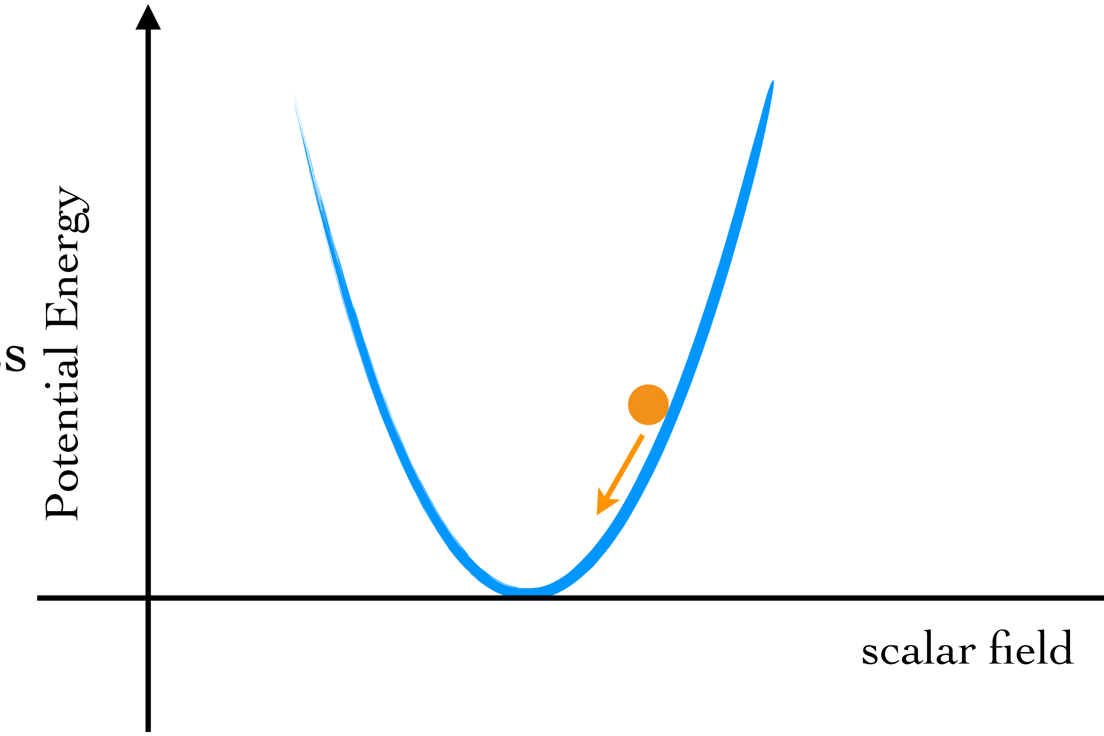


Equivalent to a Scalar Wave

Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1$ eV/c^2

we can talk about DM $\phi(x,t)$ and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

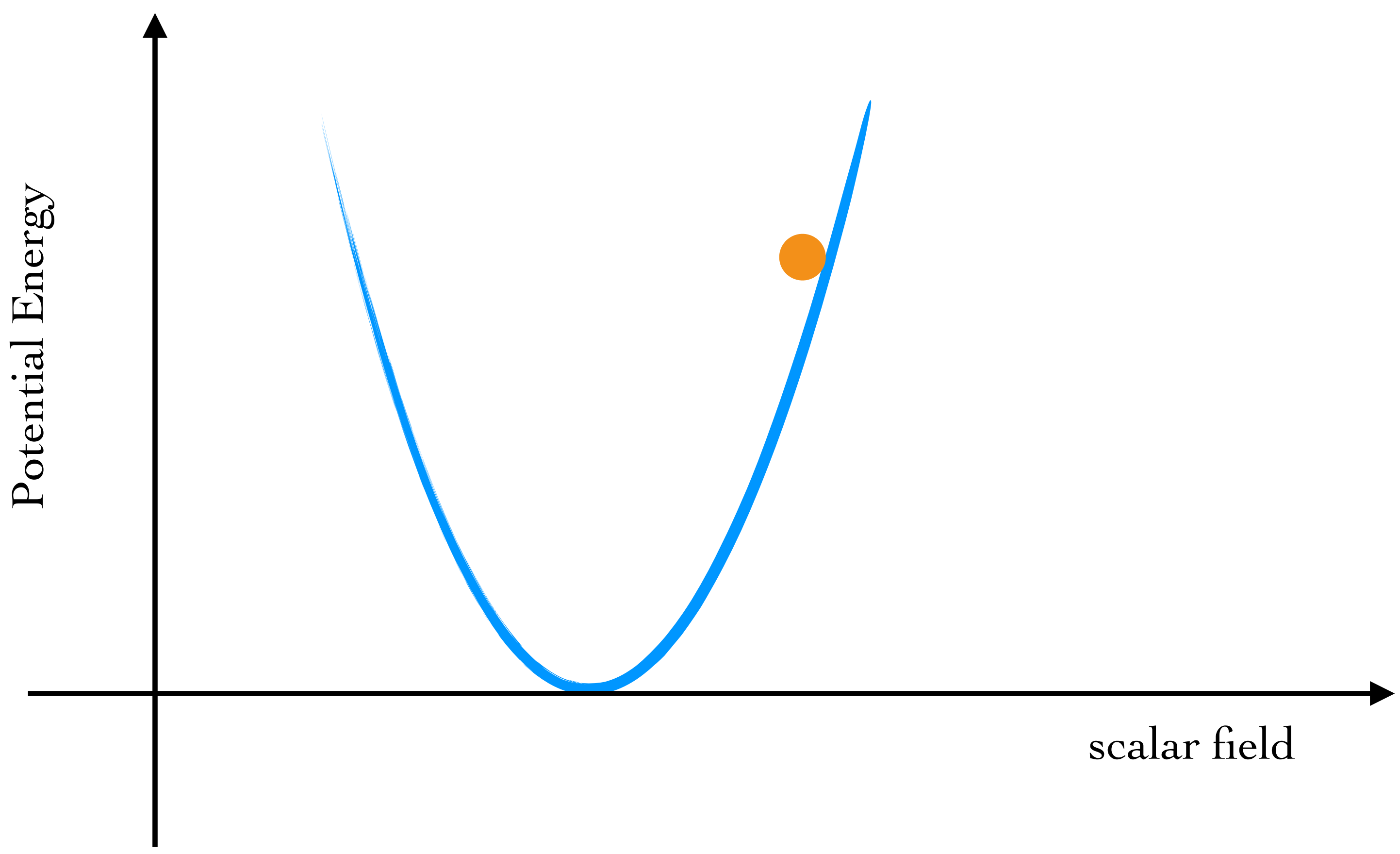
$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{\phi} + 3\ H\ \dot{\phi} + m_\phi^2 \phi = 0$$

$$\ddot{x} + \gamma\ \dot{x} + \omega^2 x = 0$$



Frozen when:
Hubble > m_ϕ

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

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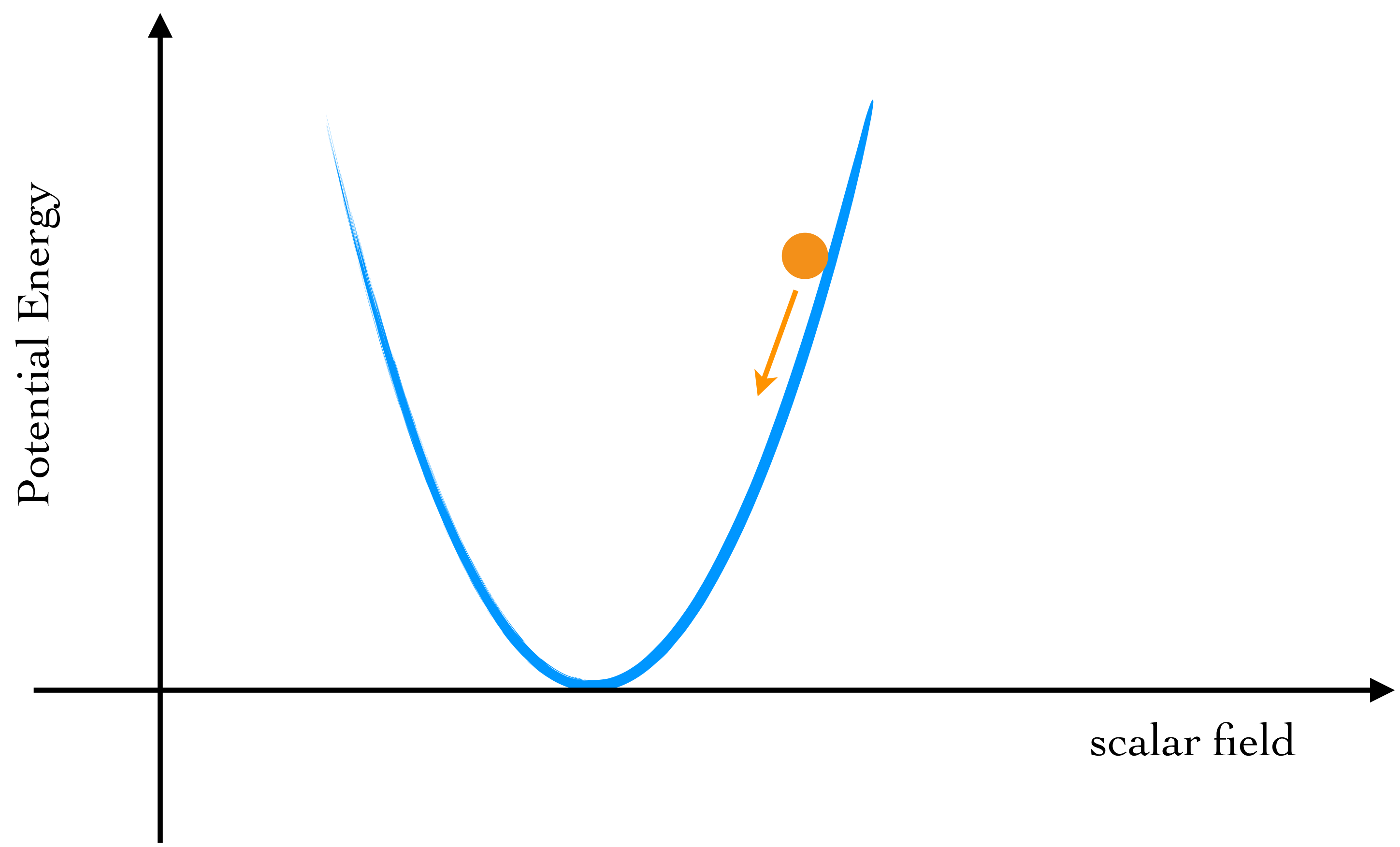

Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

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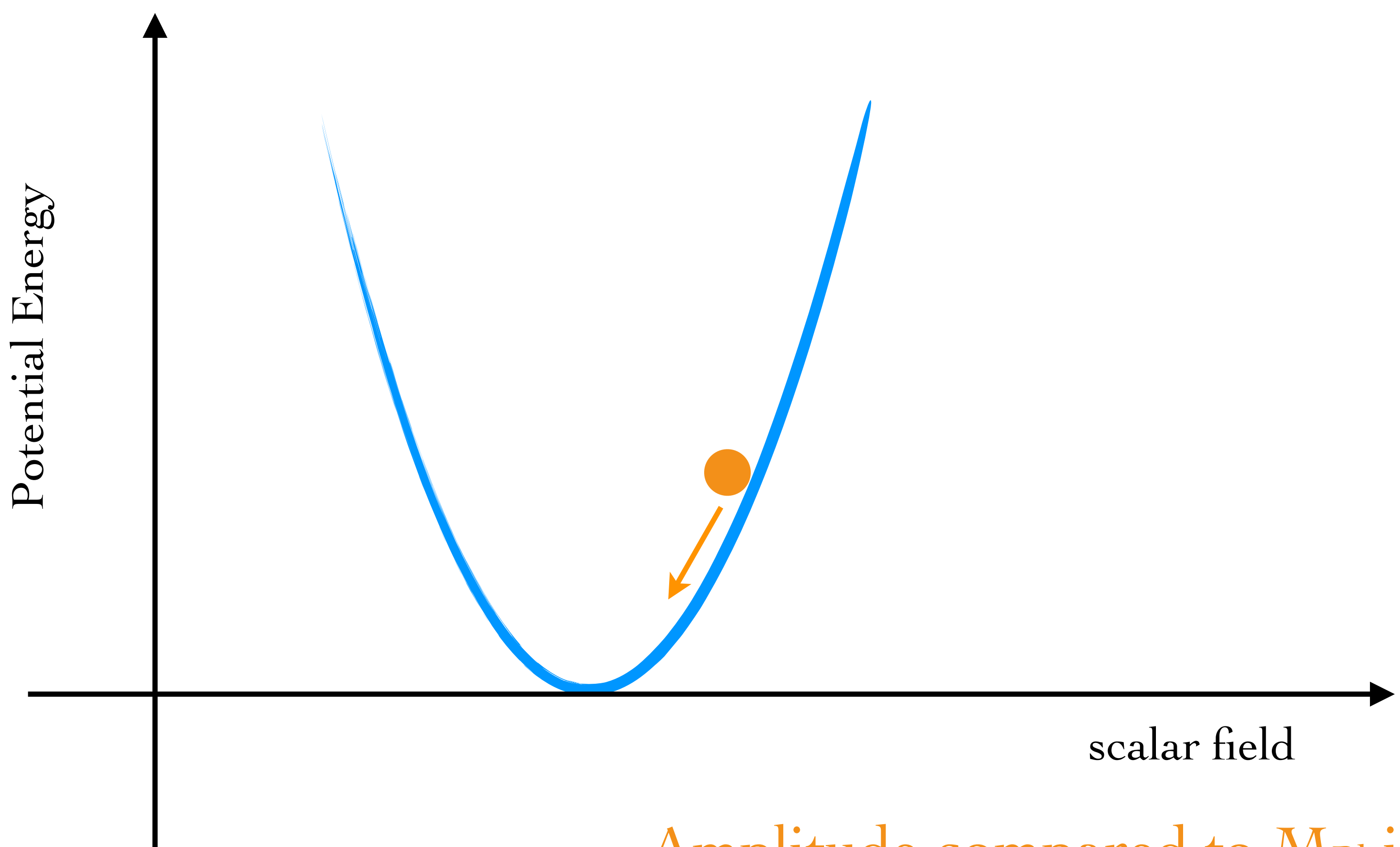
Light Scalar Dark Matter Today

- If m_ϕ < 1 eV, can still be thought of as a scalar field today



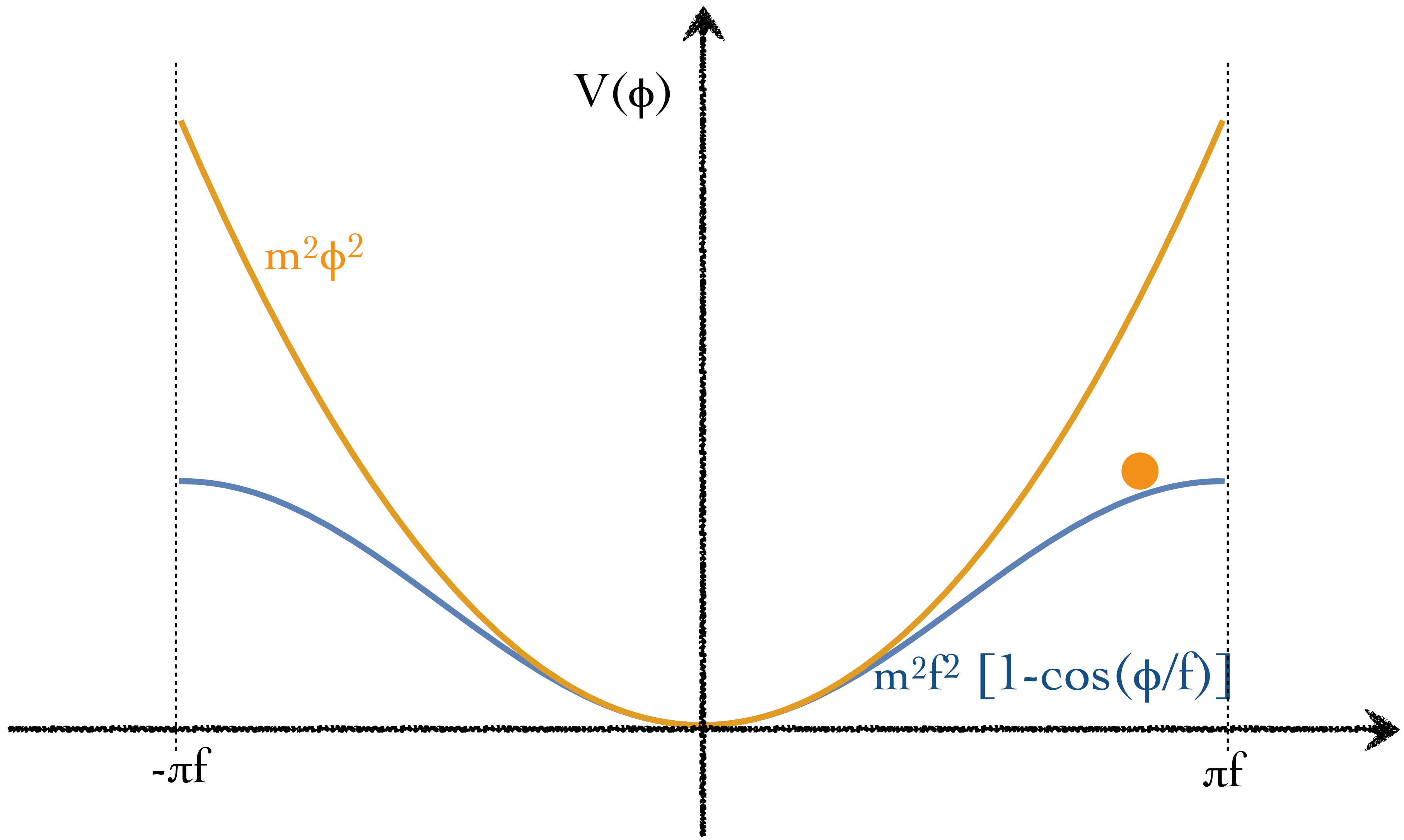
$m_\phi{}^2\ \phi_o{}^2\ \cos^2(m_\phi\, t) \sim \rho_\phi$

Coherent for $\upsilon_{vir}{}^{-2} \sim 10^6$ periods

Amplitude compared to M_{Pl} in the galaxy:

$$\kappa\phi_0 = \frac{\sqrt{8\pi\rho_\phi}}{m_\phi M_{\rm Pl}} = 6.4\cdot 10^{-13}\left(\frac{10^{-18}\,{\rm eV}}{m_\phi}\right)$$

Axion Dark Matter and the Large Misalignment Mechanism



Axions generically have attractive self-interactions

Axion self-interactions affect evolution at $H \sim m$

Structure growth due to axion self-interactions

Attractive self-interactions boost scales of size

$\lambda^* \sim 2\pi/m$ at the time of oscillation

corresponding today to:

