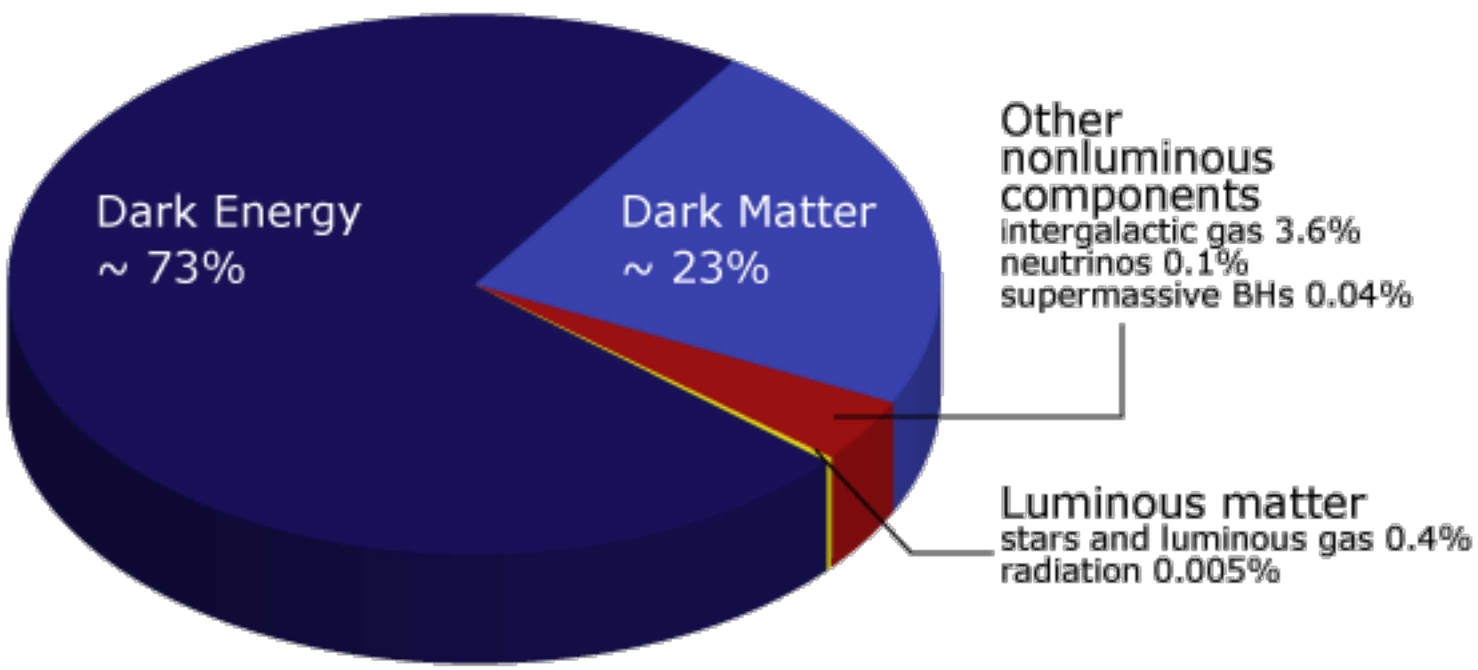
Dark Matter Halos from Parametric Resonance and their Signatures

Asimina Arvanitaki
Perimeter Institute

with S. Dimopoulos, M. Galanis, L. Lehner, J. Thompson, and K. Van Tilburg

The Mystery of Dark Matter

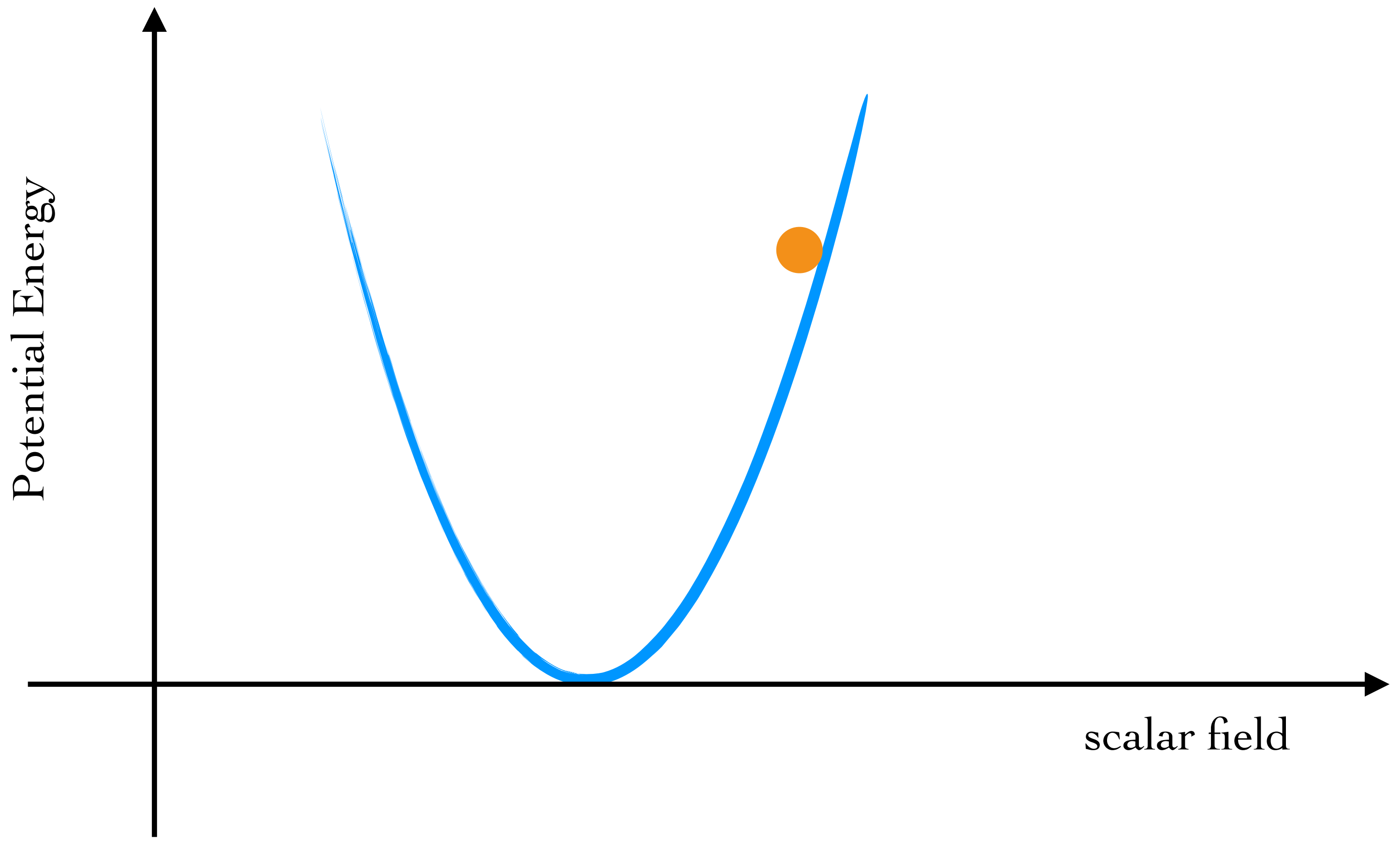


Light Scalar Dark Matter

- 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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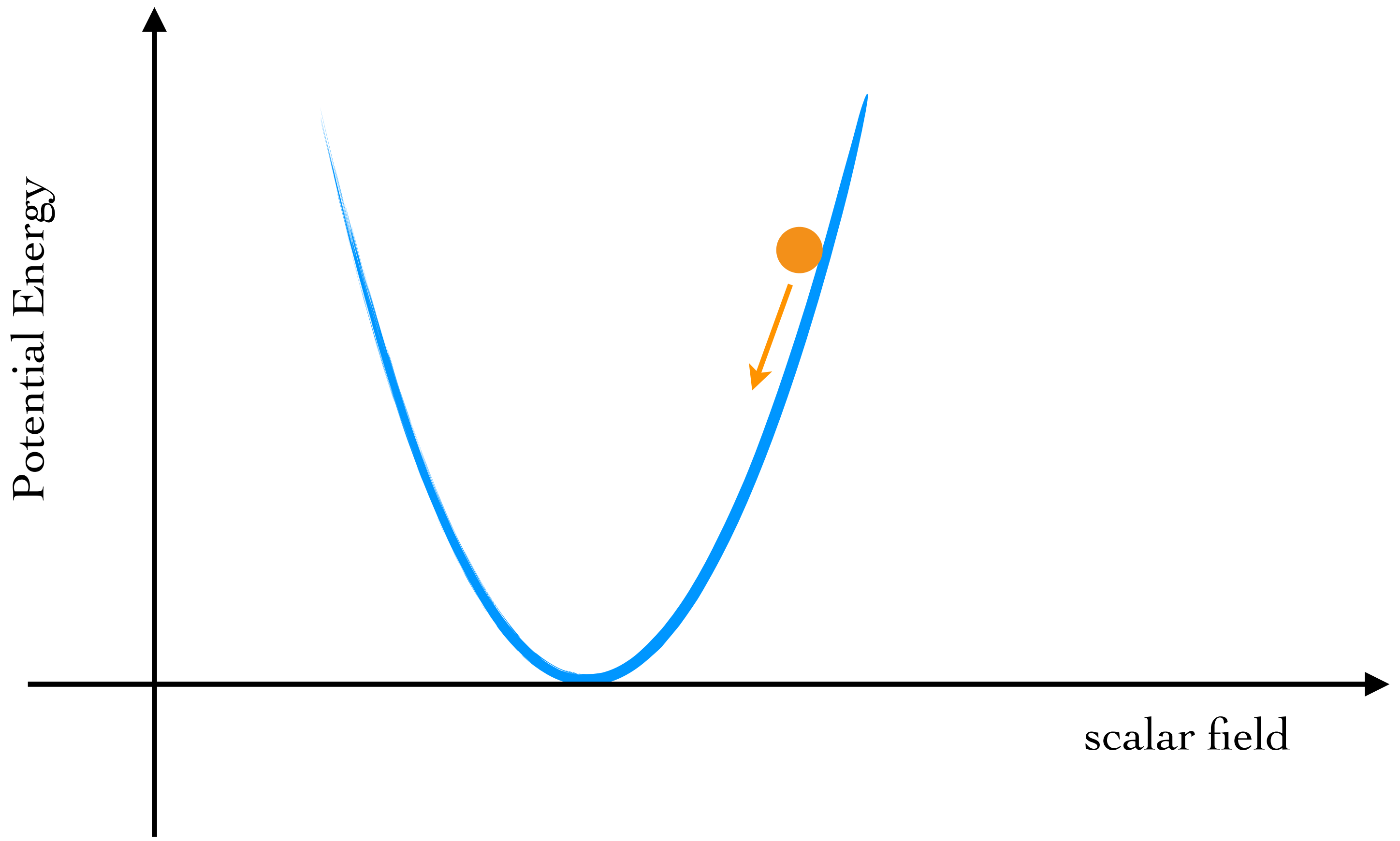


Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

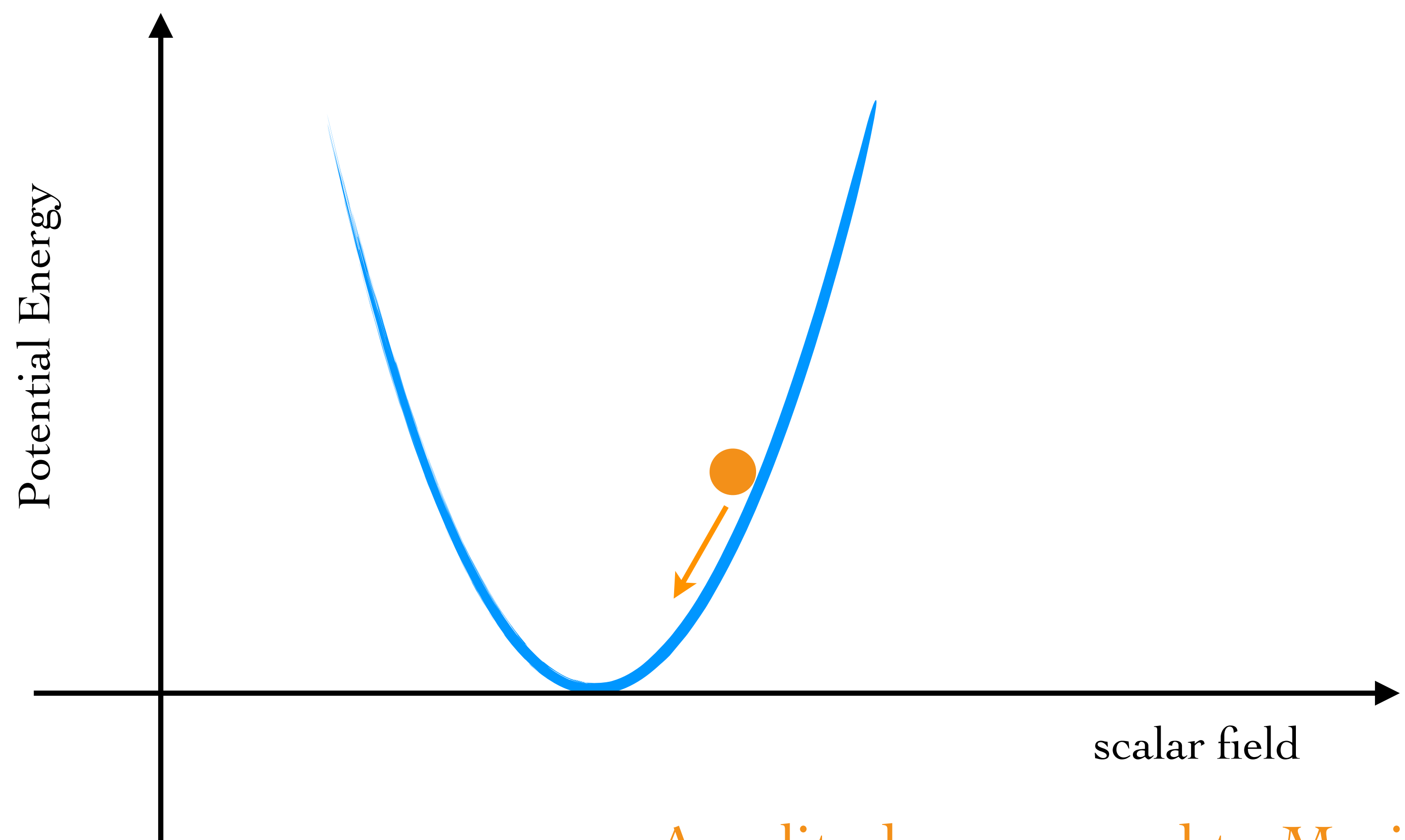
ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter Today

- If $m_\phi < 1$ eV, can still be thought of as a scalar field today



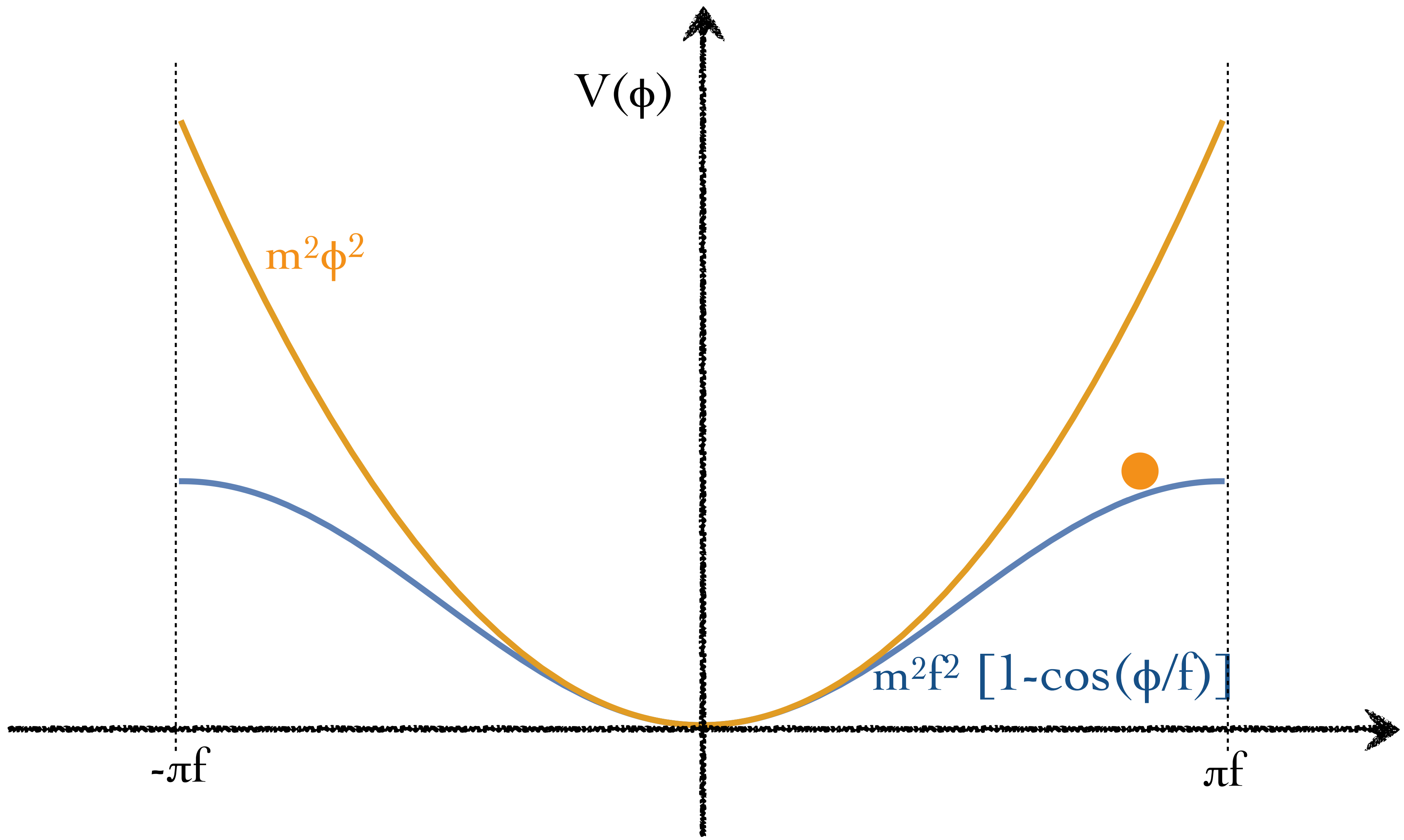
$m_\phi^{\ 2}\ \phi_o^{\ 2}\ \cos^2(m_\phi\ t) \sim \rho_\phi$

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:

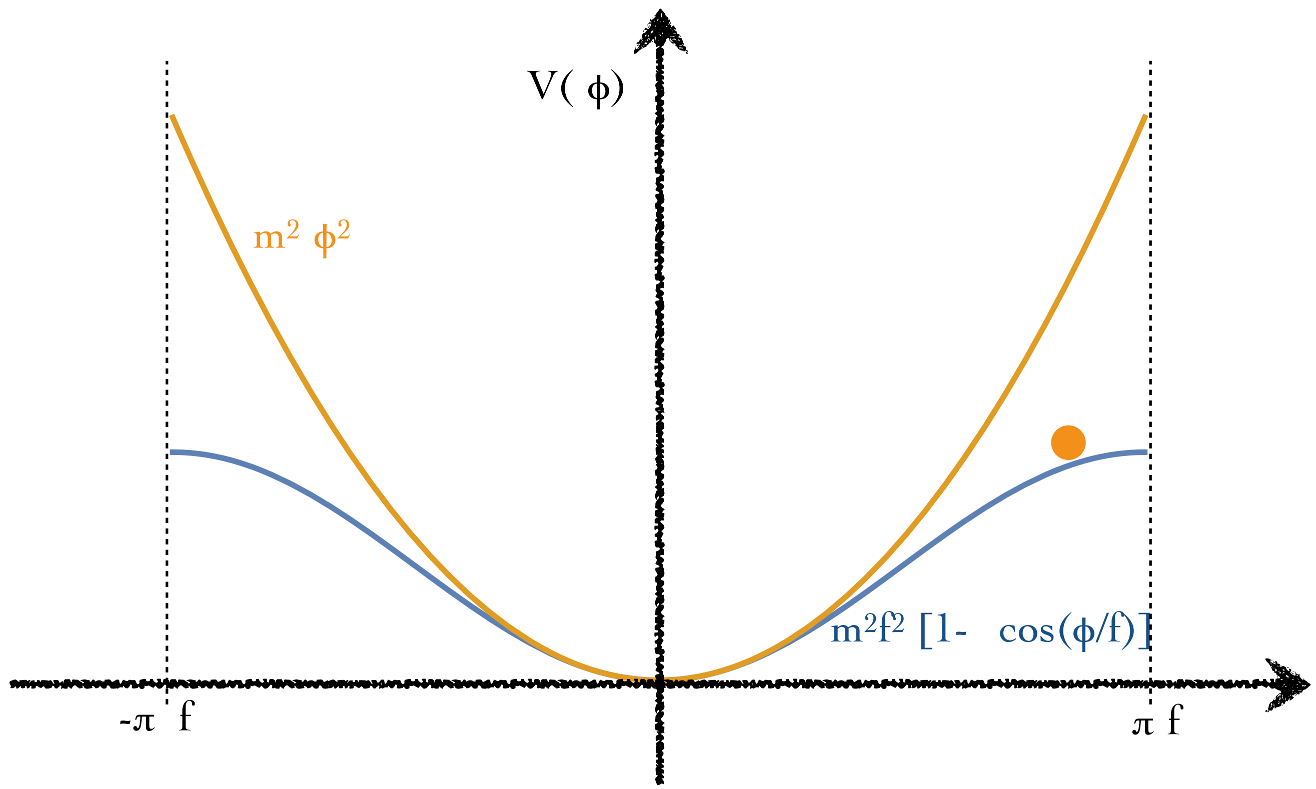
$$0.69\,\mathrm{Mpc}\sqrt{10^{-22}\,\mathrm{eV}/m}$$

or mass of:

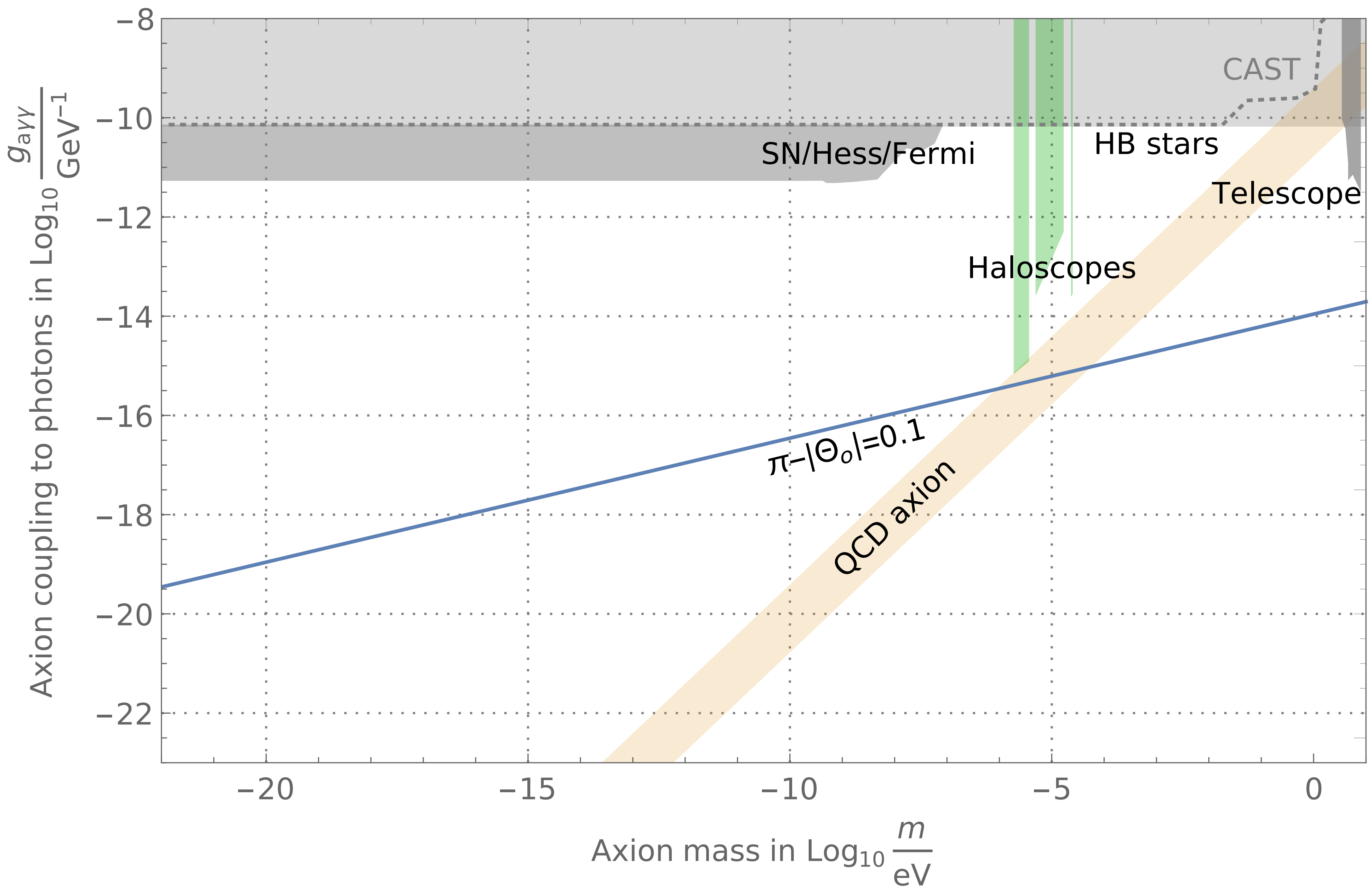
$$M_s^* = \frac{4\pi\rho^0_{\rm DM}}{3}\left(\frac{\lambda_*}{2}\right)^3 \approx 5\times 10^9\,\mathrm{M}_\odot\left[\frac{10^{-22}\,\mathrm{eV}}{m}\right]^{3/2}$$

or physical size of:

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

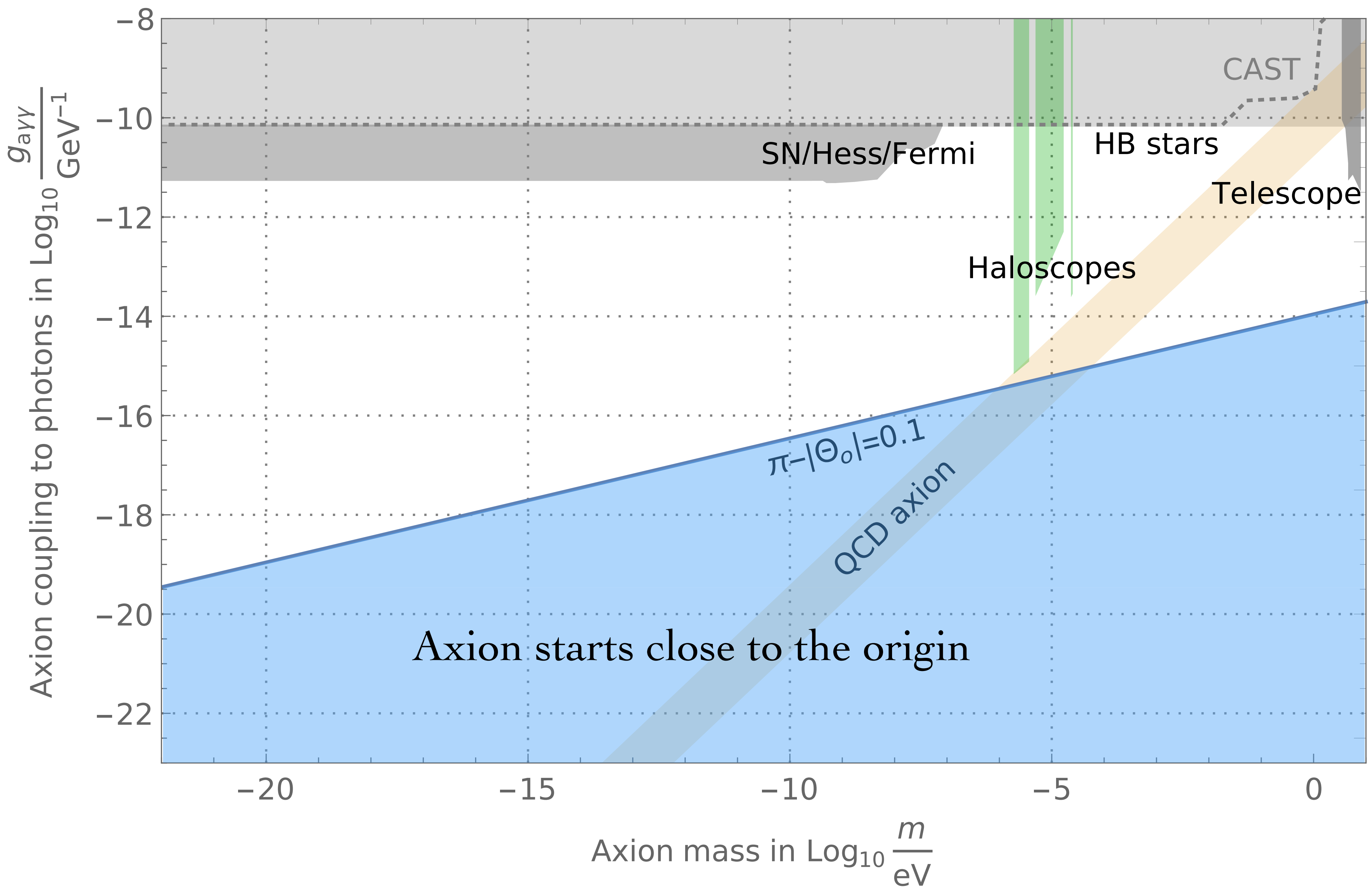


Large Misalignment vs Small Misalignment



$\Theta_o = \phi_o / f$

Large Misalignment vs Small Misalignment



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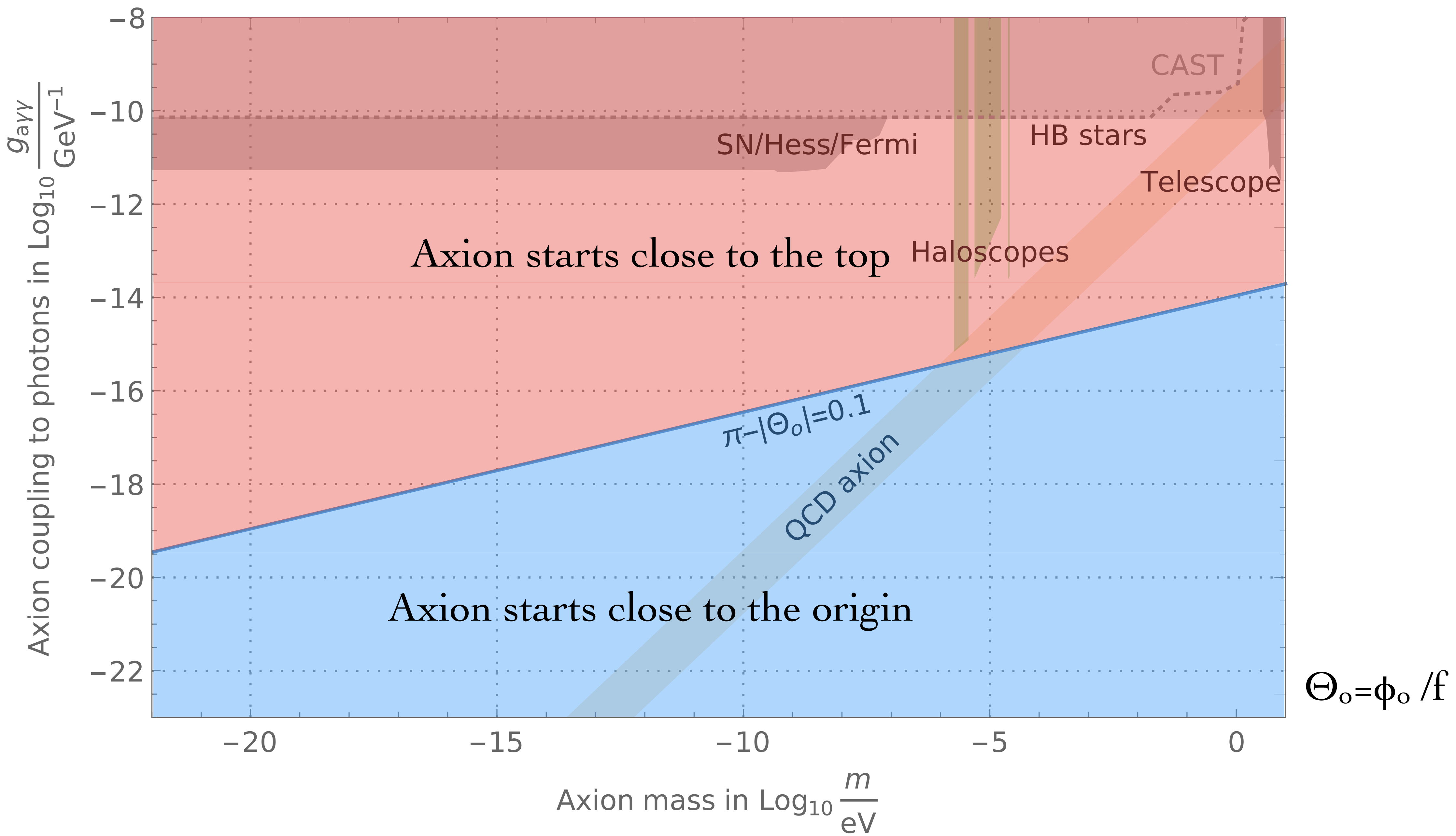