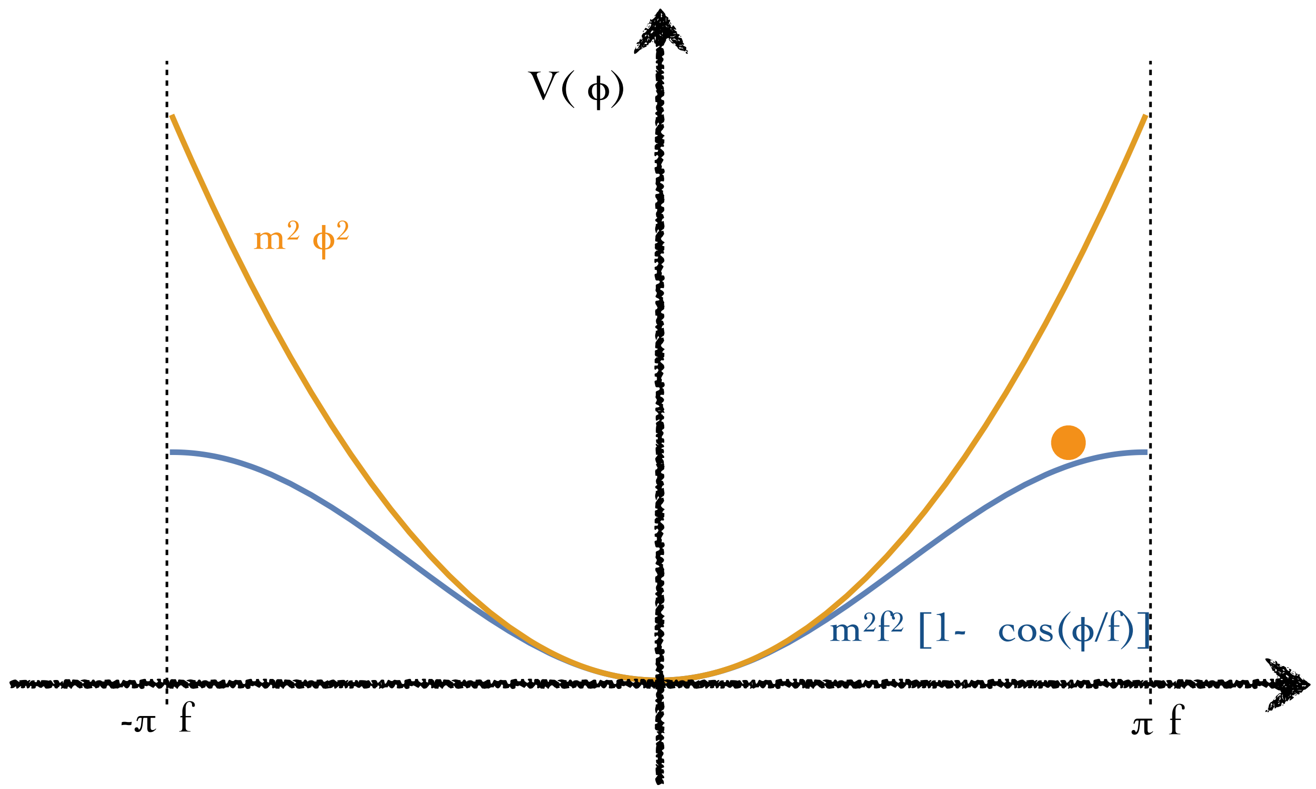
$$0.69\,\mathrm{Mpc}\sqrt{10^{-22}\,\mathrm{eV}/m}$$

or mass of:

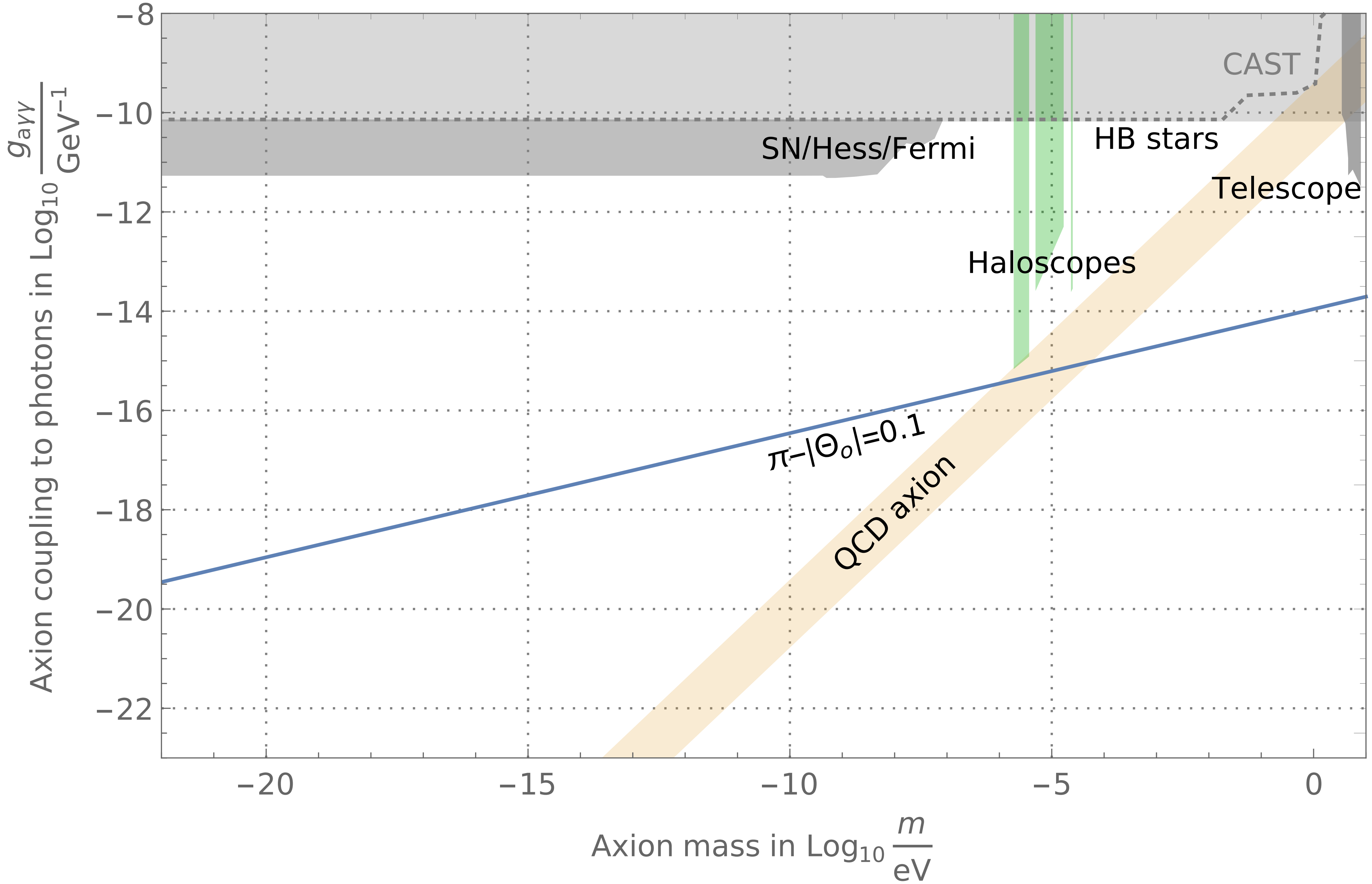
$$M_s^* = \frac{4\pi\rho_{\rm DM}^0}{3}\left(\frac{\lambda_*}{2}\right)^3 \approx 5\times10^9\,\mathrm{M}_\odot\left[\frac{10^{-22}\,\mathrm{eV}}{m}\right]^{3/2}$$

or physical size of:

$$r_s = 87\ \mathrm{pc}\left(\frac{M_s}{5\times10^9 M_\odot}\right)^{1/3}\left(\frac{10^5}{\mathcal{B}}\right)^{1/3}$$

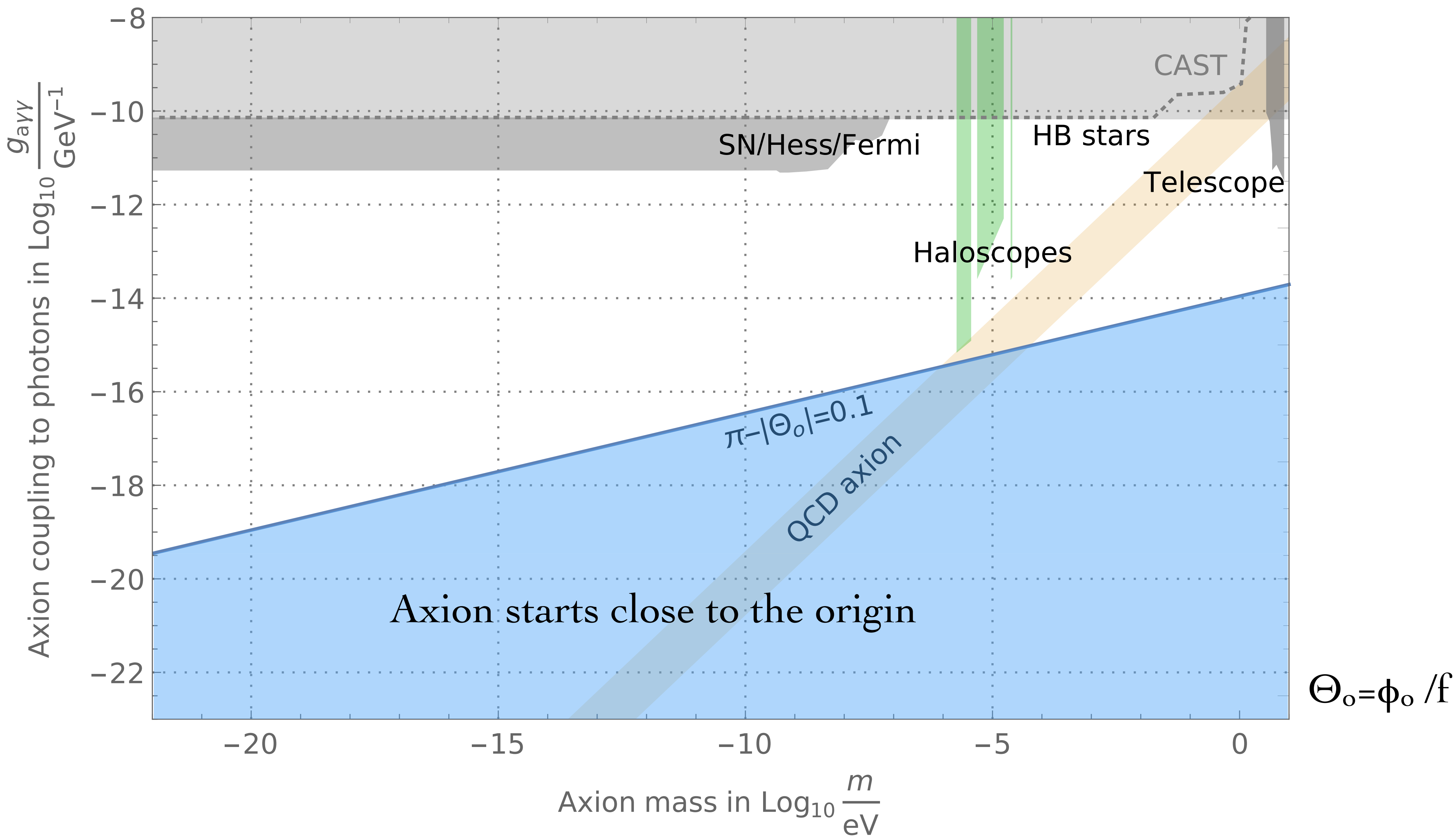


Large Misalignment vs Small Misalignment



$\Theta_o = \phi_o / f$

Large Misalignment vs Small Misalignment



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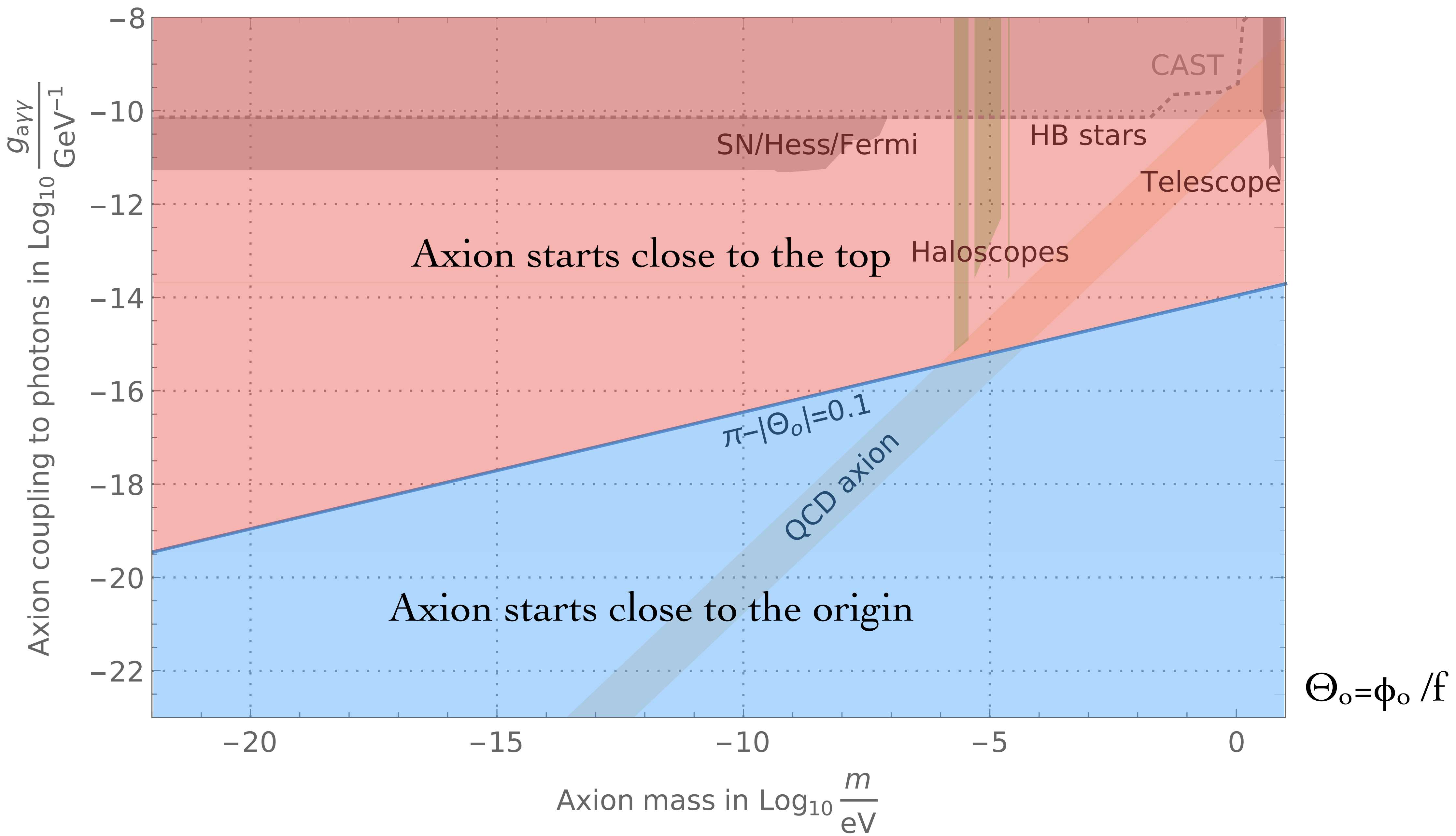

Large Misalignment is most relevant where experiments have good sensitivity

Effects of the large misalignment mechanism

- Formation of compact halos as a component of DM

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- Formation of compact halos as a component of DM

- Formation of solitons as a component of DM

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- Formation of structures well before matter-radiation equality:
  Oscillons as an (early) component of Dark Matter

Effects of the large misalignment mechanism

- Formation of compact halos as a component of DM

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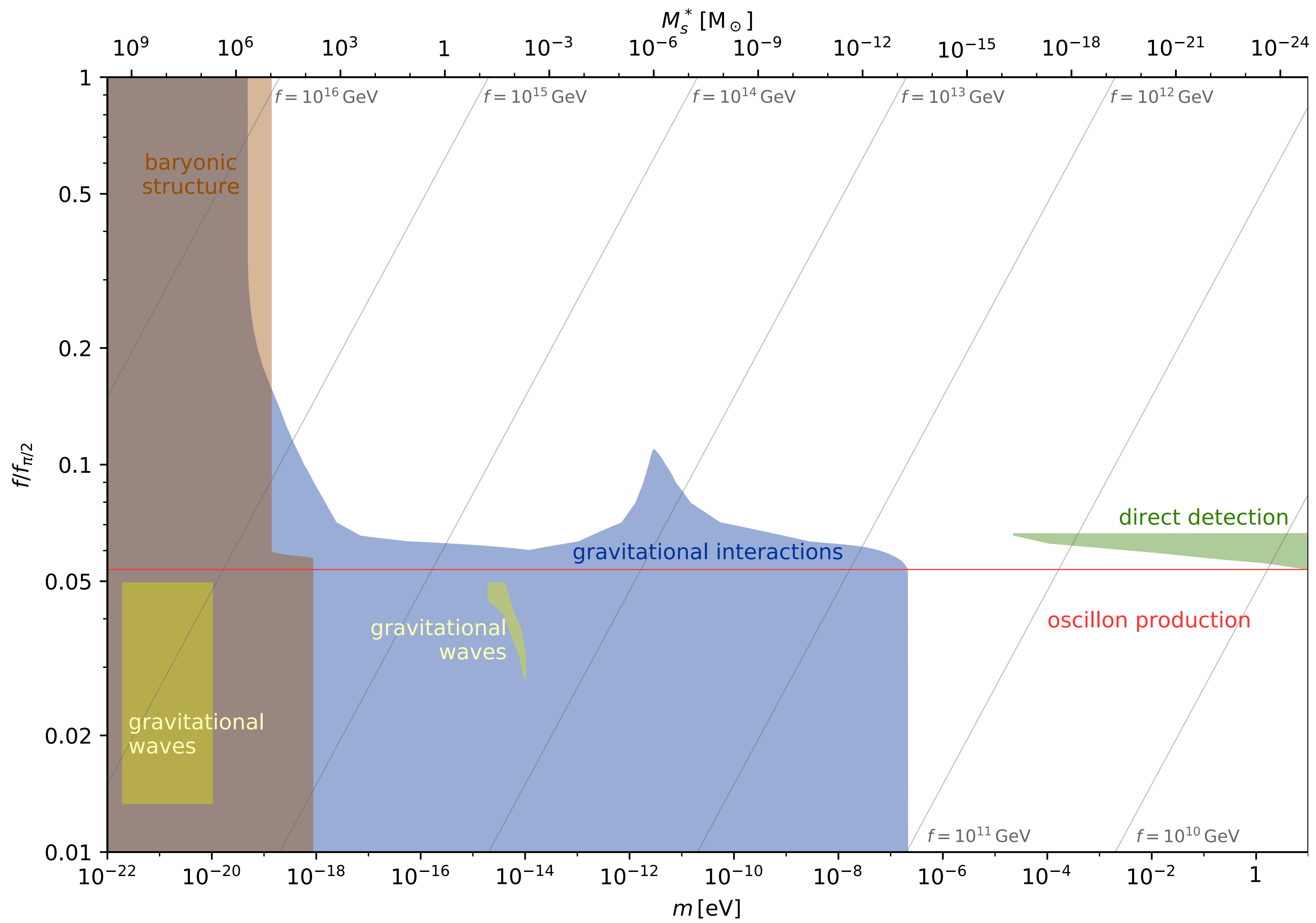
- Formation of structures well before matter-radiation equality:
  Oscillons as an (early) component of Dark Matter

- Happens without the need of a phase transition, starting from a scale-invariant spectrum

Signatures of the large misalignment mechanism



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

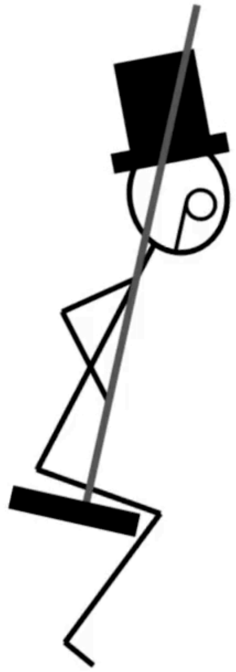
Outline

- Dynamics of the large misalignment mechanism
- Signatures of the large misalignment mechanism
- Comments and future prospects

Parametric Resonance Growth

$$\ddot{x} + \gamma \dot{x} + \omega^2 \left(1 + h \cos\left((2\omega + \epsilon)t\right)\right) = 0$$

Instability occurs when h> γ/(2ω) and ε~0



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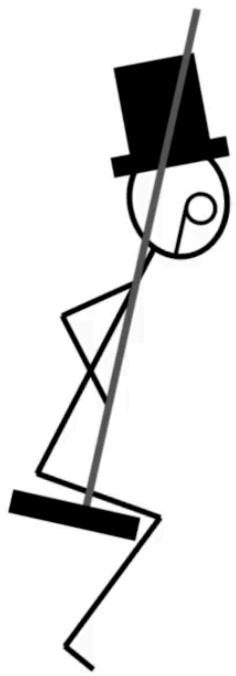