Large Misalignment is most relevant where experiments have good sensitivity

Effects of the large misalignment mechanism

- Formation of compact halos as a component of DM

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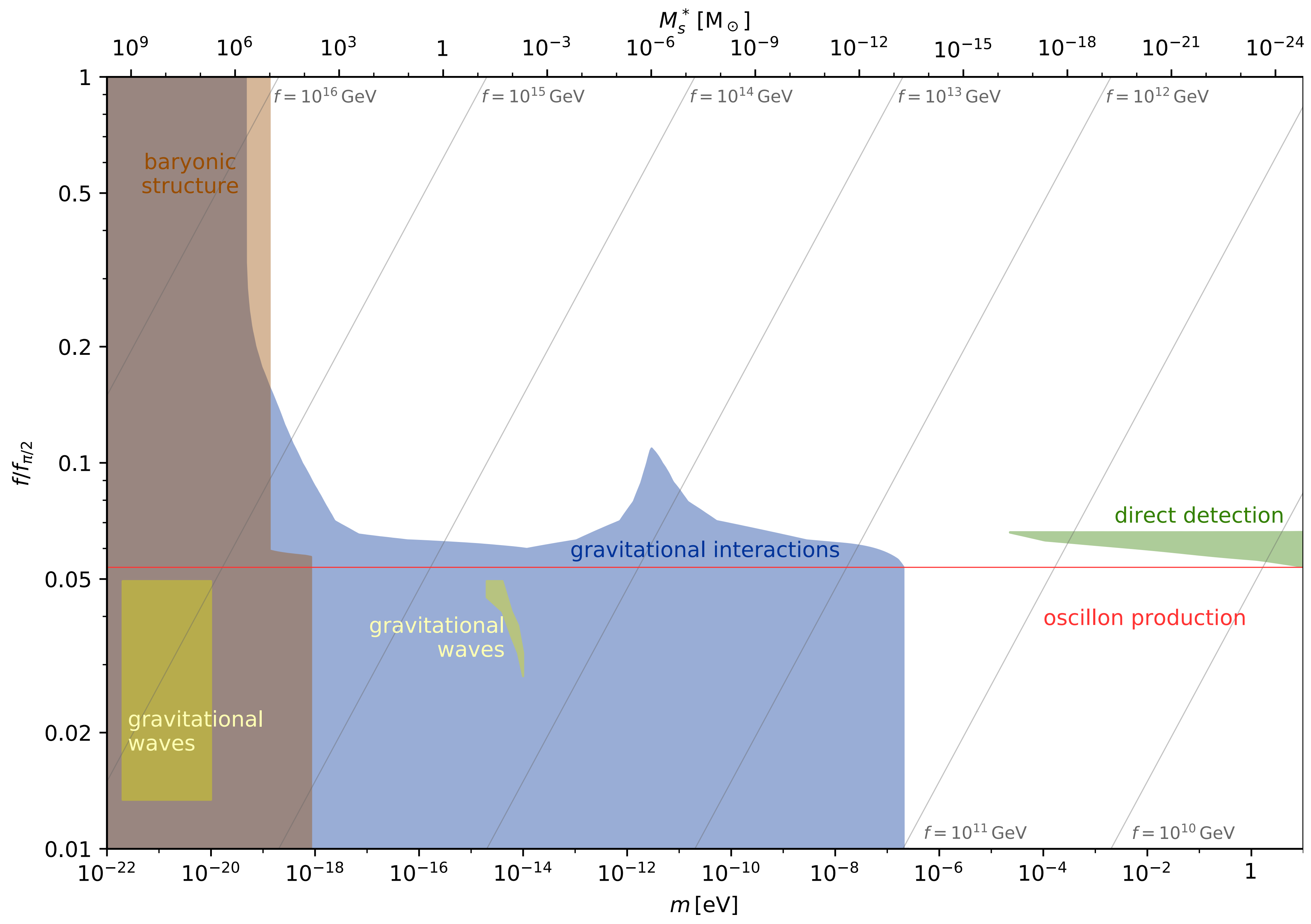
- Happens without the need of a phase transition, starting from a scale-invariant spectrum

Signatures of the large misalignment mechanism



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

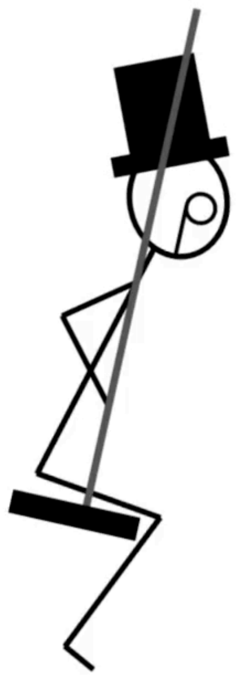
Outline

- 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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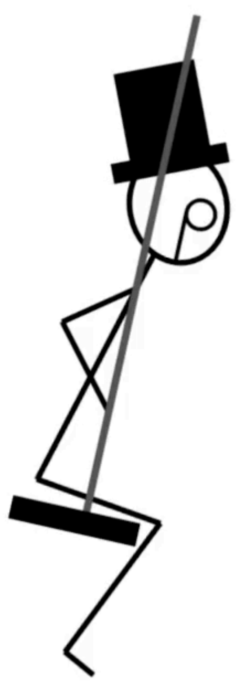

Parametric Resonance Growth

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

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

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

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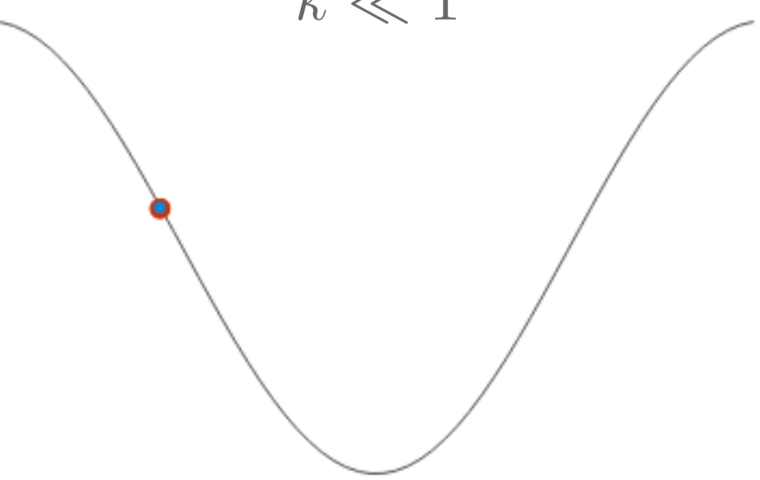
nonrelativistic mode
$\tilde{k} \ll 1$



enters horizon when
nonlinearities are small

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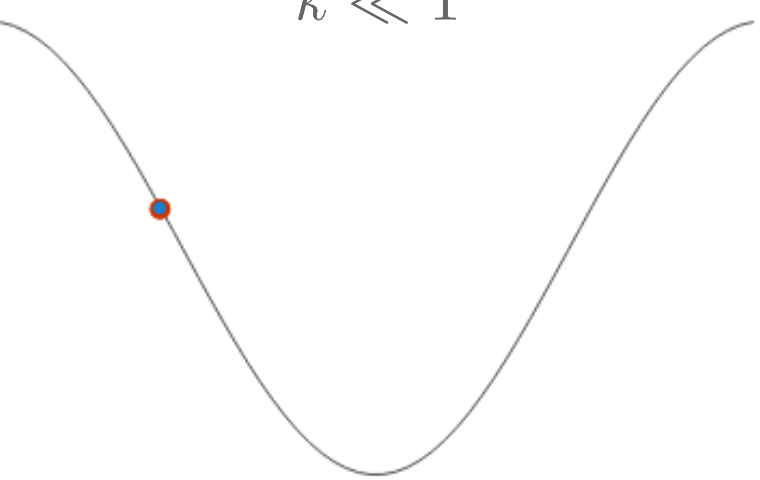

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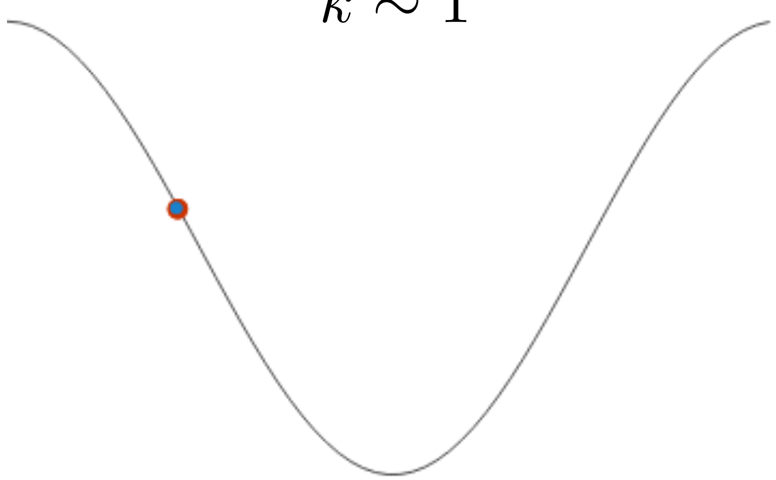

frequency match;
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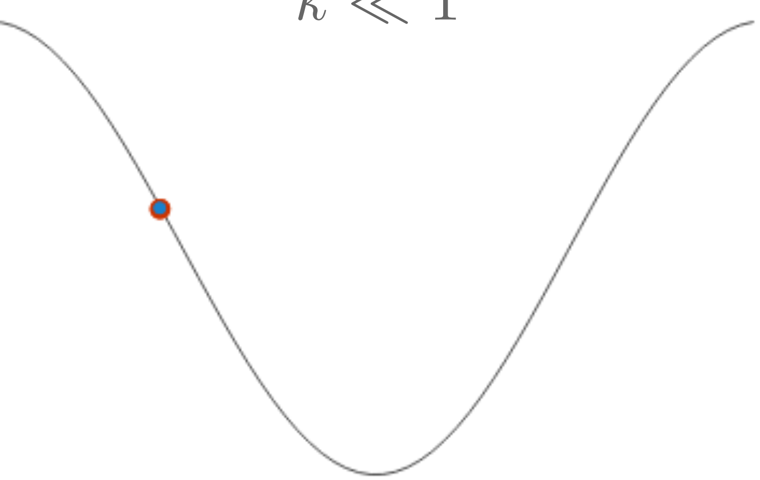
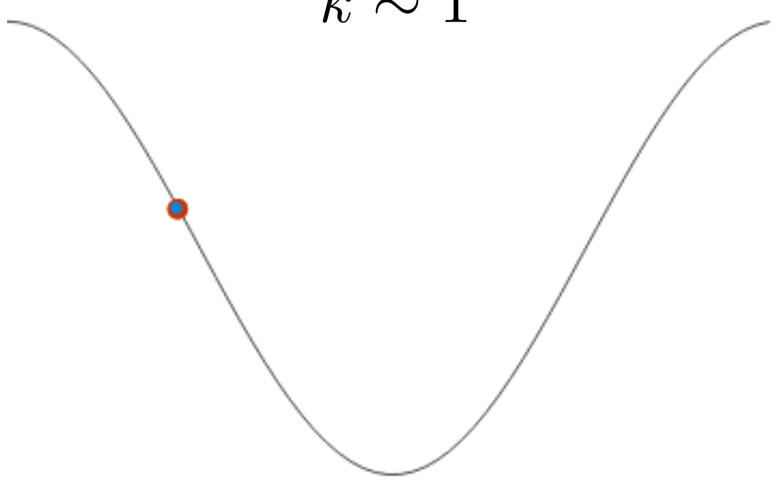