Parametric Resonance Growth

For the axion field and small $\Theta_0(t)+\theta_k\, e^{-ik.x}$:

$$\ddot{\theta}_k + \boxed{\frac{3}{2t_m}}\dot{\theta}_k + \left(\boxed{1 - \frac{\Theta_0(t_m)^2}{4} + \frac{\tilde{k}^2}{t_m}} - \boxed{\frac{\Theta_0(t_m)^2}{4}\cos(2t_m)}\right)\theta_k = 0$$

Friction term resonant frequency Driving term

t_m :time in units of 1/m

$\tilde{k}$:dimensionless variable — size of the mode compared to m at t_m=1

Parametric Resonance Growth

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Semi-relativistic modes $\tilde{k} \sim 1$ are the ones with frequency match

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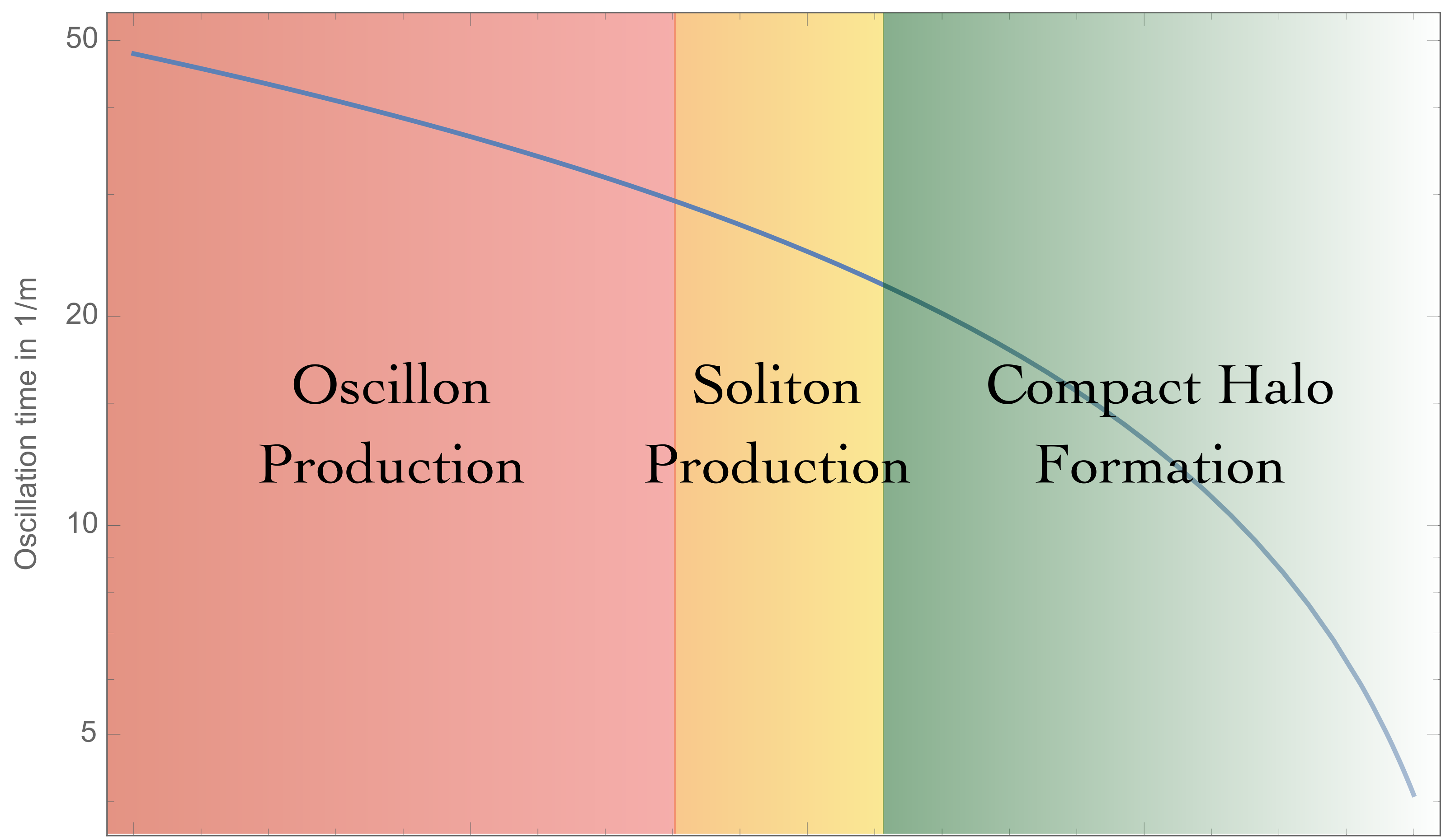
Semi-relativistic modes $\tilde{k} \sim 1$ are the ones with frequency match

In order to overcome the friction the field needs to start close to the top to delay the oscillation time: $\Theta_0(t_{m,0})^2 > 8/t_{m,0}$

Delayed onset of oscillation



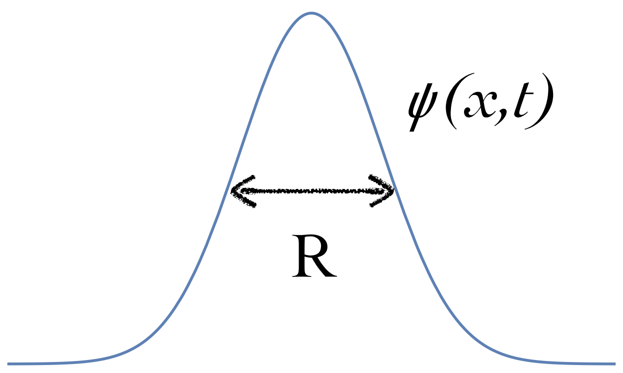
←Starting closer and closer to the top

Boost relative to CDM $\mathcal{B} \equiv \frac{\rho_s}{\rho_s^{\mathrm{CDM}}} \sim \exp\{\xi\, m\, t_{\mathrm{osc}}\}$

Need to start close to the top of the potential to get a non-trivial effect in structure formation

What are solitons?
What are oscillons?

Scalar field configuration of size R and total mass M



$$\text{Hamiltonian energy density} = \frac{|\nabla\psi|^2}{2m} + V_{grav}(\psi) - \lambda|\psi|^4 + \lambda'|\psi|^6$$

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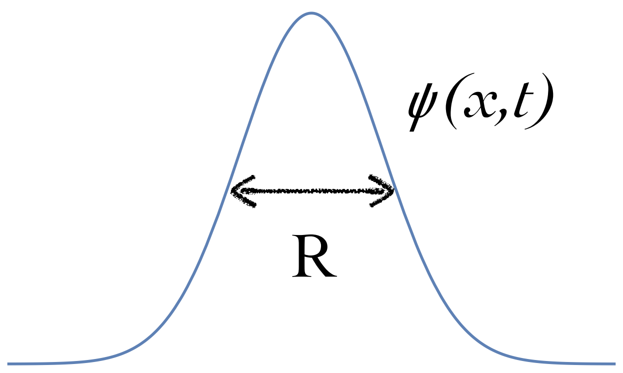

$$\text{Hamiltonian energy density} = \frac{|\nabla\psi|^2}{2m} + V_{grav}(\psi) - \lambda|\psi|^4 + \lambda'|\psi|^6$$

Integrate over volume

$$\text{Energy}(M,R) = \frac{M}{m^2R^2} - \frac{G_N M^2}{R} - \lambda\frac{M^2}{m^2R^3} + \lambda'\frac{M^3}{m^3R^6}$$

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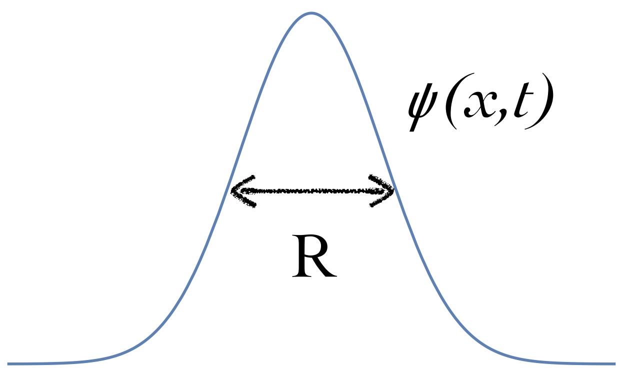

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Solitons: Large (R> 1/m) scalar field configurations balancing kinetic pressure against gravity

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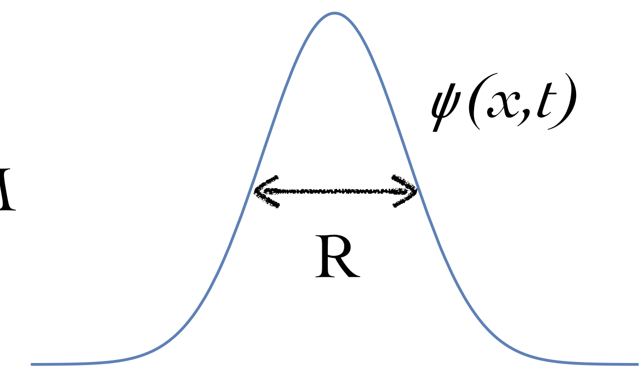

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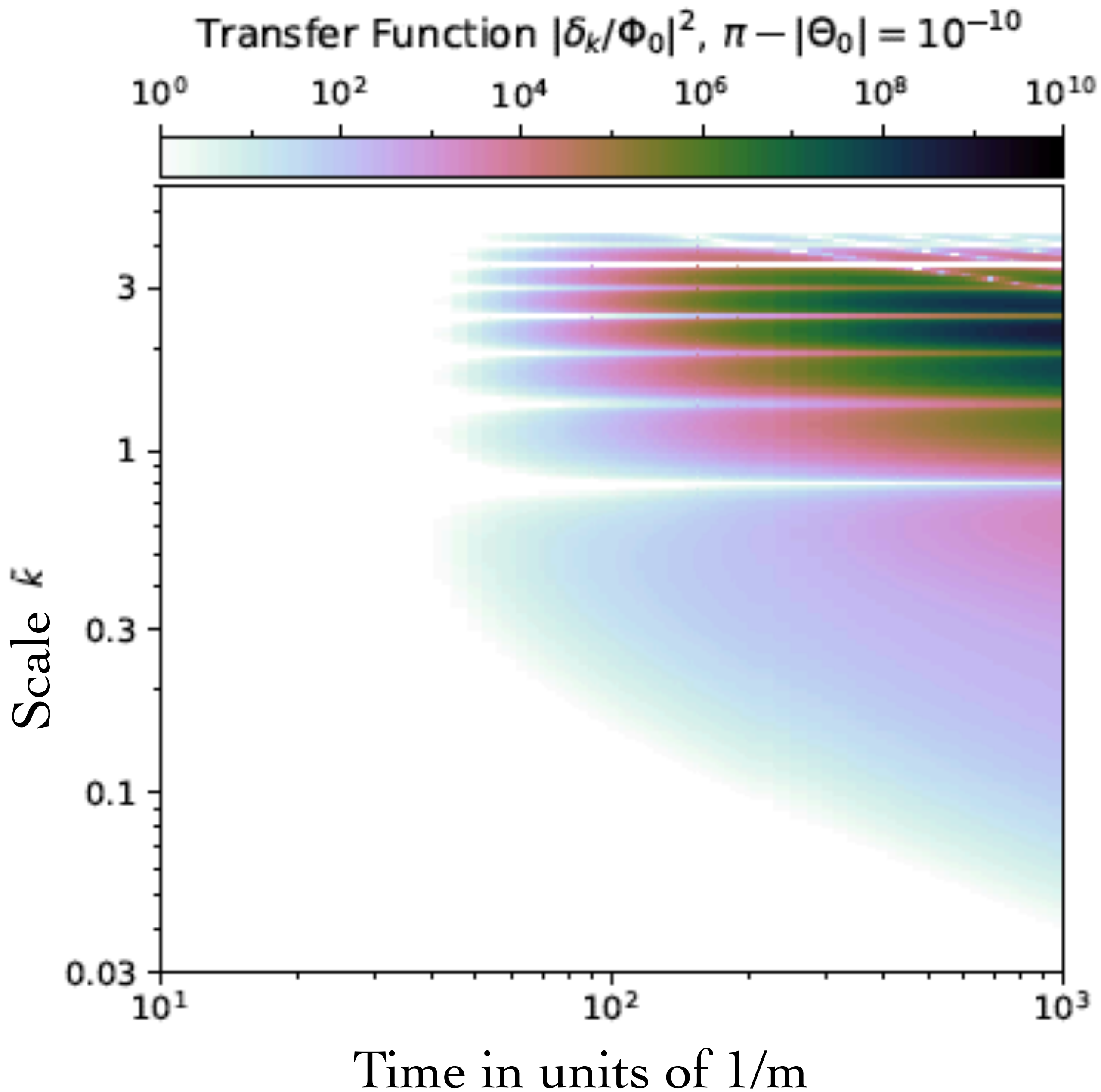
Solitons: Large (R> 1/m) scalar field configurations balancing kinetic pressure against gravity

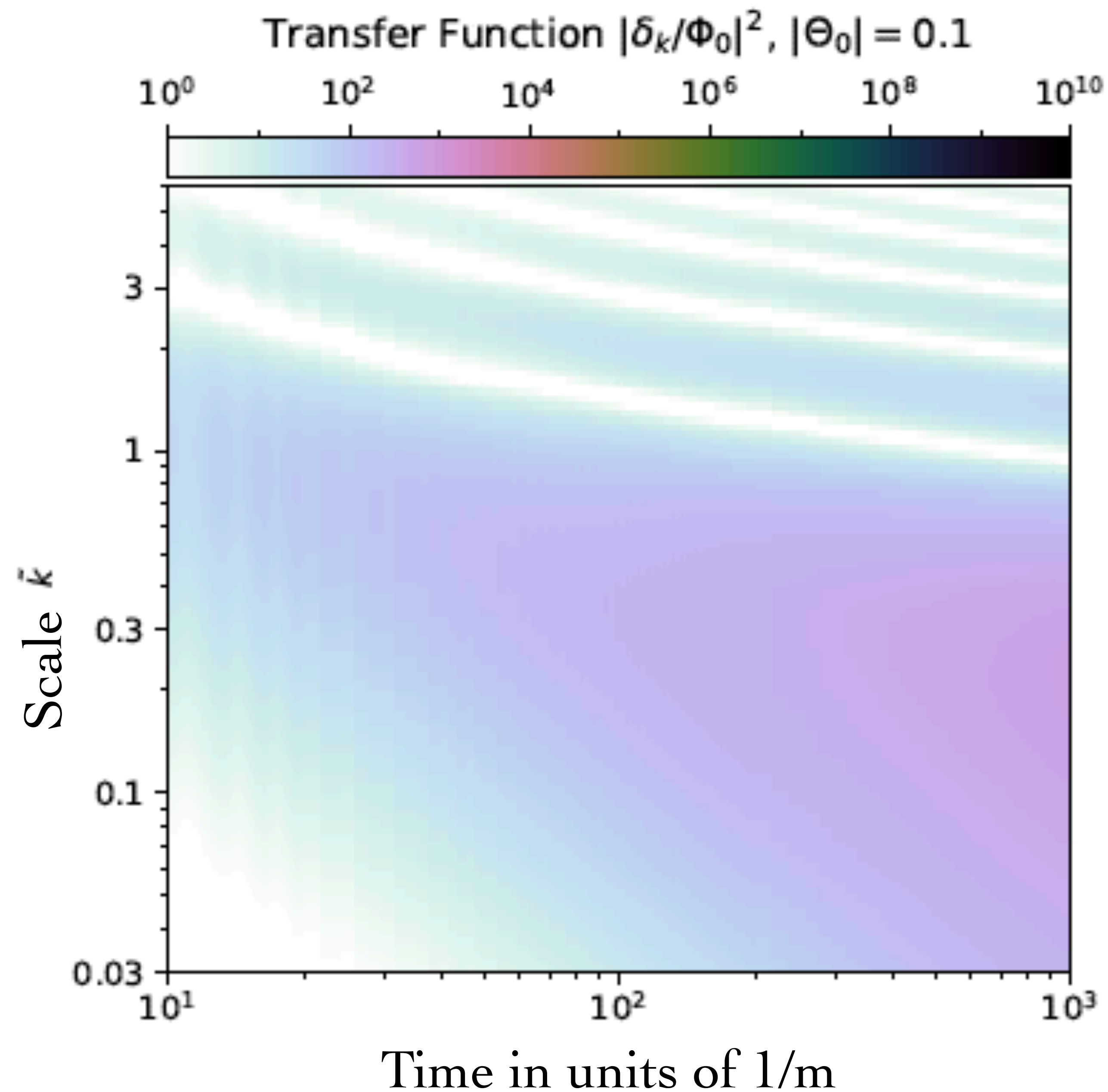
Oscillons: Small (R~ 1/m) scalar field configurations balanced by self-interactions

Evolution of perturbations

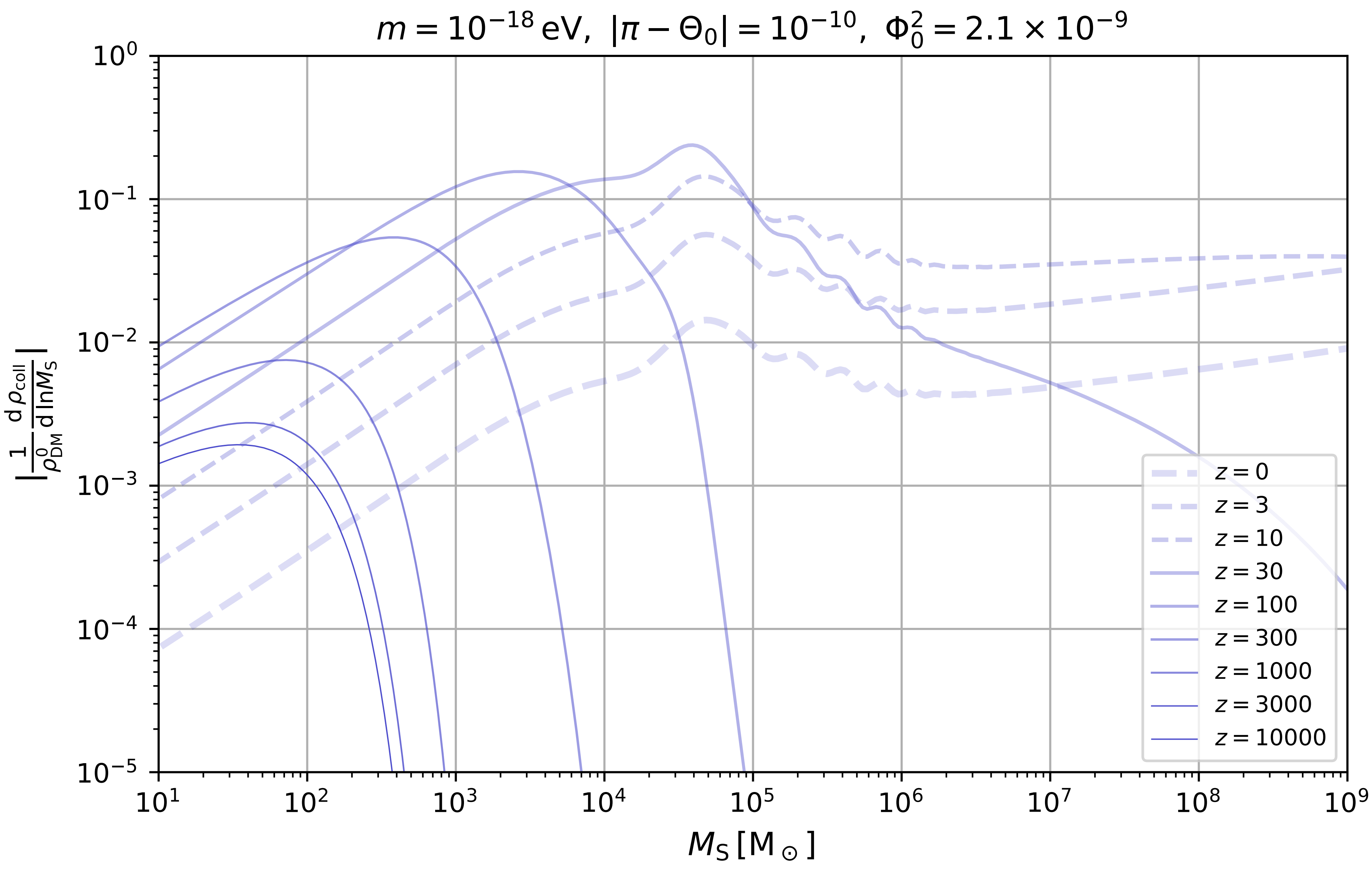
Axion DM



CDM



Press-Schechter



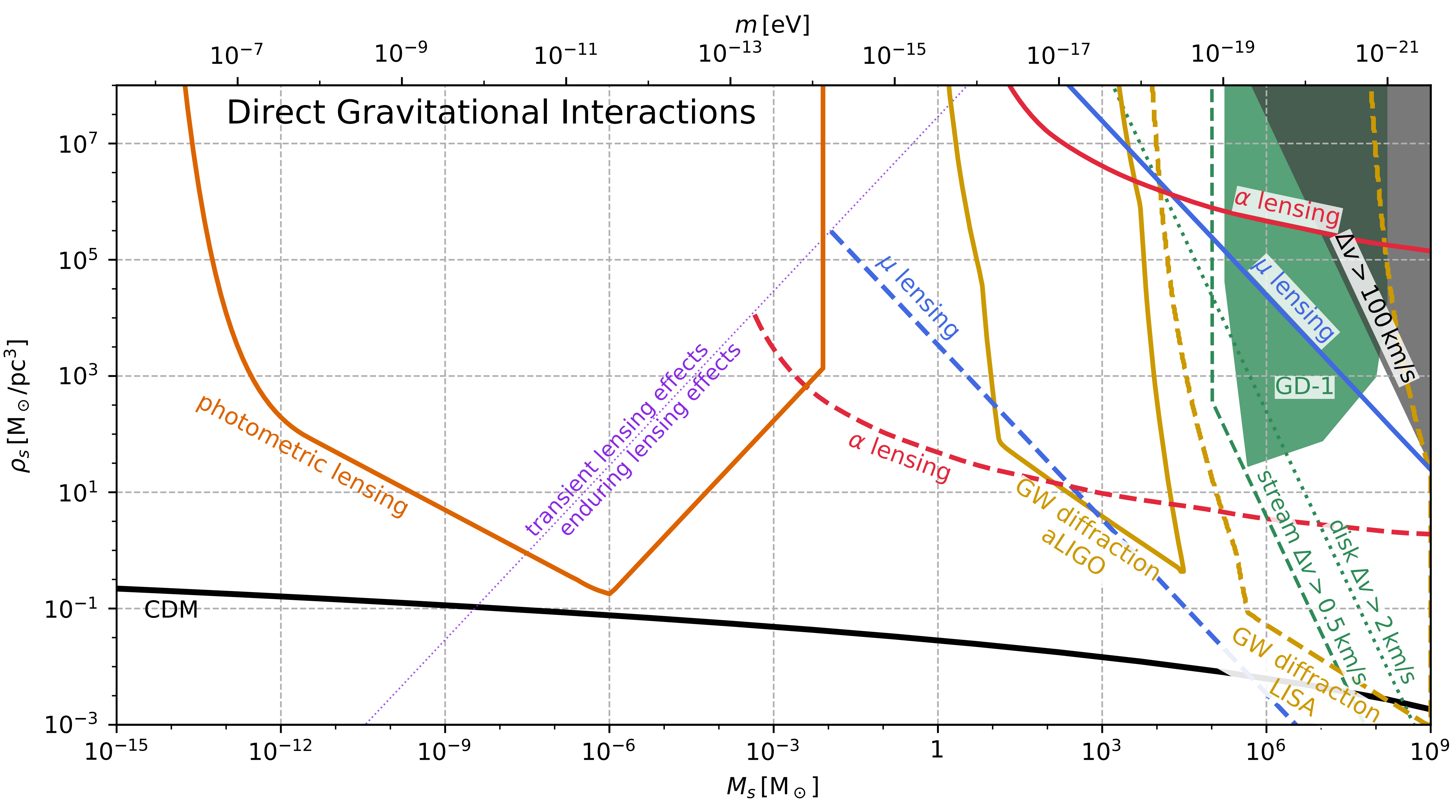
Outline

- Dynamics of the large misalignment mechanism
- Signatures of the large misalignment mechanism
- Comments and future prospects

Signatures of the Large misalignment mechanism

- Direct Gravitational Interactions
- Gravitational Waves
- Star Formation
- Direct Detection