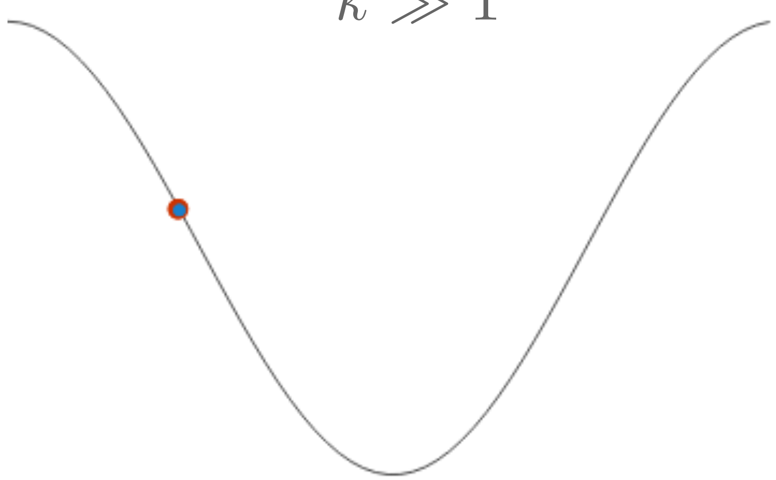
enters horizon when nonlinearities are small

semi-relativistic mode
$\tilde{k} \sim 1$



frequency match; nonlinearity > friction

ultra-relativistic mode
$\tilde{k} \gg 1$



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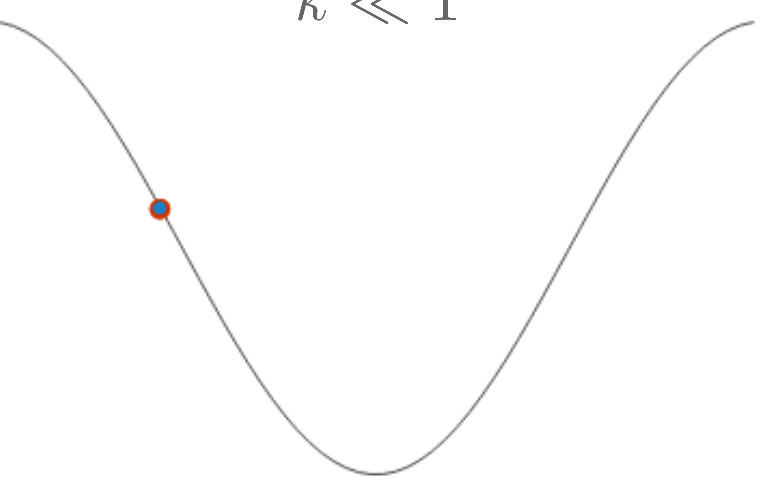

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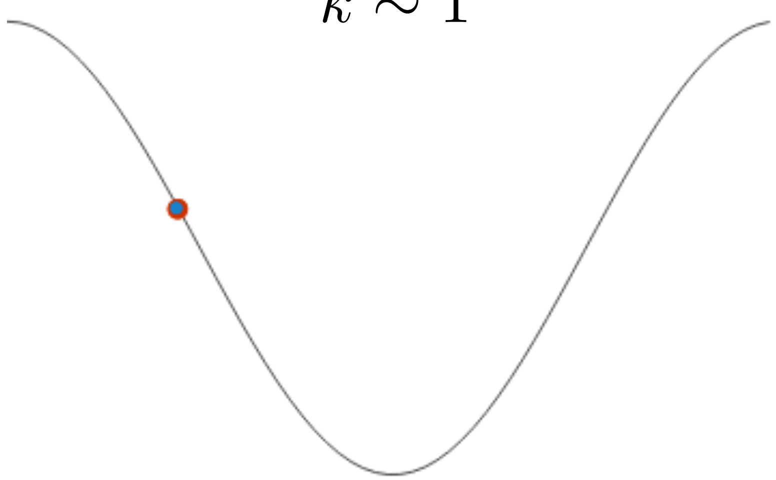

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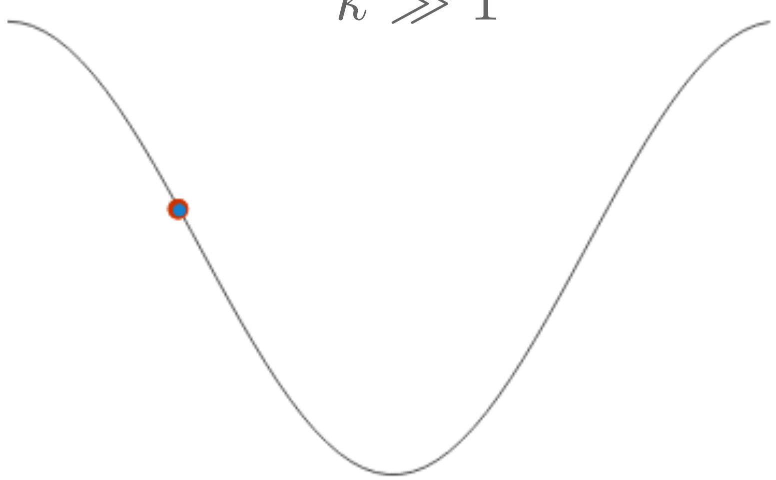
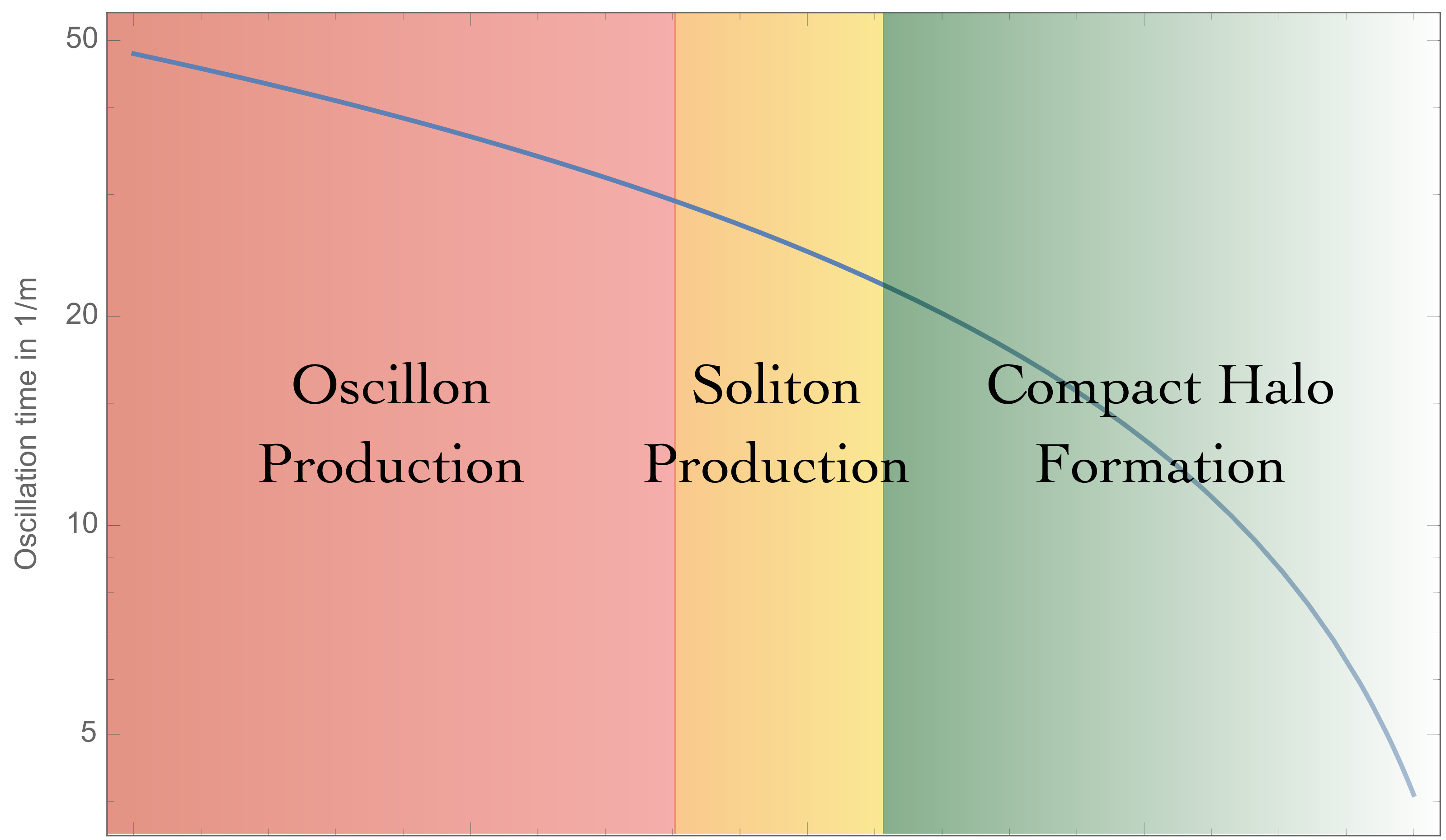


frequency mismatch

In order to overcome the friction the field needs to start close to the top
to delay the oscillation time