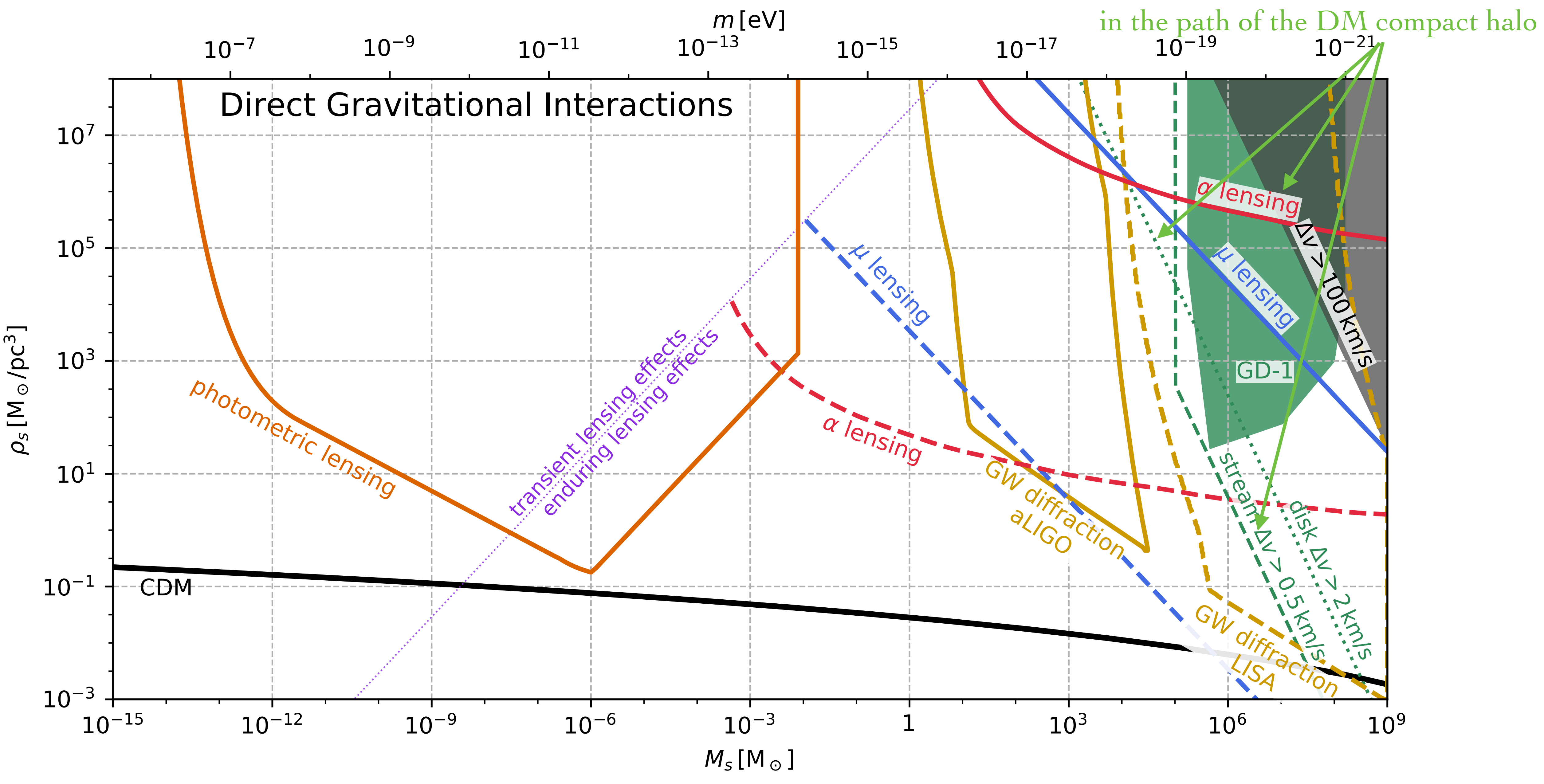
Direct Gravitational Signatures



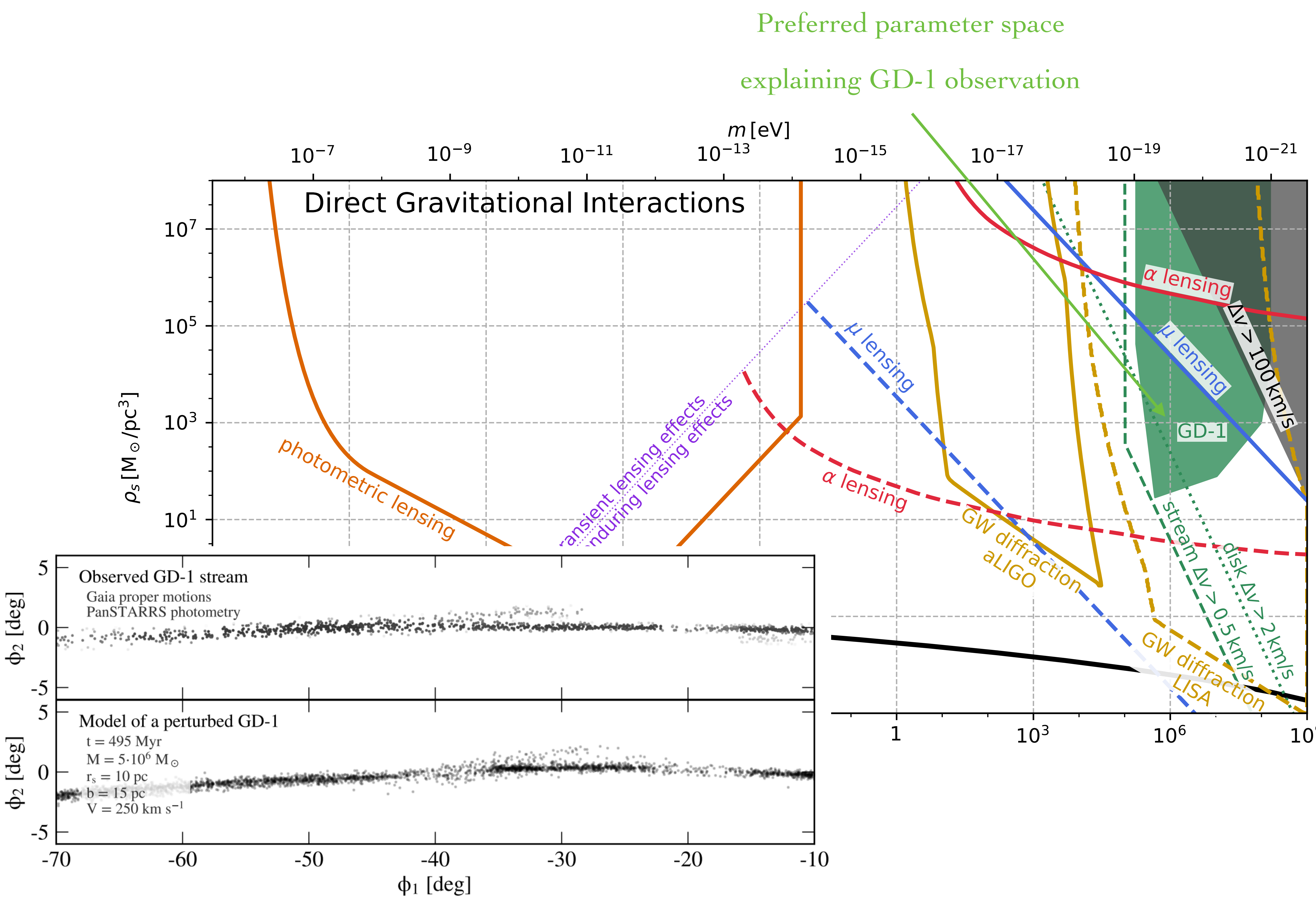
Direct Gravitational Signatures

Velocity “kicks” on stars

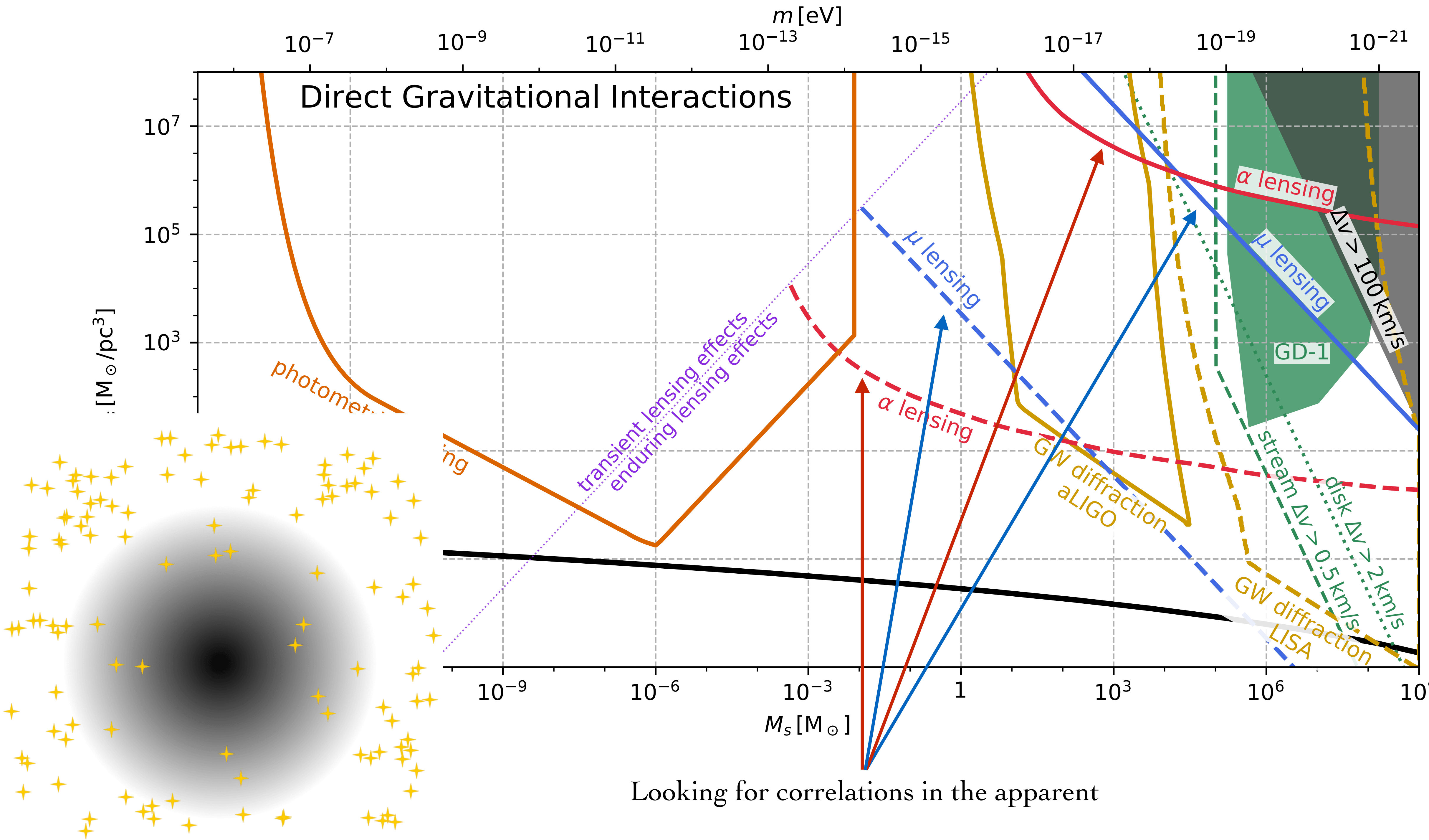
in the path of the DM compact halo



Direct Gravitational Signatures



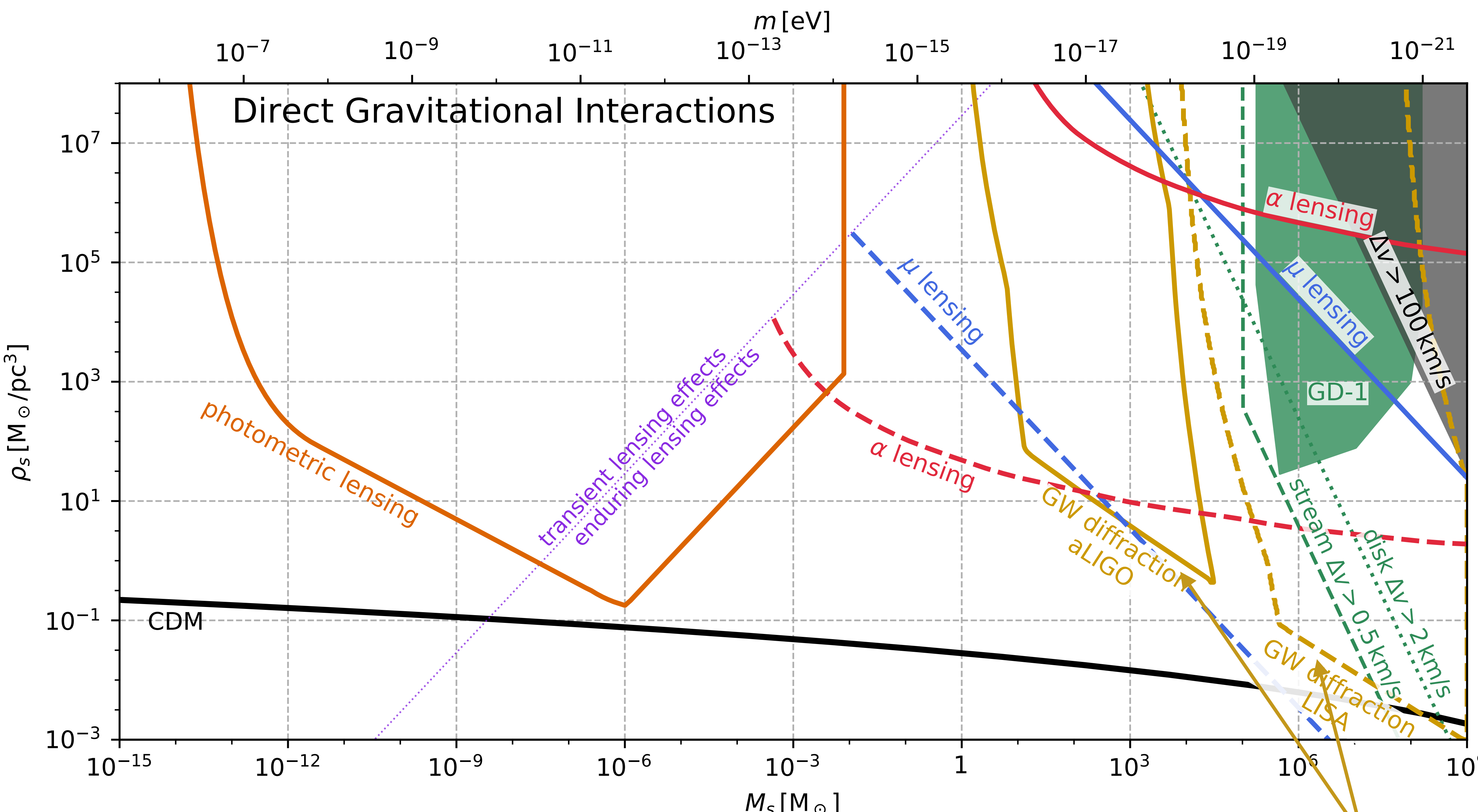
Direct Gravitational Signatures



Looking for correlations in the apparent

velocities and accelerations of stars in GAIA and THEIA

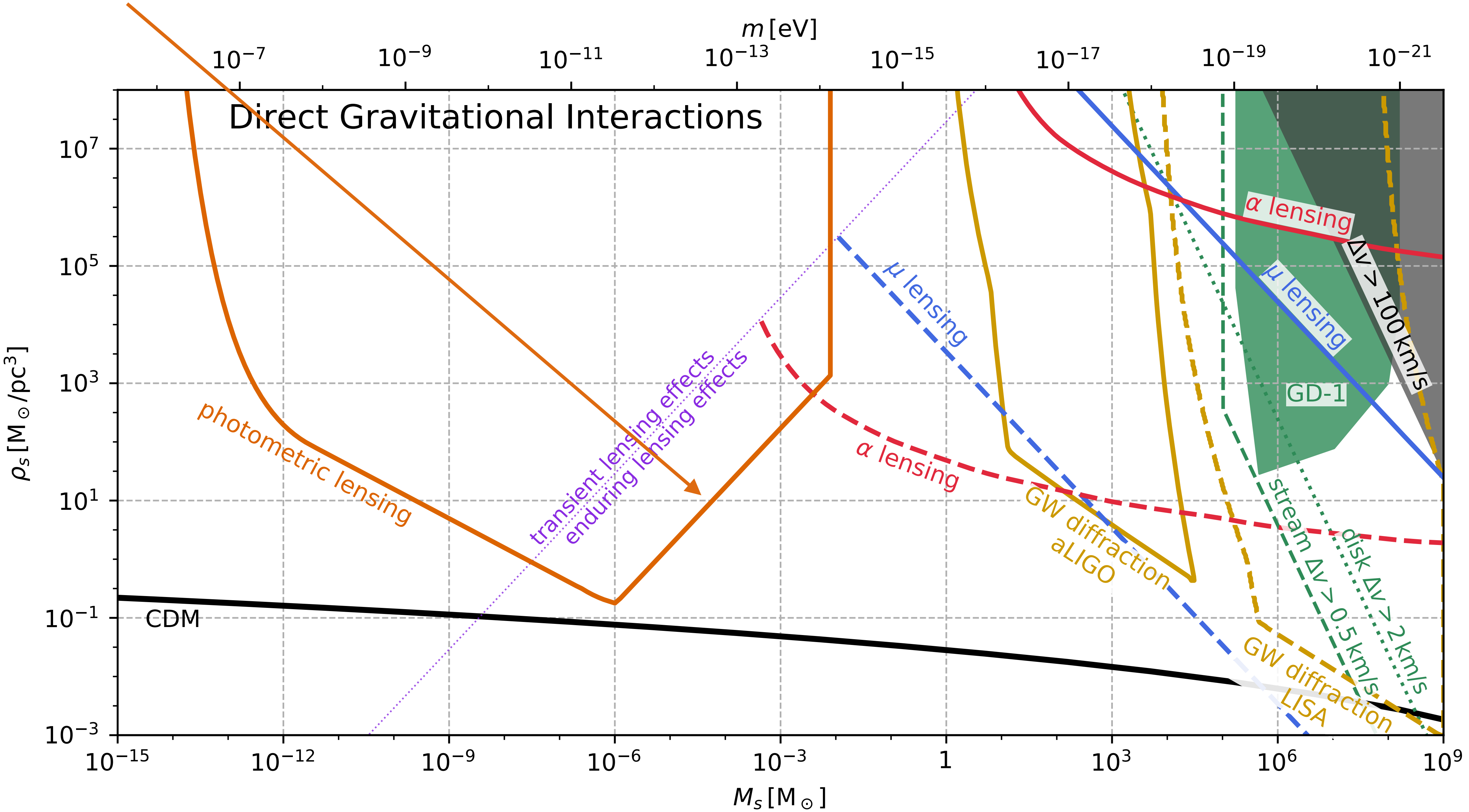
Direct Gravitational Signatures



Diffraction of GWs from mergers

Direct Gravitational Signatures

Modulations in rare high amplification of distant stars

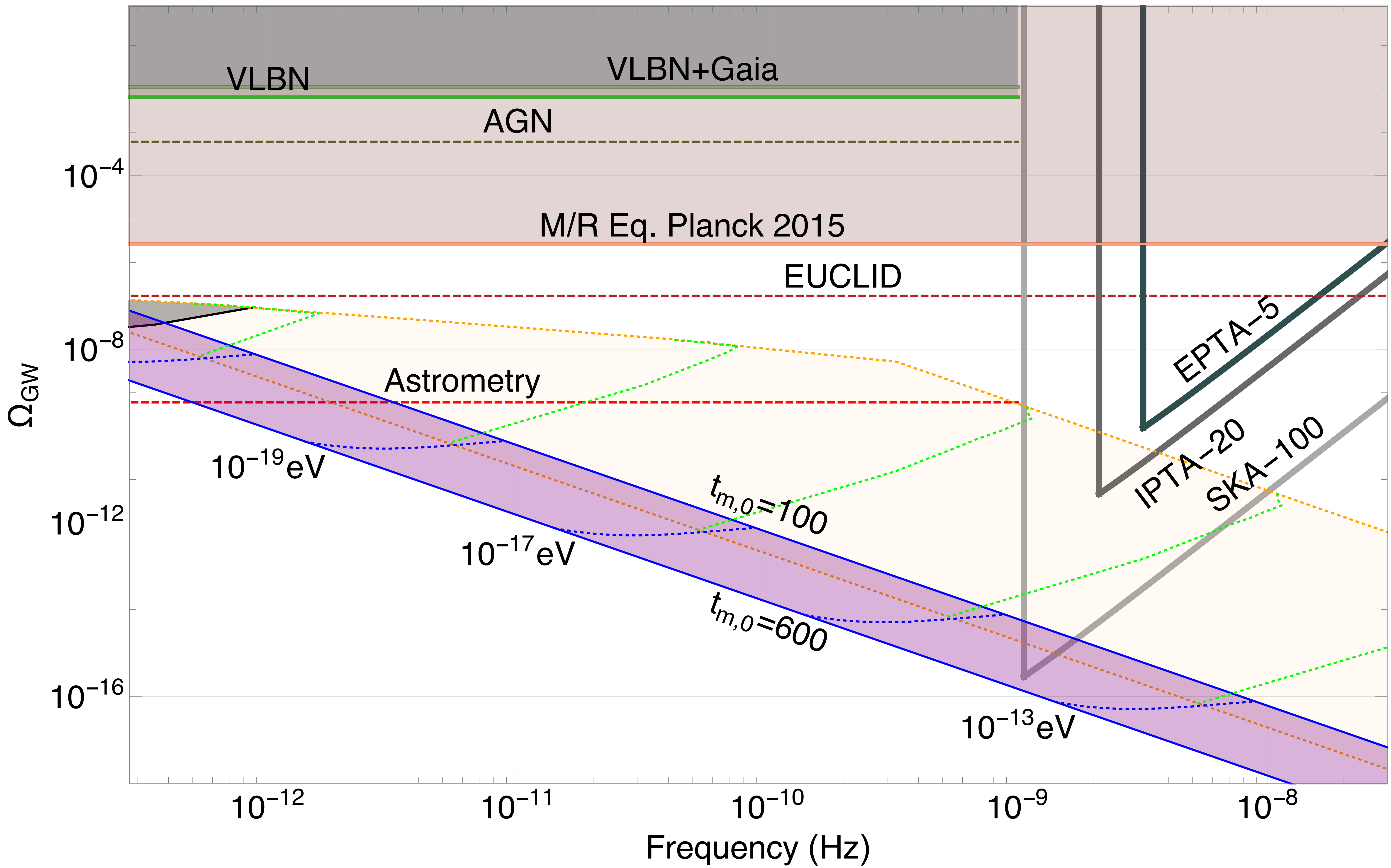


Gravitational Wave Emission

- Attractive self-interactions can overcome Hubble expansion long before matter radiation equality

- Dense structures collapsing can lead to gravitational wave production

Gravitational Wave Emission



Compact halos jumpstarting star formation

- Necessary (but not sufficient) requirements for star formation:
  - Gravitational pressure from Dark Matter needs to be bigger than kinetic pressure from baryons

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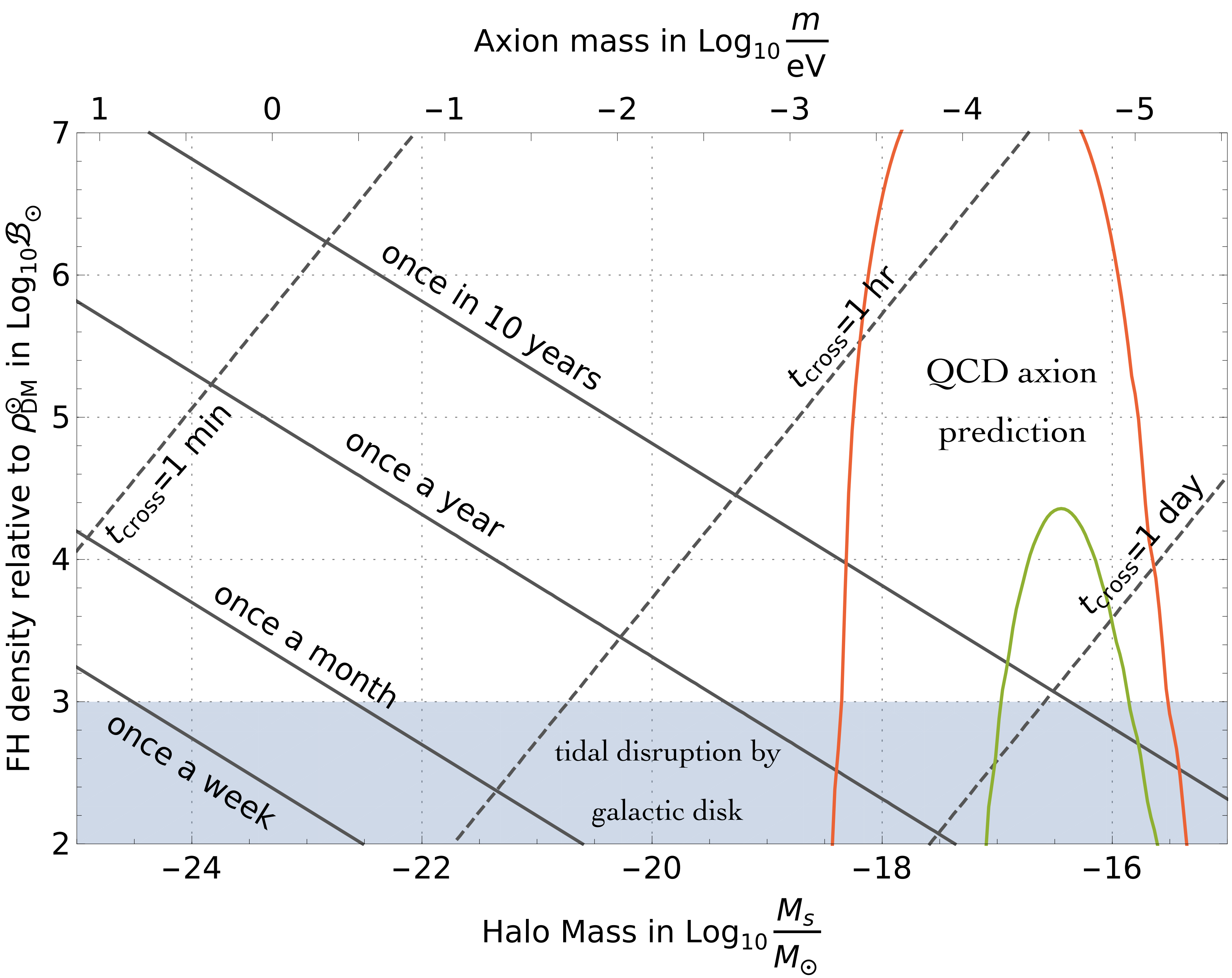
For pressure-less cold dark matter no stars in halos less than ~ 10^8 M_{solar}

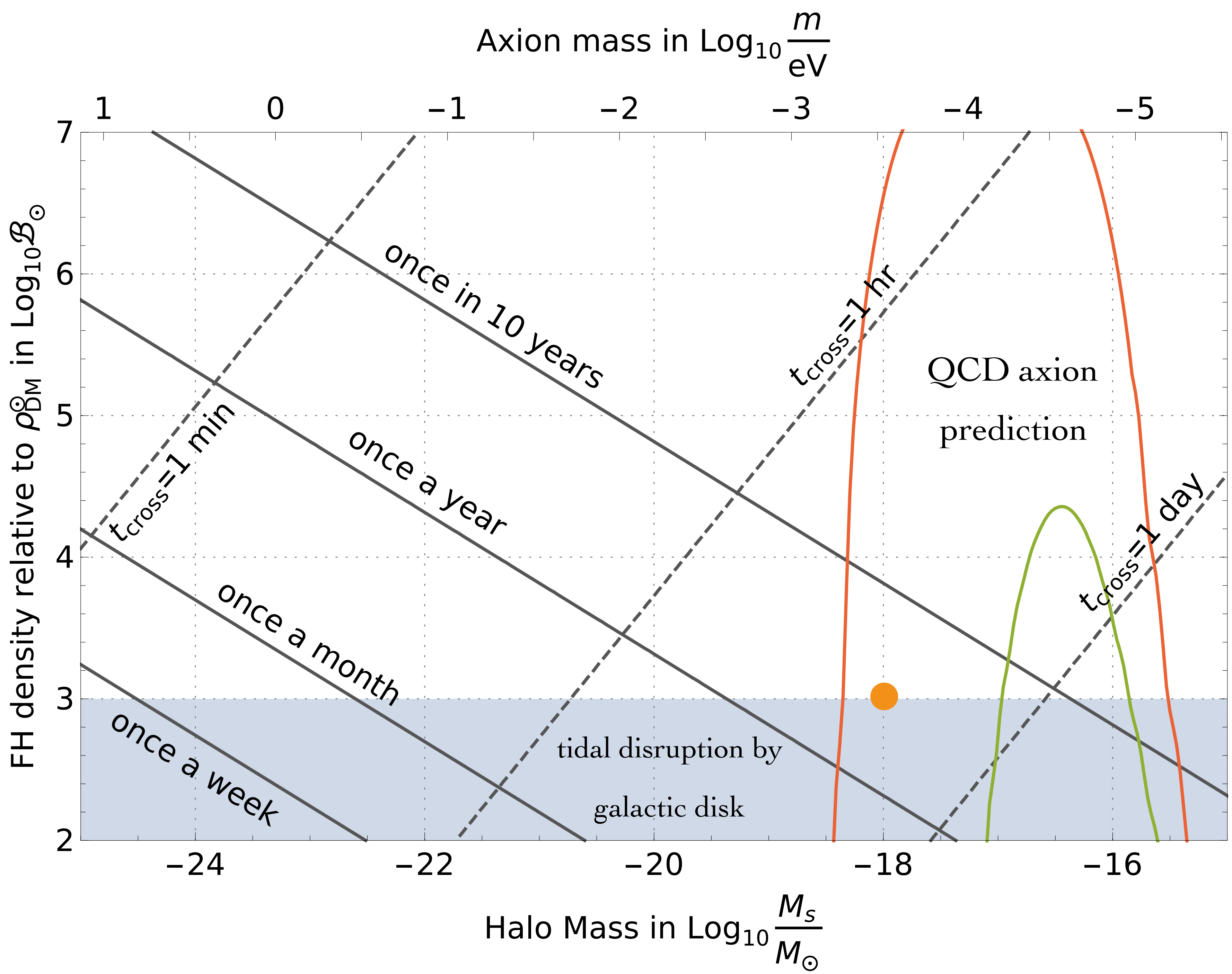
In our case, star forming halos as small as ~ 10^5 M_{solar}

Could also jumpstart black hole formation

Effects on Earth-bound Experiments

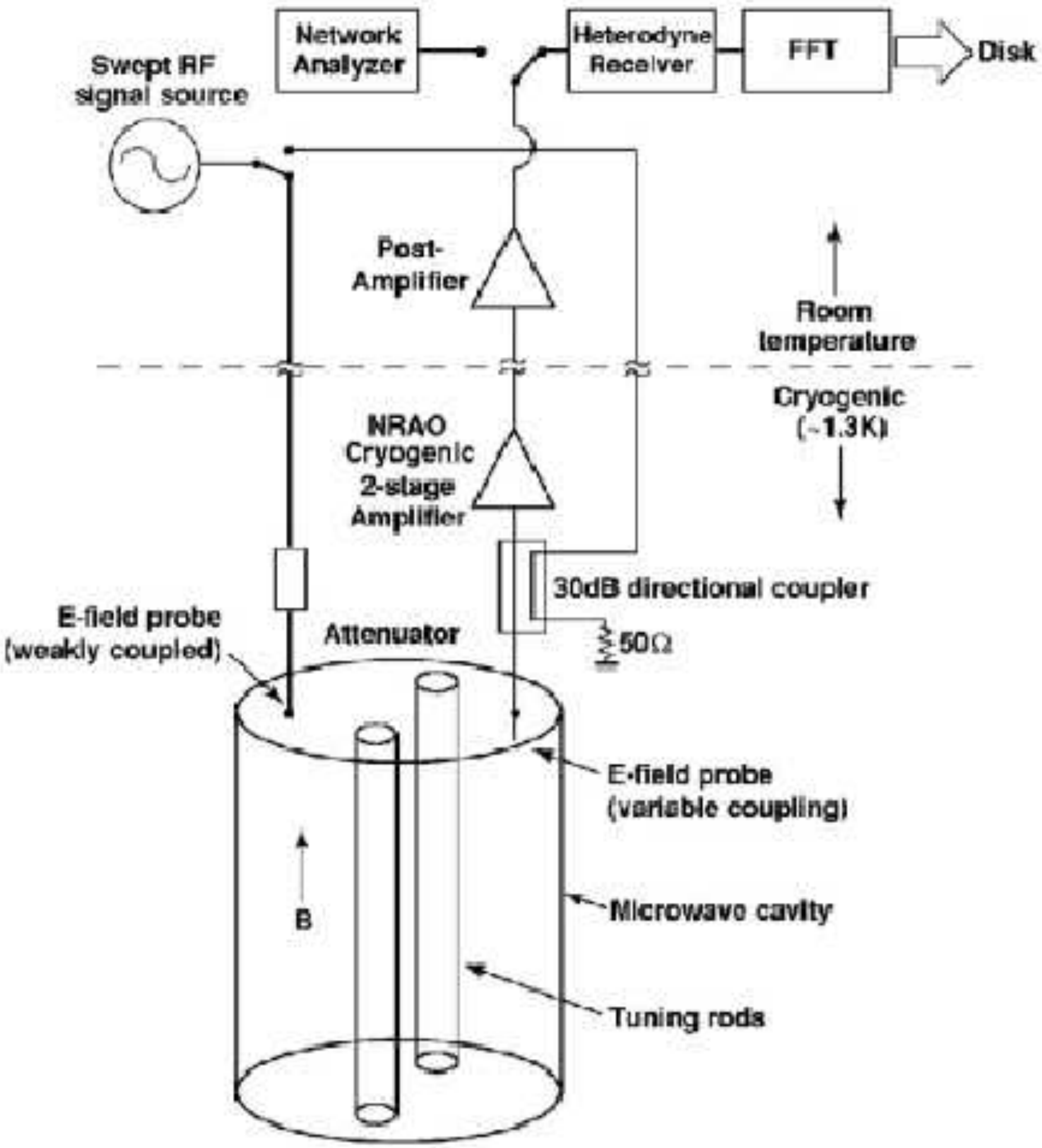


Effects on Earth-bound Experiments

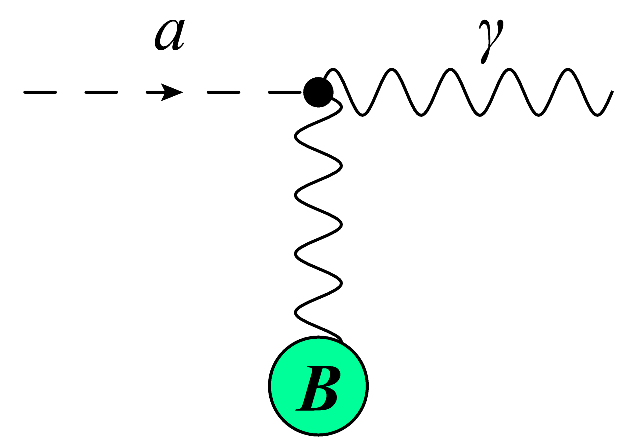


Let's examine the case of a 10^{-18} solar mass halo
that is 1000 times more dense than CDM