Delayed onset of oscillation



←Starting closer and closer to the top

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

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

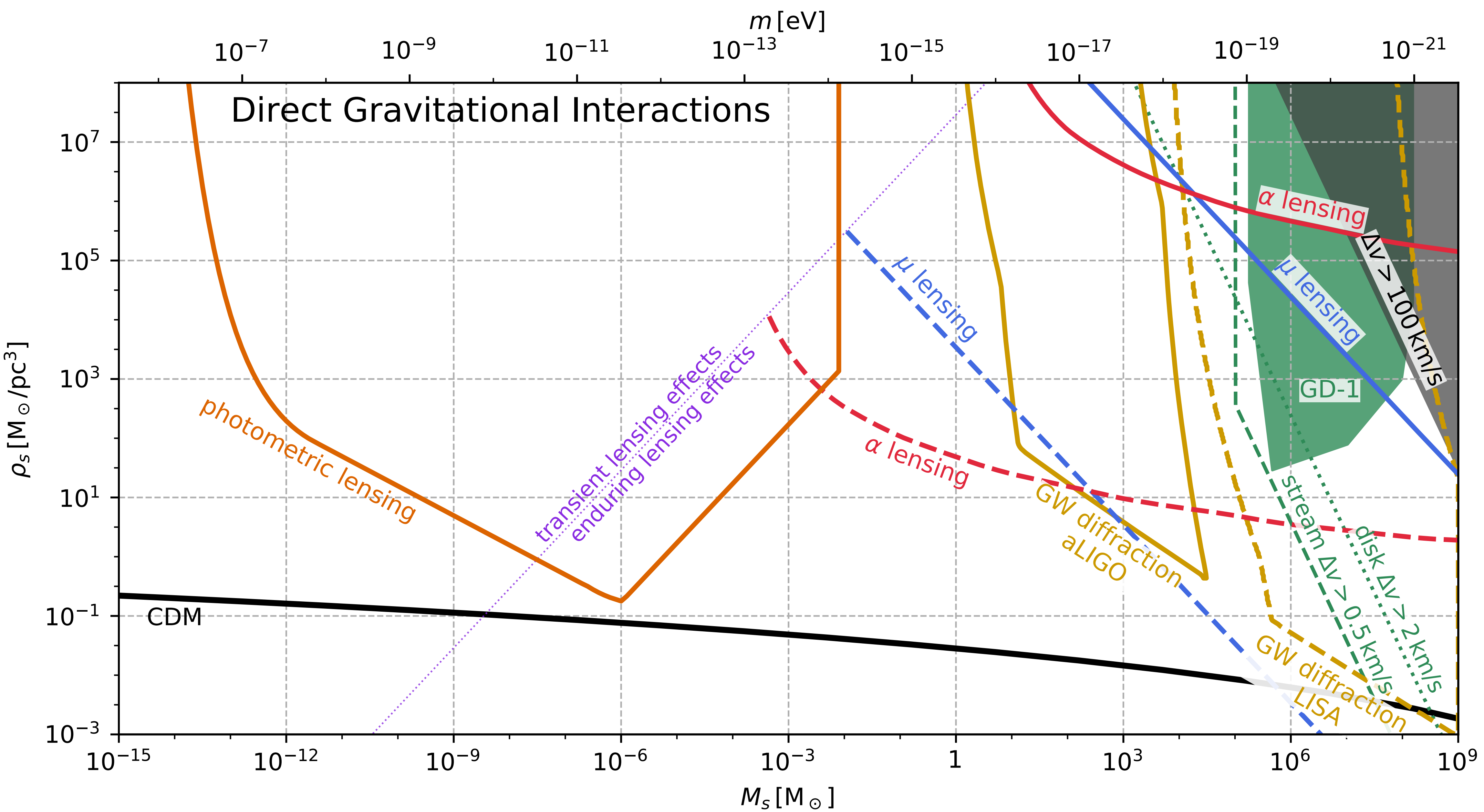
Outline

- 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

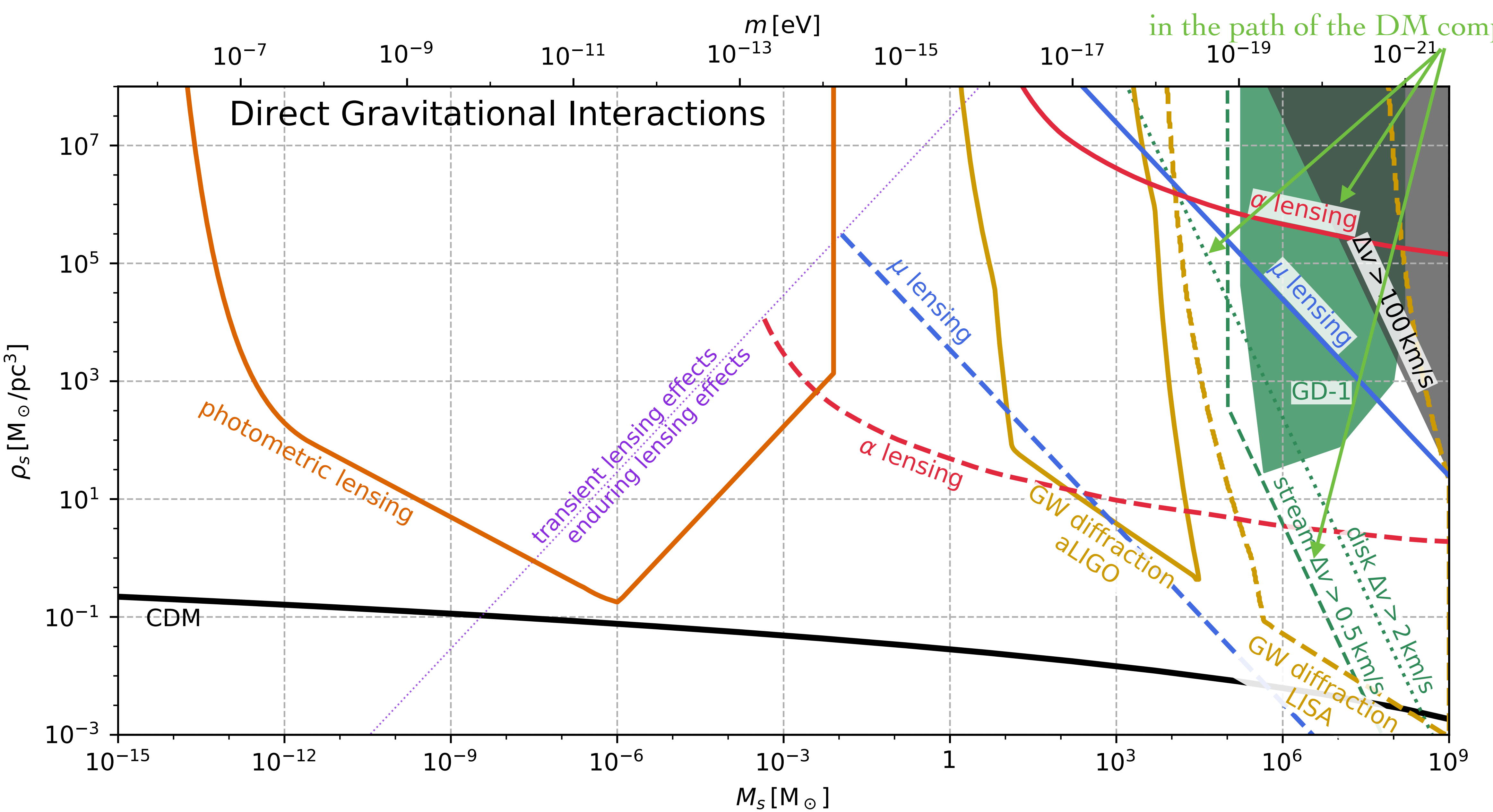
Direct Gravitational Signatures



Direct Gravitational Signatures