Resonant Axion Searches



ADMX



$$g_{a\gamma\gamma} a(x) \vec{E} \cdot \vec{B}$$

Harmonic oscillator analog:

Axion Dark Matter $\rightarrow$ Driving Force
Cavity Mode $\rightarrow$ Displacement
Cavity Size $\rightarrow$ Resonant Frequency
DM coherence $\rightarrow$ Q Factor (~ 10^6)

Effects on Earth-bound experiments

Ex. 10^{-18} solar mass halo
1000 times more dense than CDM

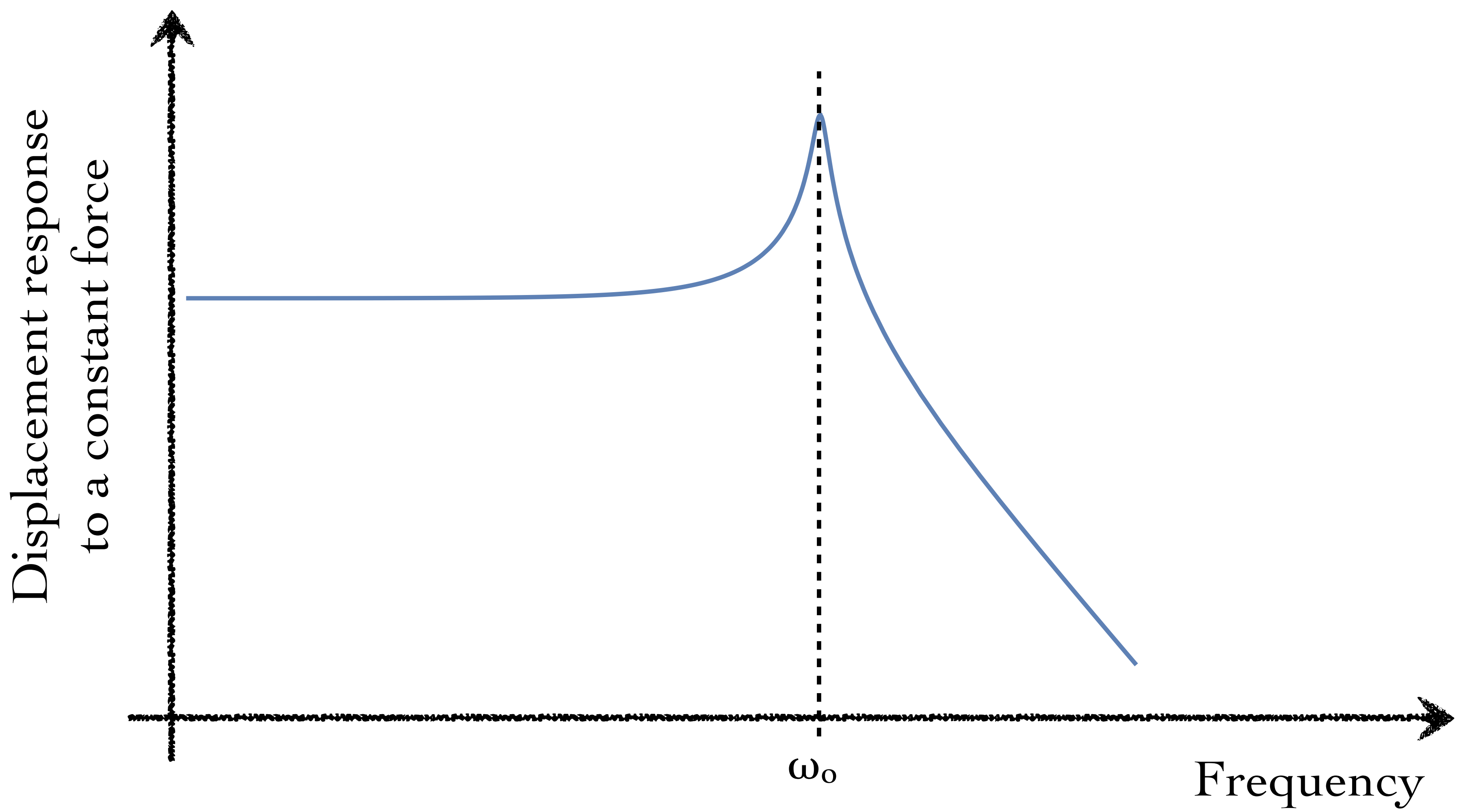
- Every ~3 years, power goes up by the over-density factor for approximately 6 hours

- Effective DM Q factor> 10^{11} vs 10^{6} for CDM

- Need to make sure experiment is running at the right frequency
  Favors broadband approach

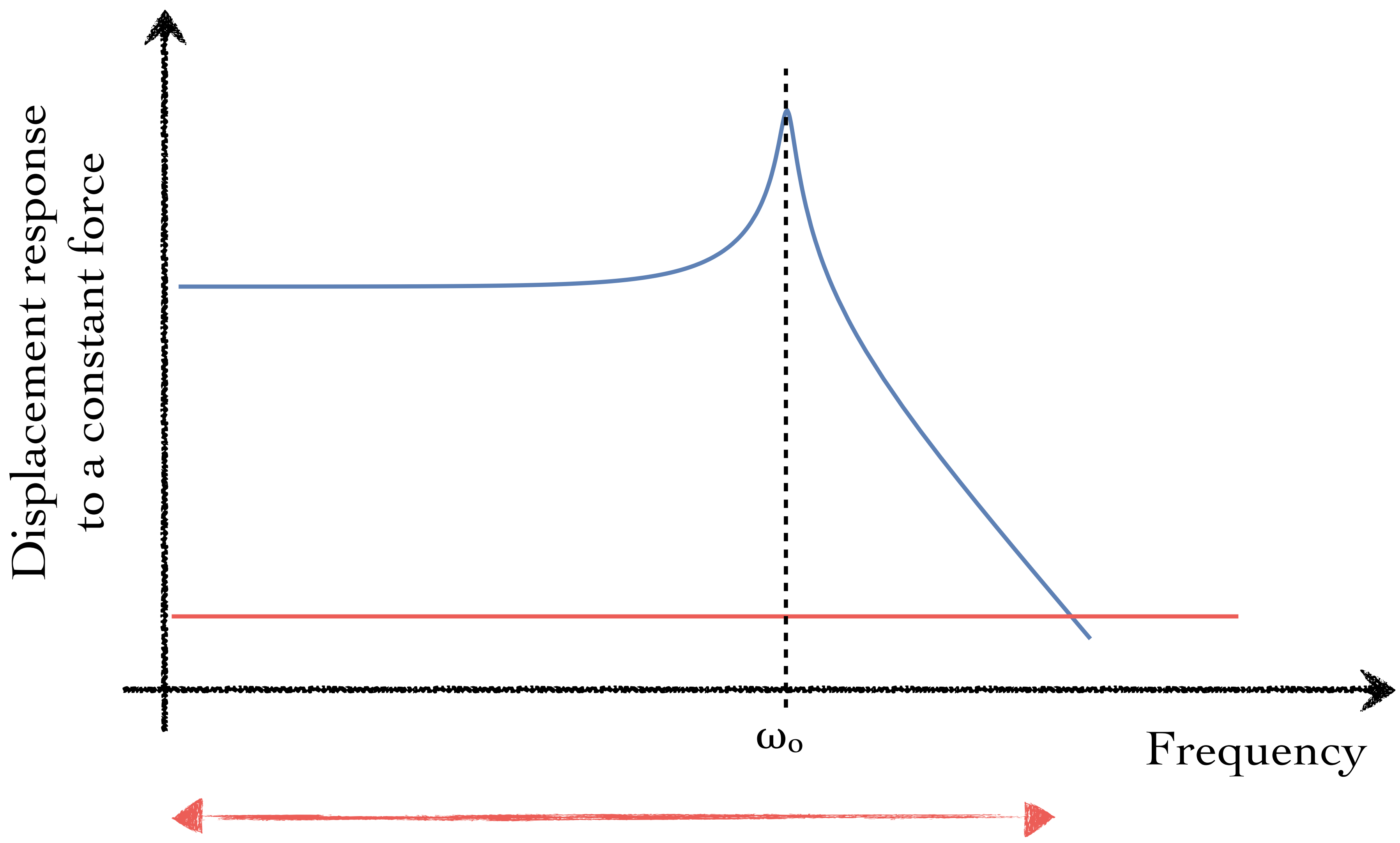
Can a resonant detector run in broadband mode?

For a harmonic oscillator



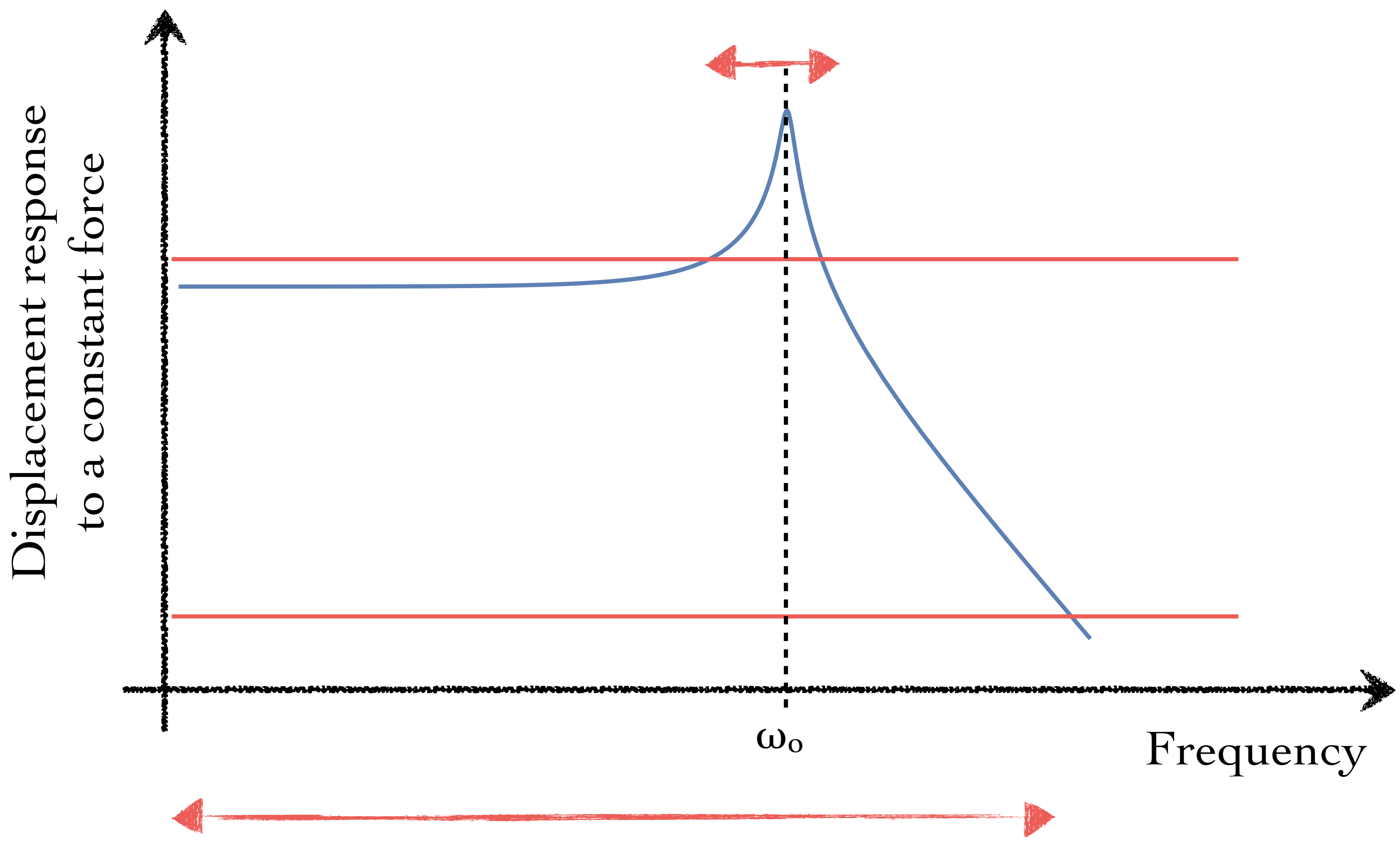
Can a resonant detector run in broadband mode?

For a harmonic oscillator



Can a resonant detector run in broadband mode?

For a harmonic oscillator



The bandwidth is determined by the detector sensitivity for displacement

Effects on Earth-bound DM Searches

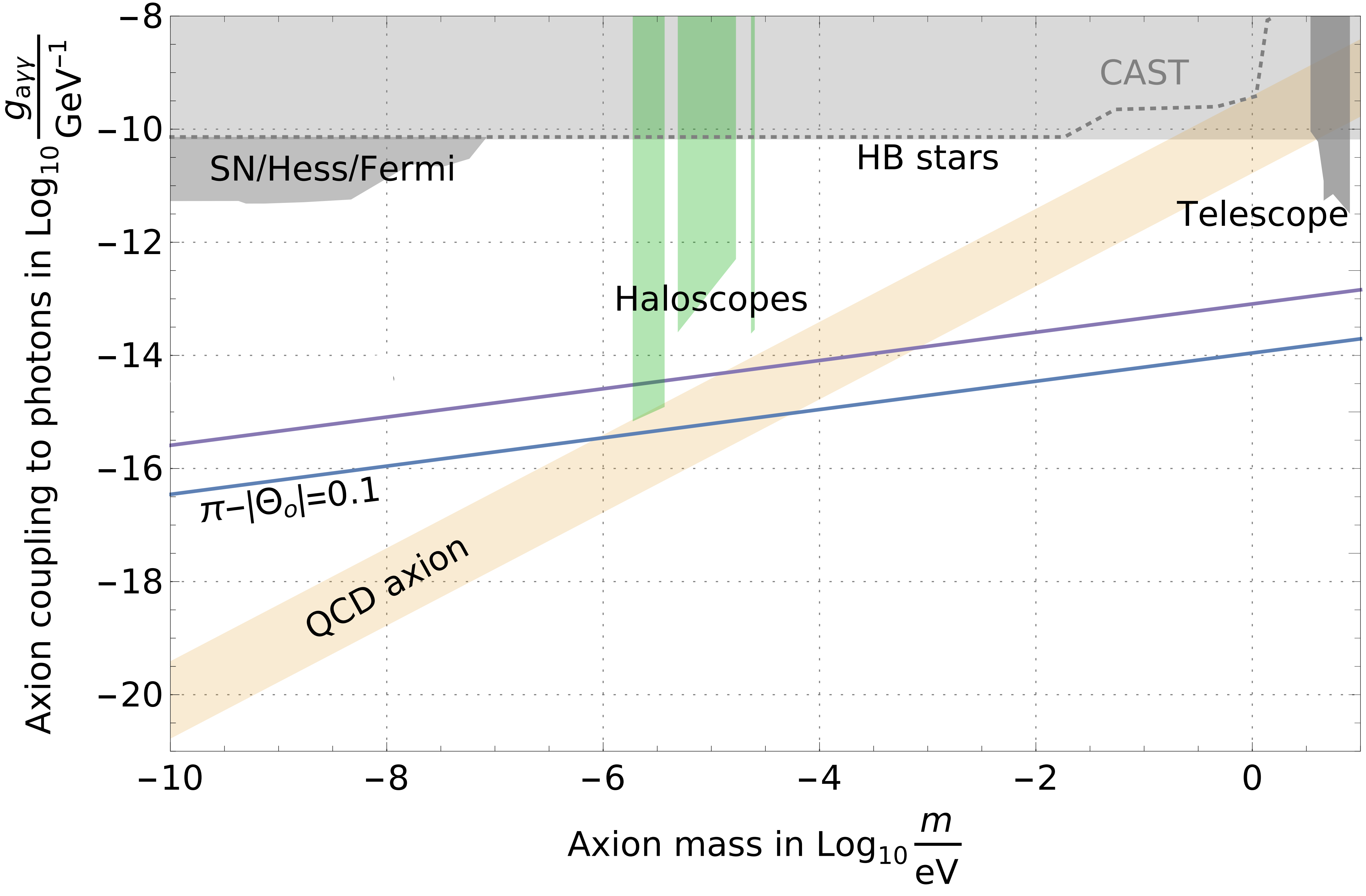
Ex. 10^{-18} solar mass halo

1000 times more dense than CDM

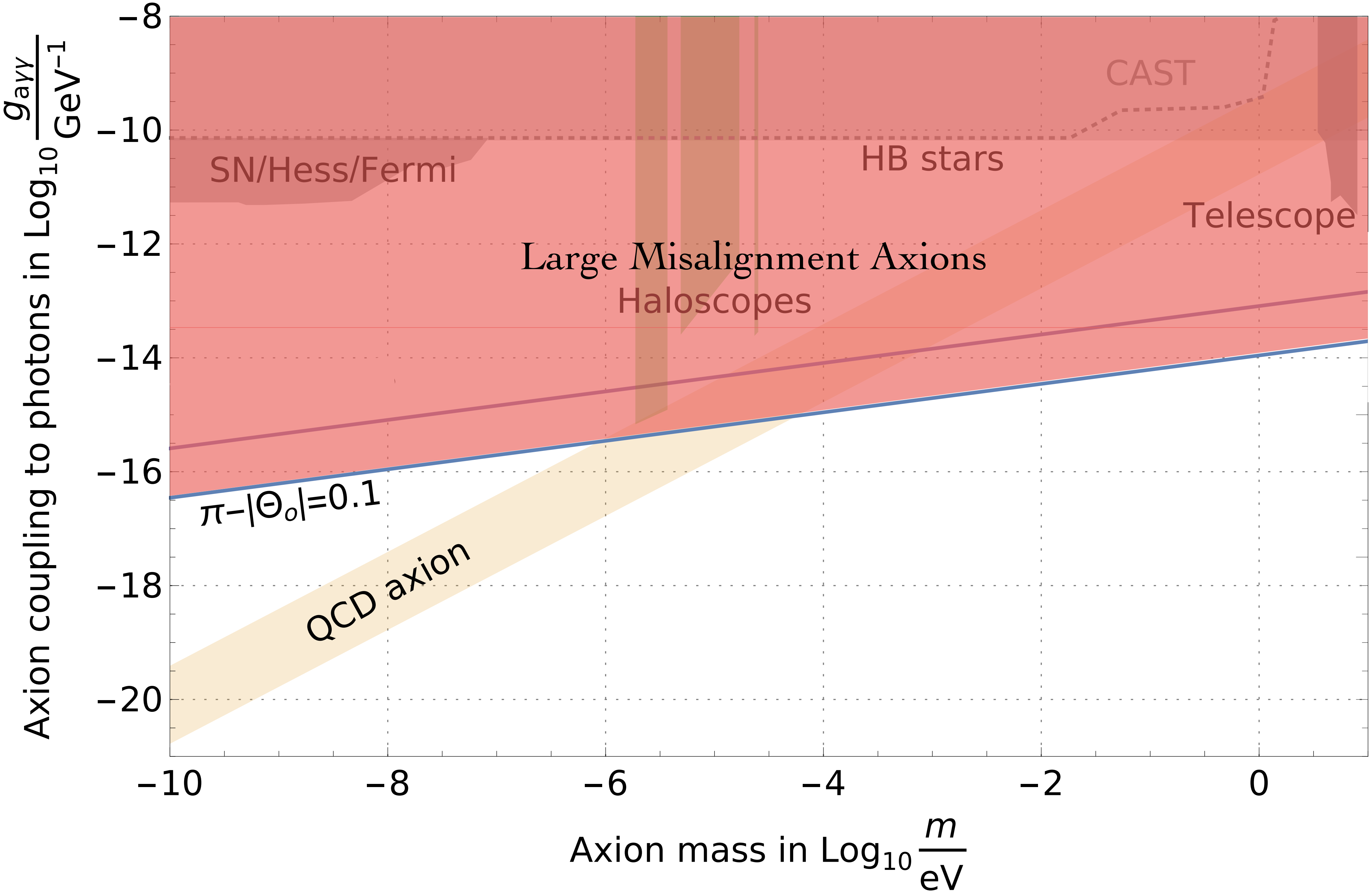
Search strategy in resonant axion searches

- Record data outside the resonance frequency
- Data taking time bins of 6 hours and look for excesses
- $Q_{\text{DM in clump}} \gg Q_{\text{DM-diffuse}}$

Effects on Earth-bound Experiments



Effects on Earth-bound Experiments

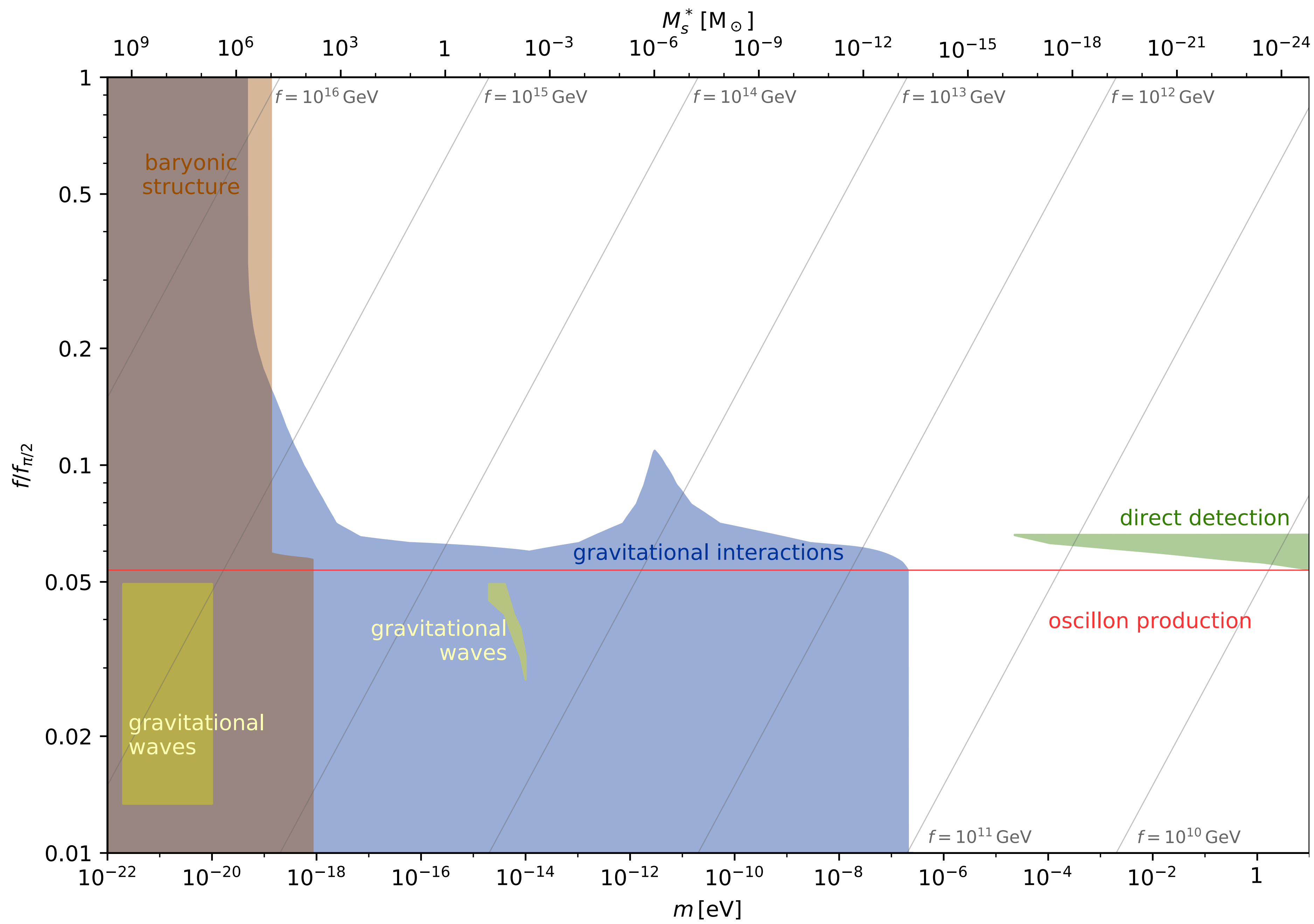


Need to reconsider existing bounds and search strategies

Open Questions

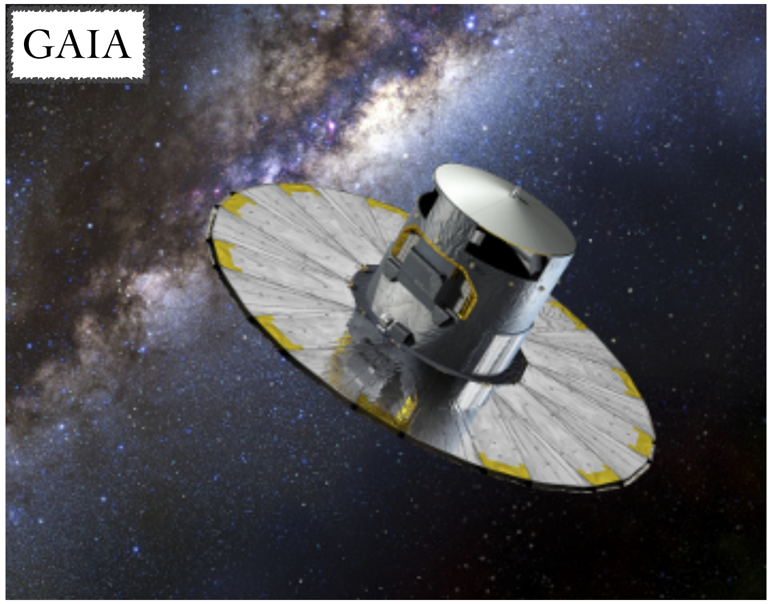
- How much can we really tell about star formation?
- Are there non gravitational probes of large DM halos?
- What fraction of DM is in these halos?
  What are the optimal strategies for laboratory DM searches?

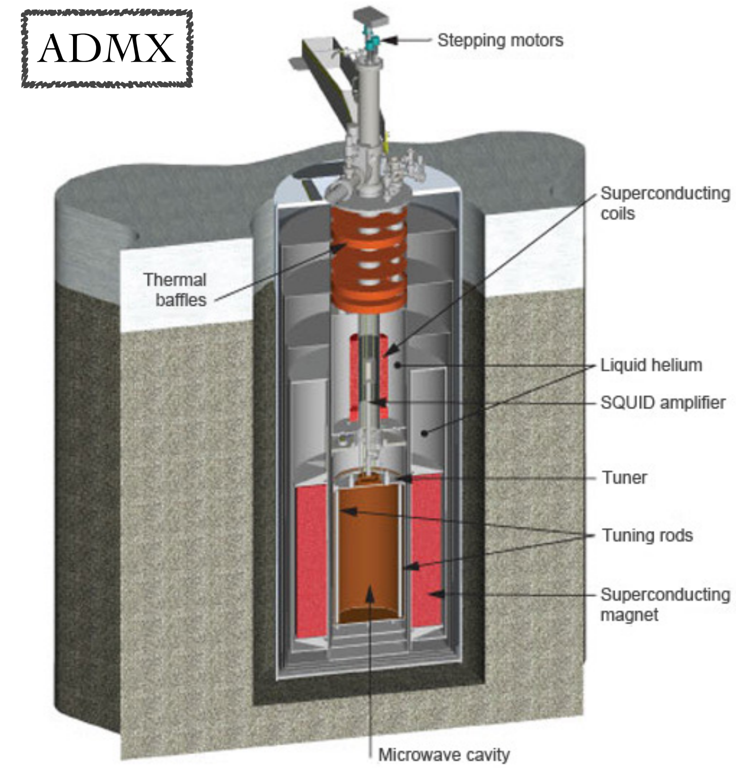
Signatures of the large misalignment mechanism

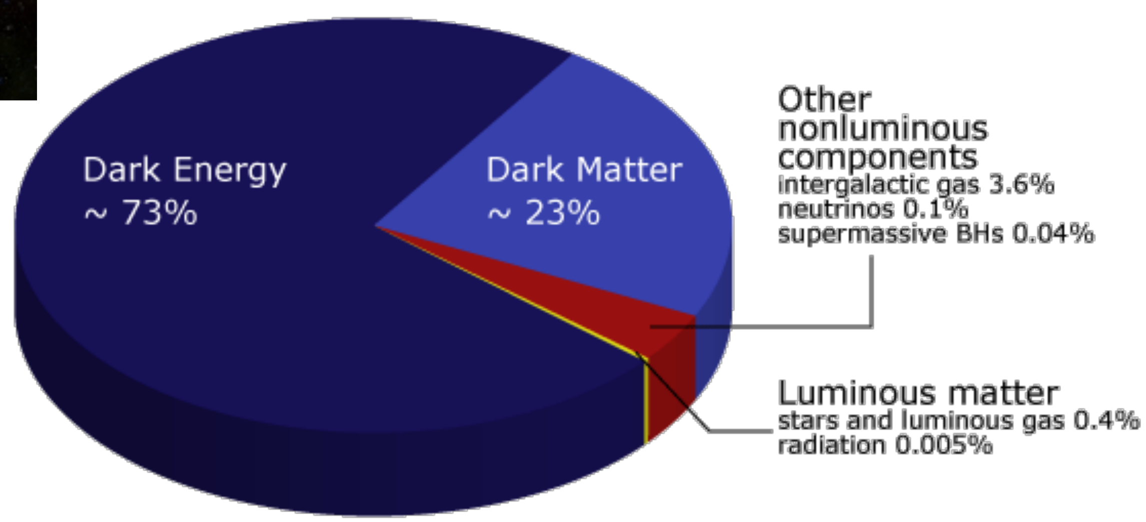


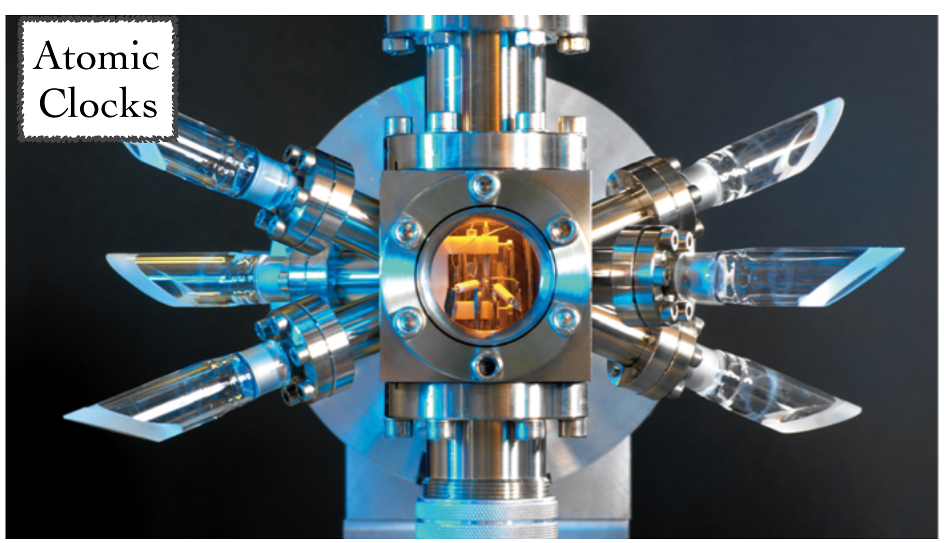
$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))$$