Velocity “kicks” on stars

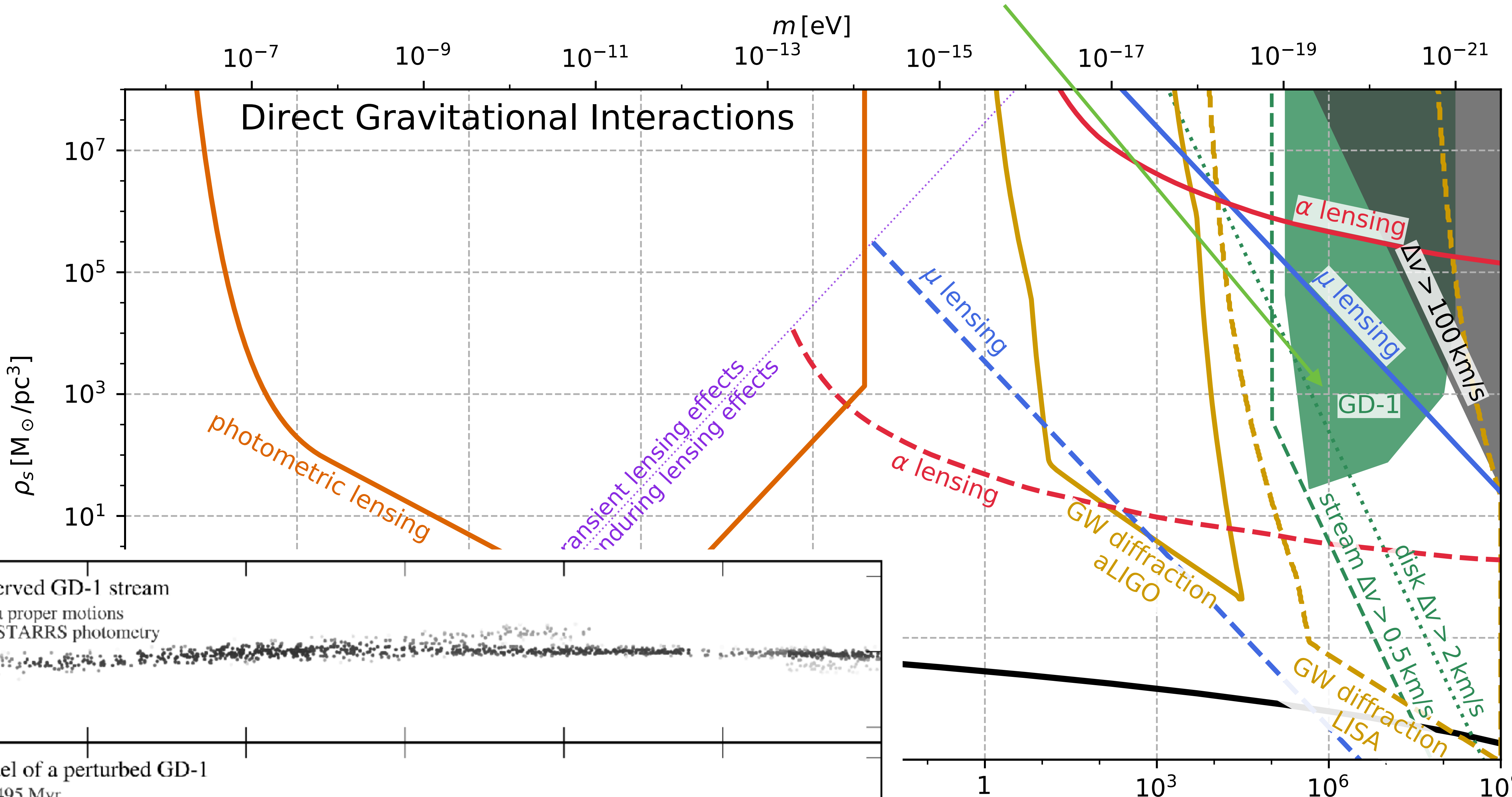
in the path of the DM compact halo

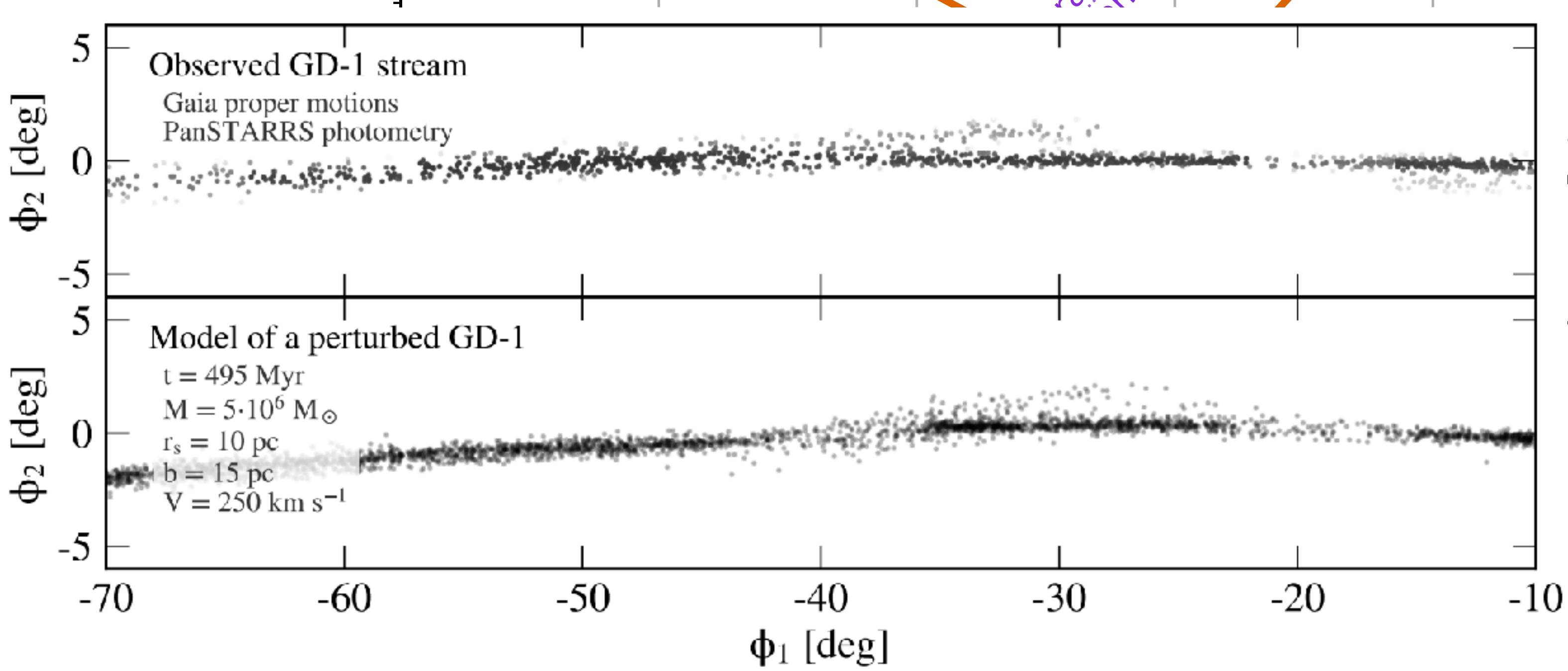


Direct Gravitational Signatures

Preferred parameter space

explaining GD-1 observation





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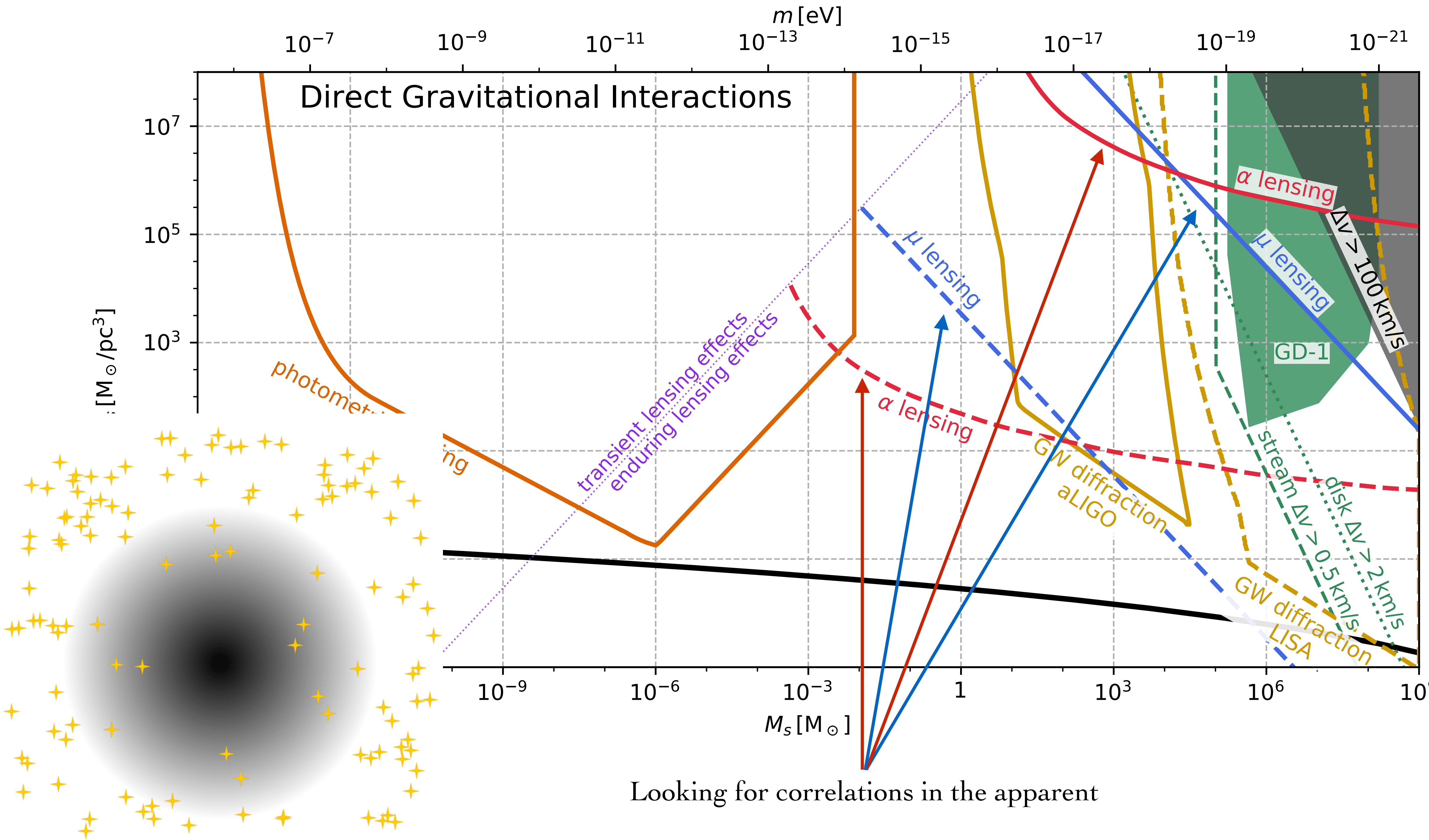
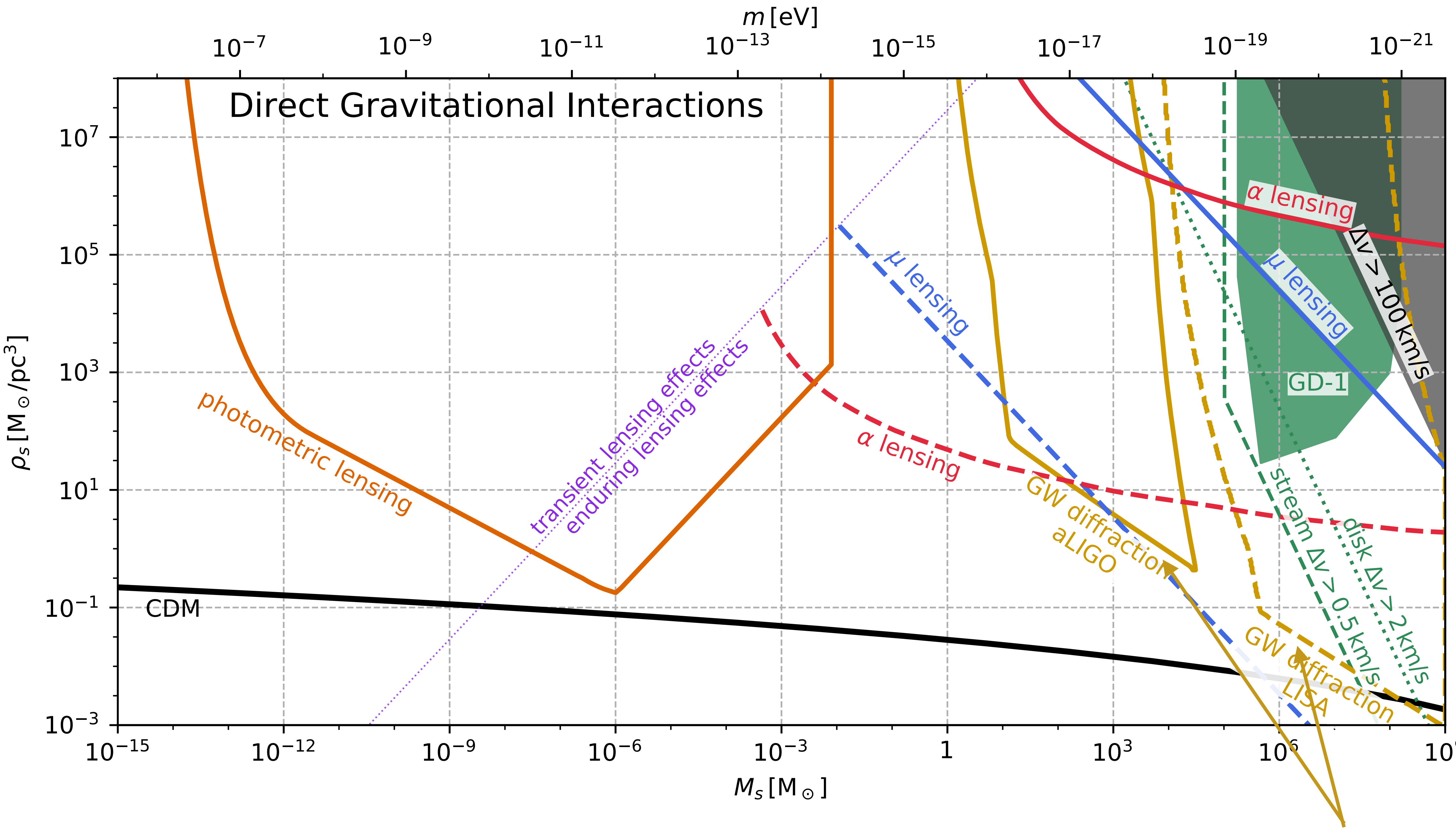