Shining Light on Dark Matter

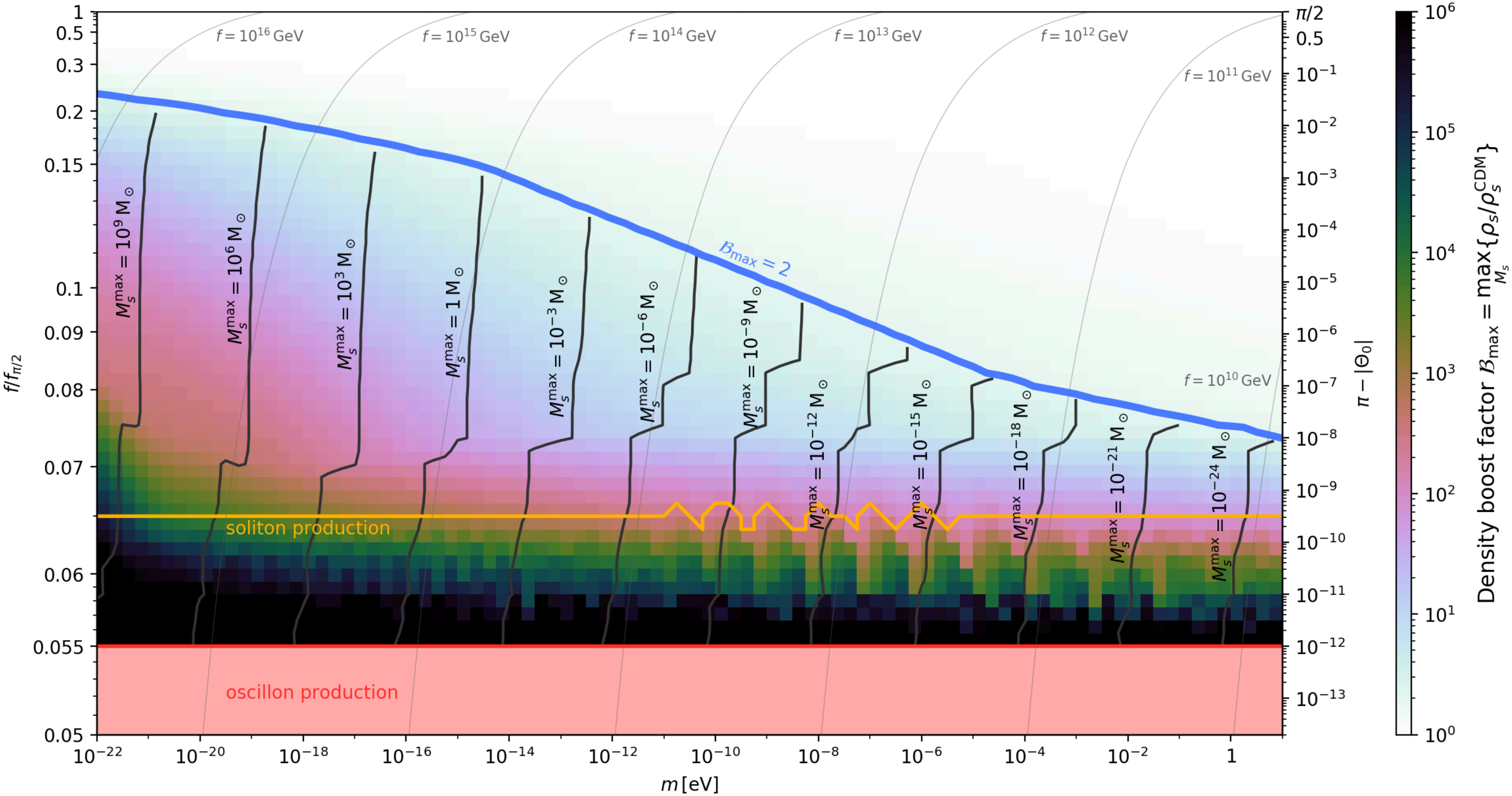




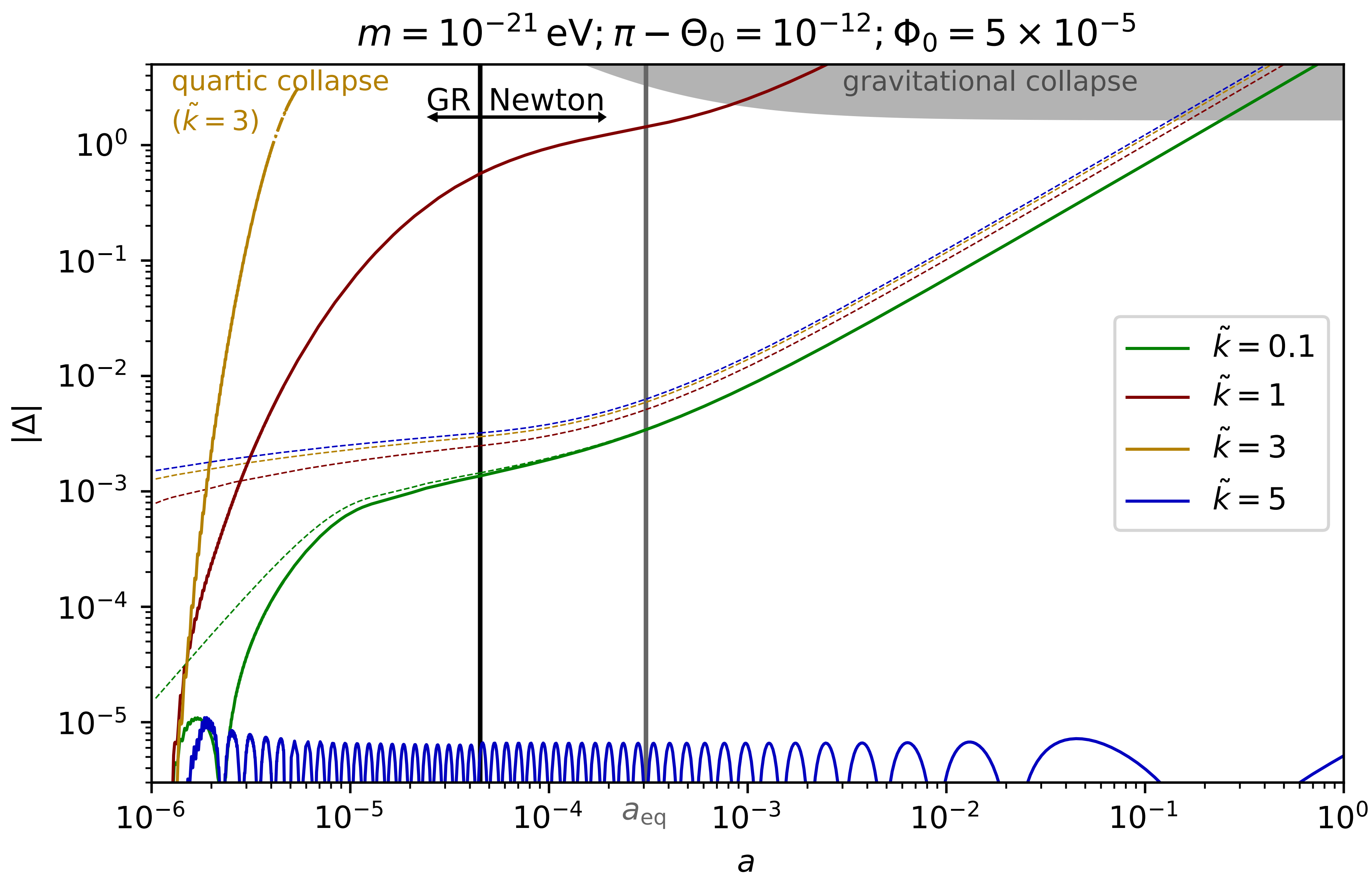




Delayed Onset of Oscillation

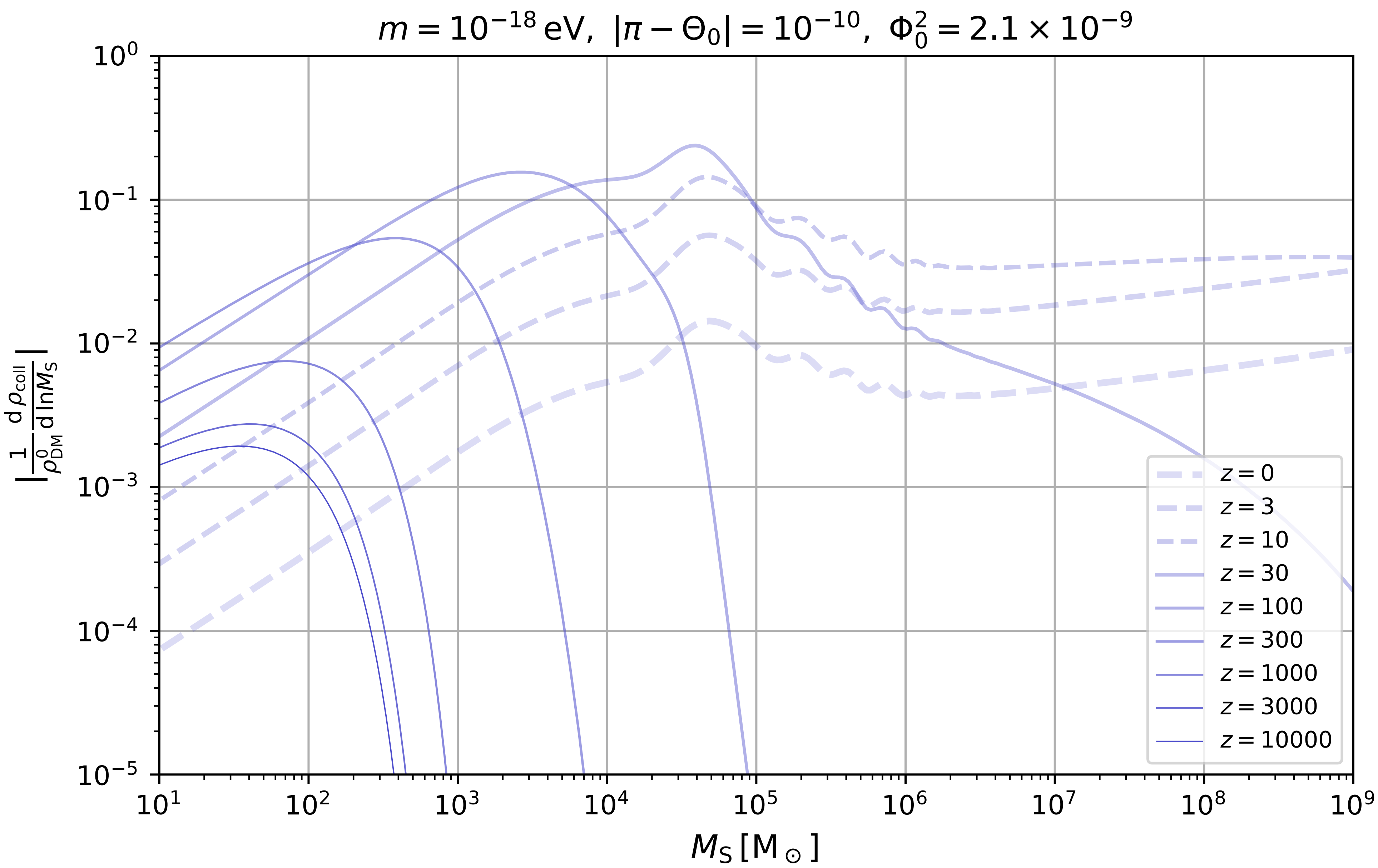


Growth of density perturbations as a function of scale and time



Initial conditions: scale invariant spectrum

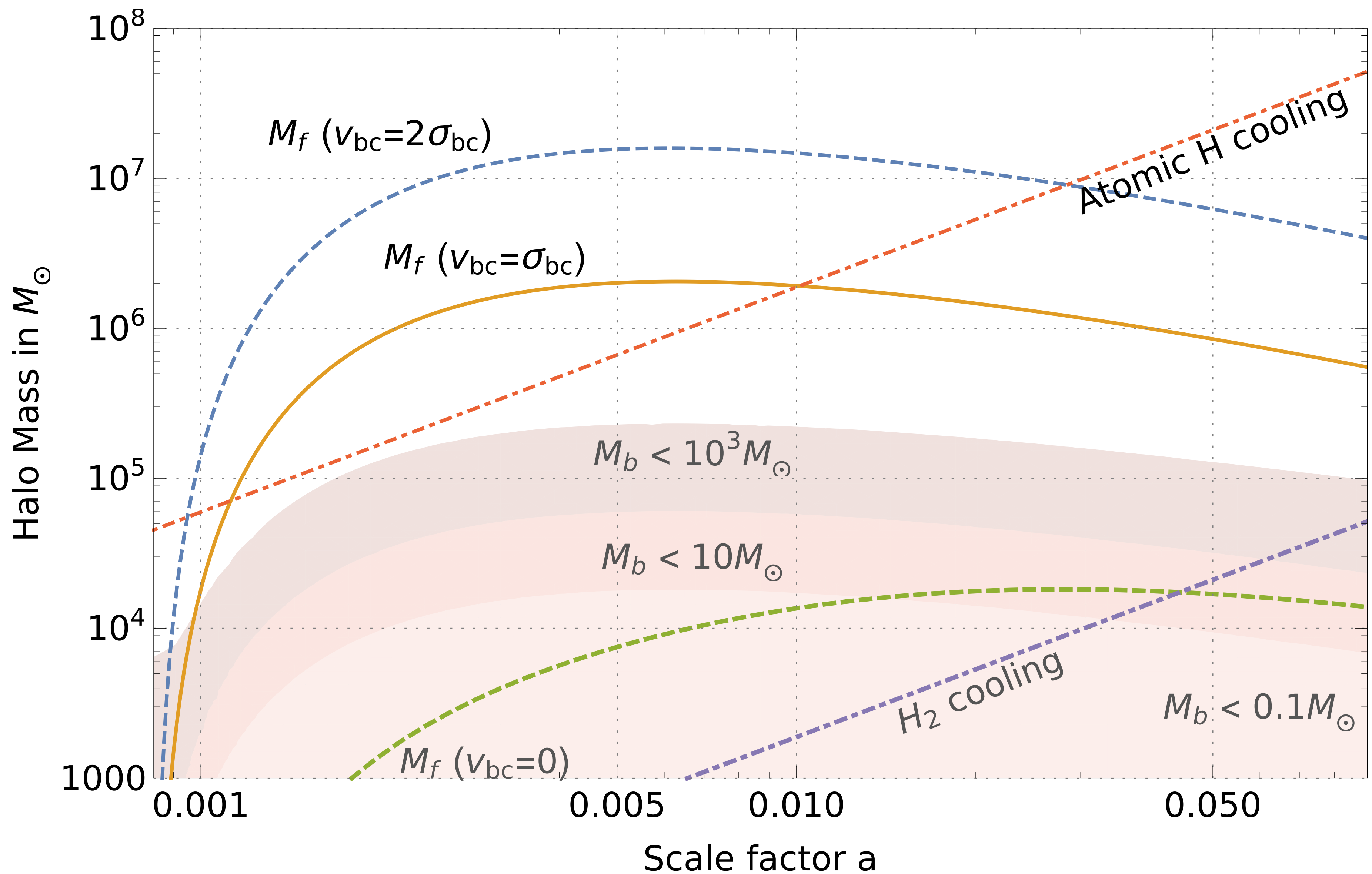
Press-Schechter



Compact DM Halos jumpstart star formation

Successful star forming halos need to have:

1. enough baryons
2. the ability to cool the baryons



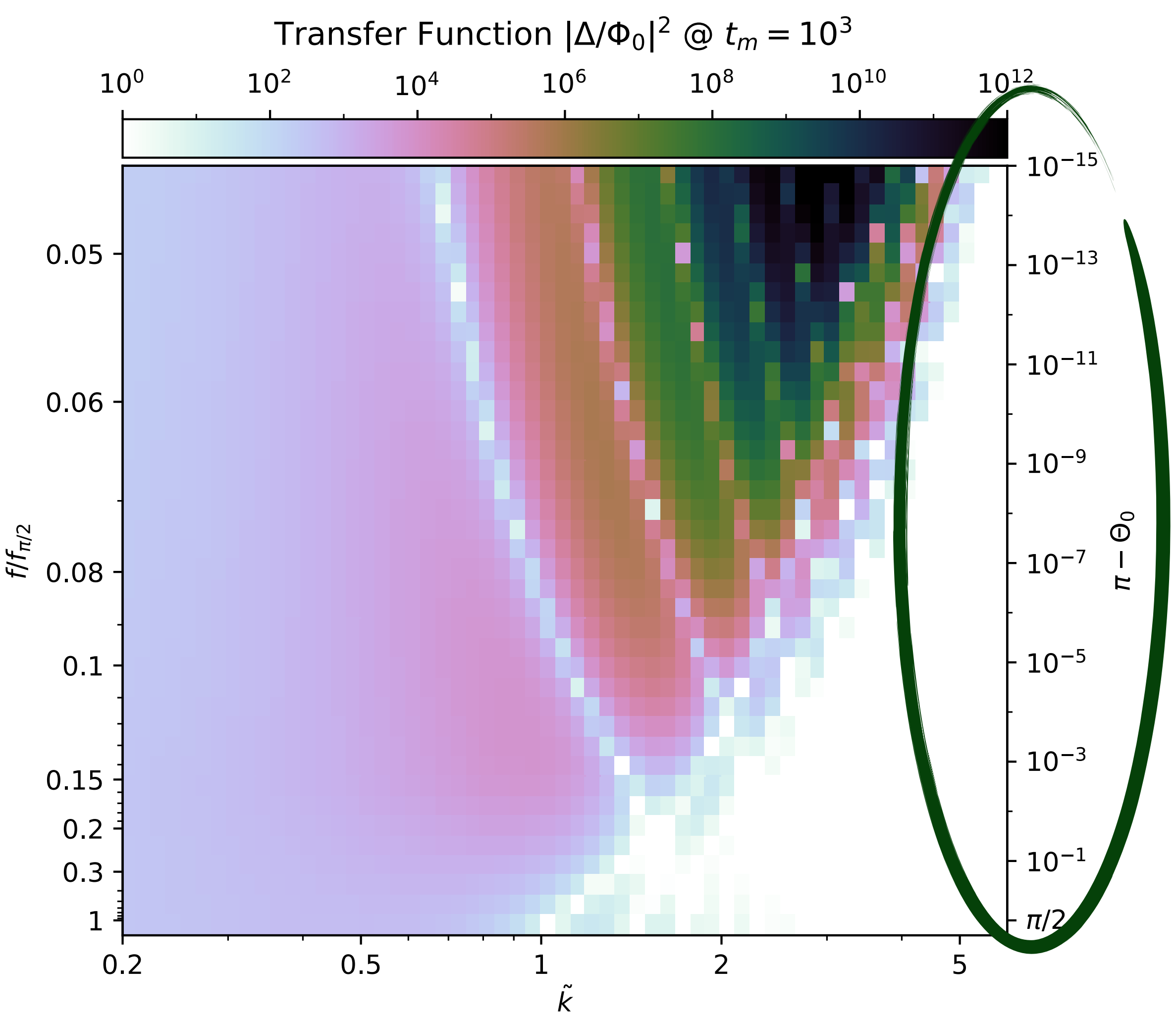
Minimum halo size that forms stars can be as smaller than 10^8 solar masses

What about tuning?

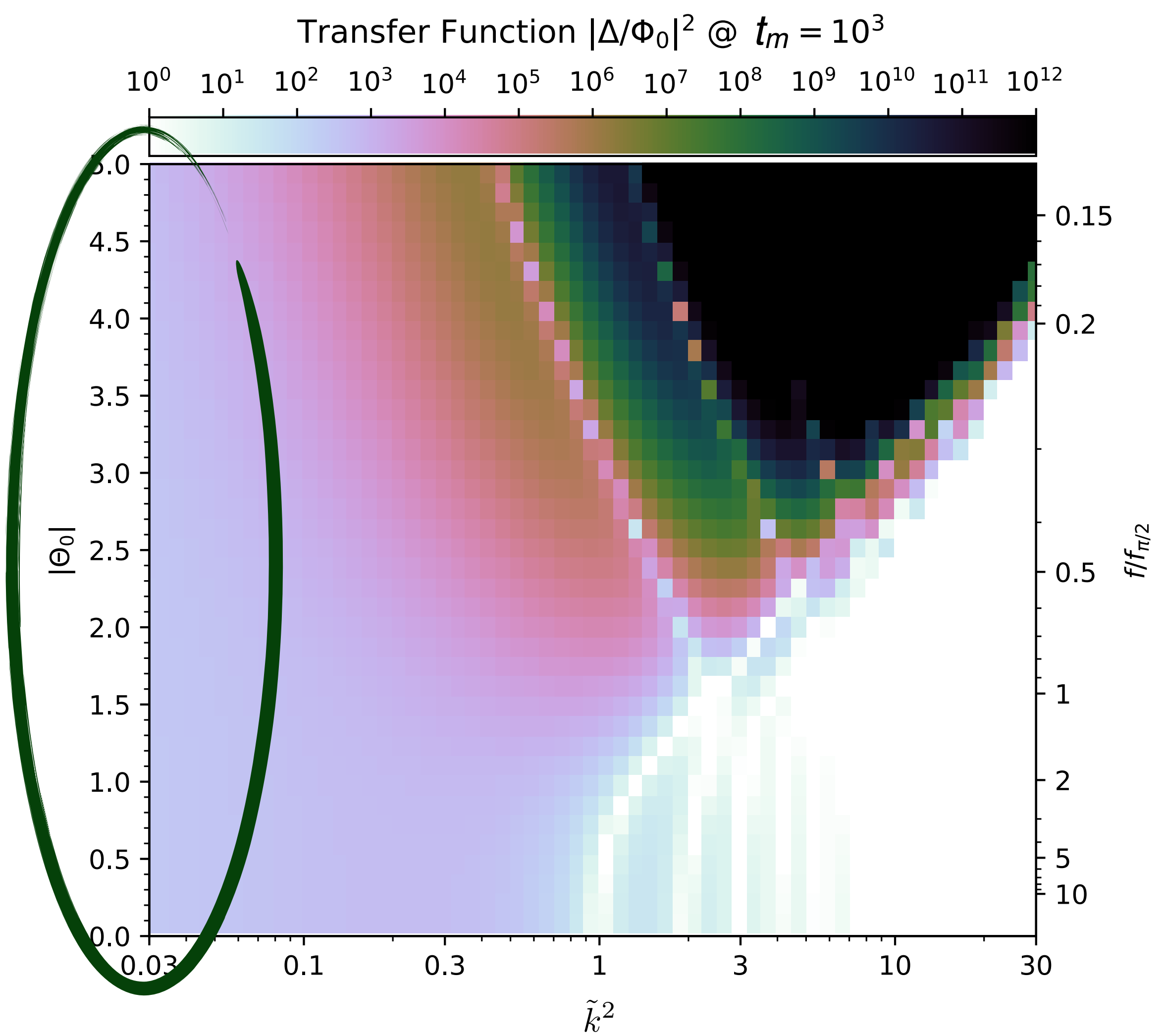
- Dynamics fixing $\Theta=\pi$ during inflation
- Environmental selection just like the case of the QCD axion outside the traditional axion window
- For string axions, a cosine potential is not the only option

What about tuning?

An example of "untuned" axion potential



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



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

Outline

- Dynamics of the large misalignment mechanism
- Signatures of the large misalignment mechanism
- The QCD axion
- Comments and future prospects

The QCD axion

Temperature dependent mass

$$V(\phi, T) = m^2(T) f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

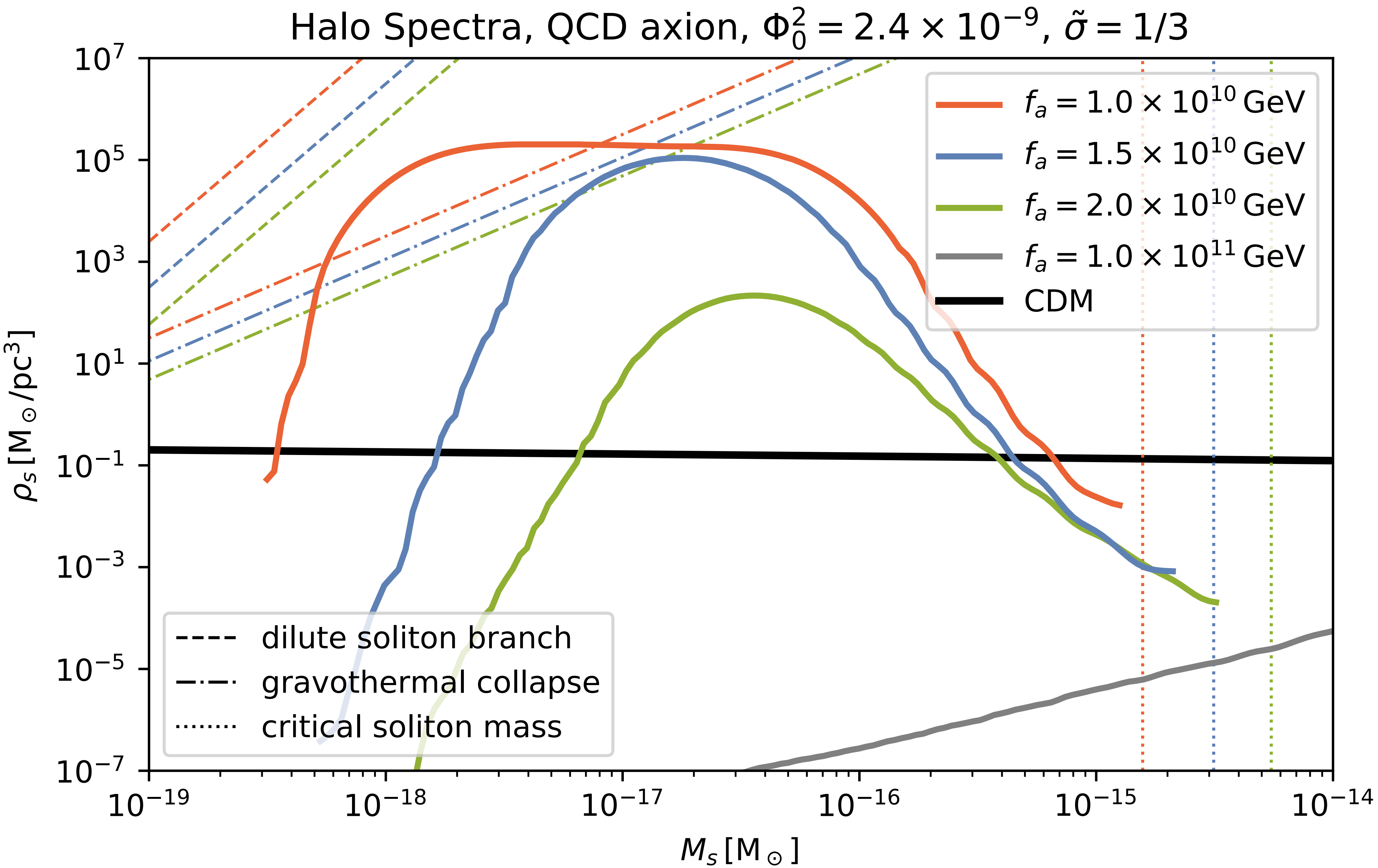
with

$$\begin{aligned} m(T)^2 &\equiv \chi_{QCD}(T)\; m(T=0)^2 \\ &\propto T^{-8.16}, \qquad T > 1\ \mathrm{GeV} \end{aligned}$$

The QCD axion field starts oscillating when H<< m(T=0)

corresponding to $\tilde{k}$~0.1

The QCD axion: Density perturbation growth



Affects high-frequency QCD axion searches (m> 10^{-4} eV)

Outline

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