Looking for correlations in the apparent

velocities and accelerations of stars in GAIA and THEIA

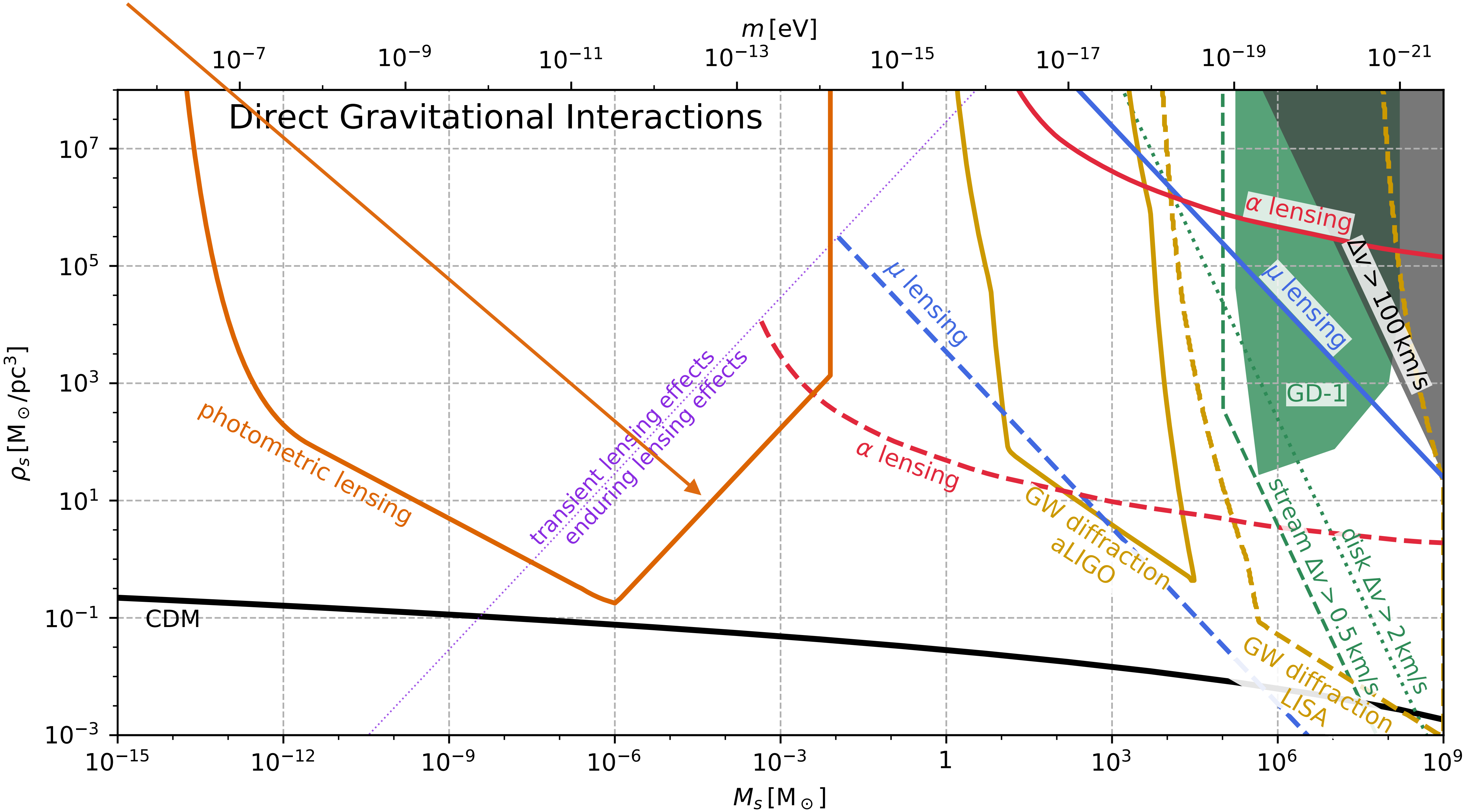
Direct Gravitational Signatures



Diffraction of GWs from mergers

Direct Gravitational Signatures

Modulations in rare high amplification of distant stars

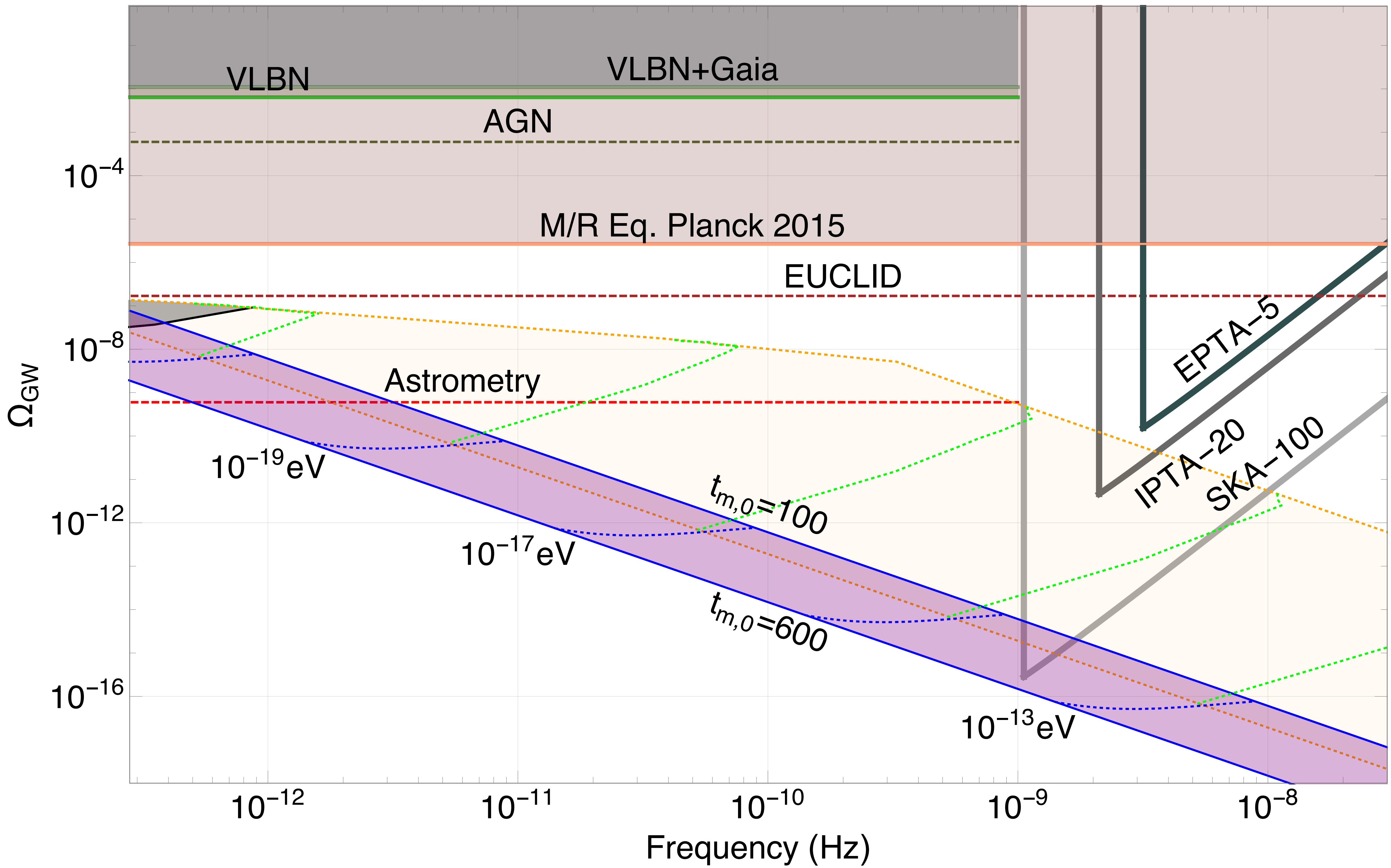


Gravitational Wave Emission

- 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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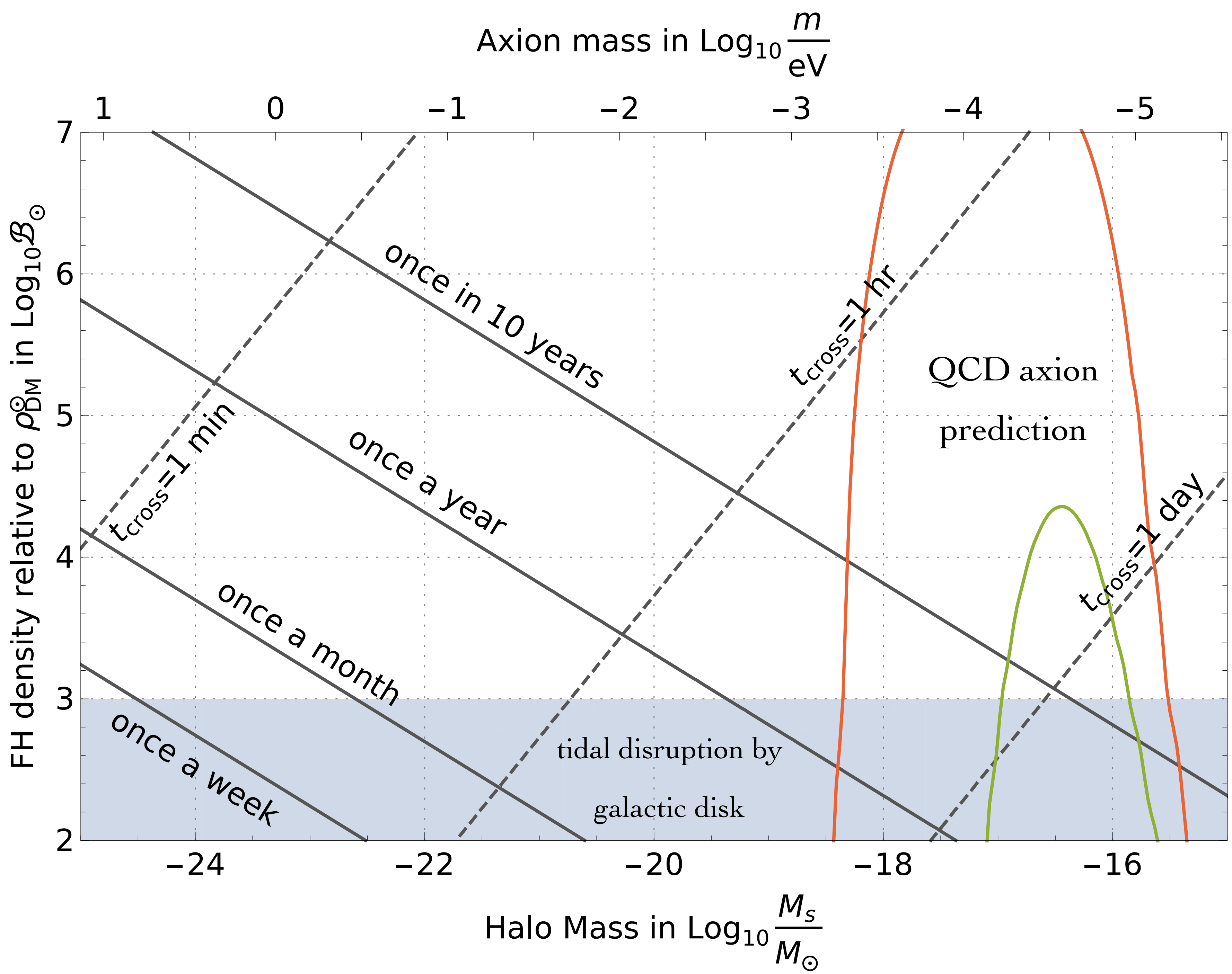
  - Need to have enough baryons

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



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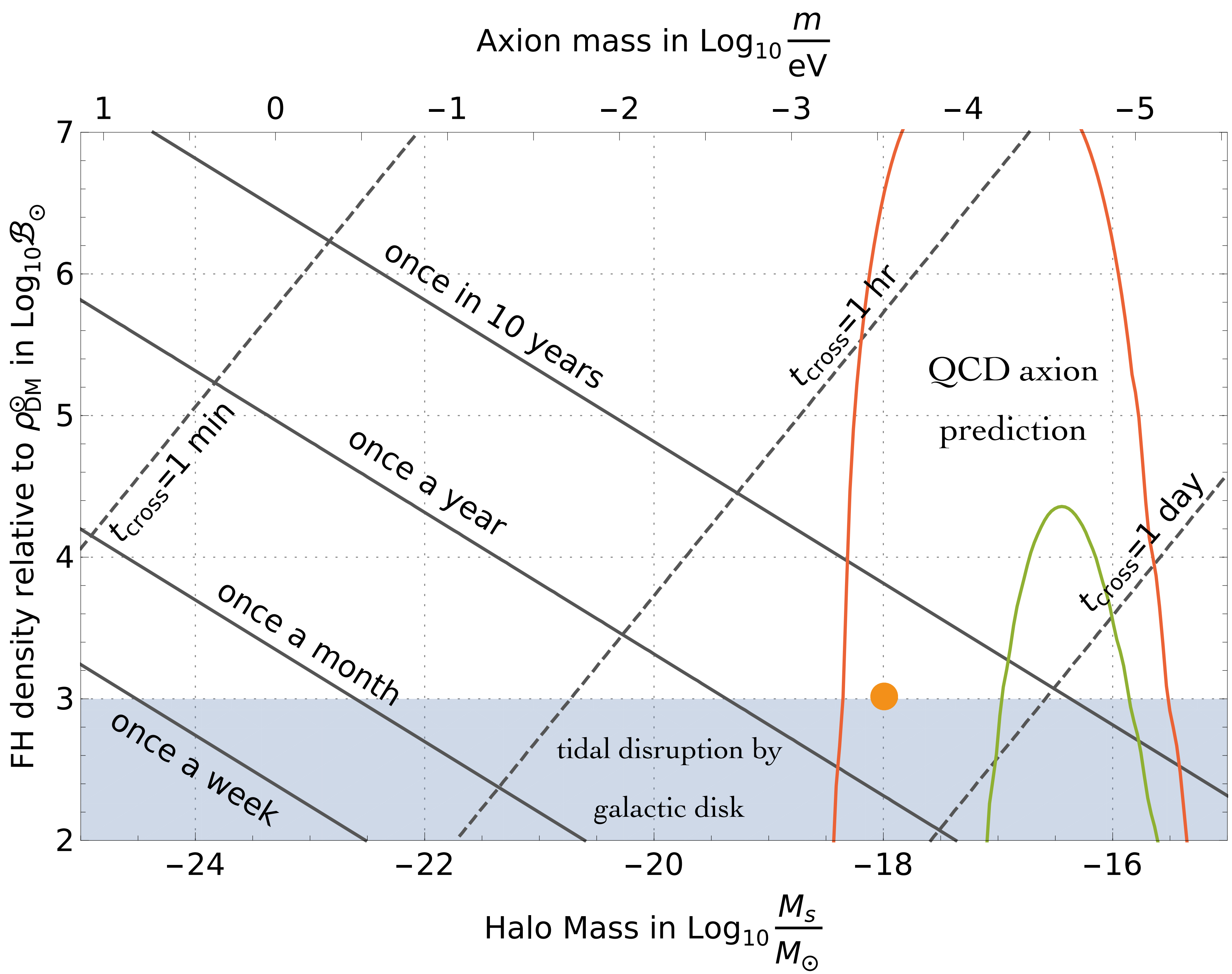
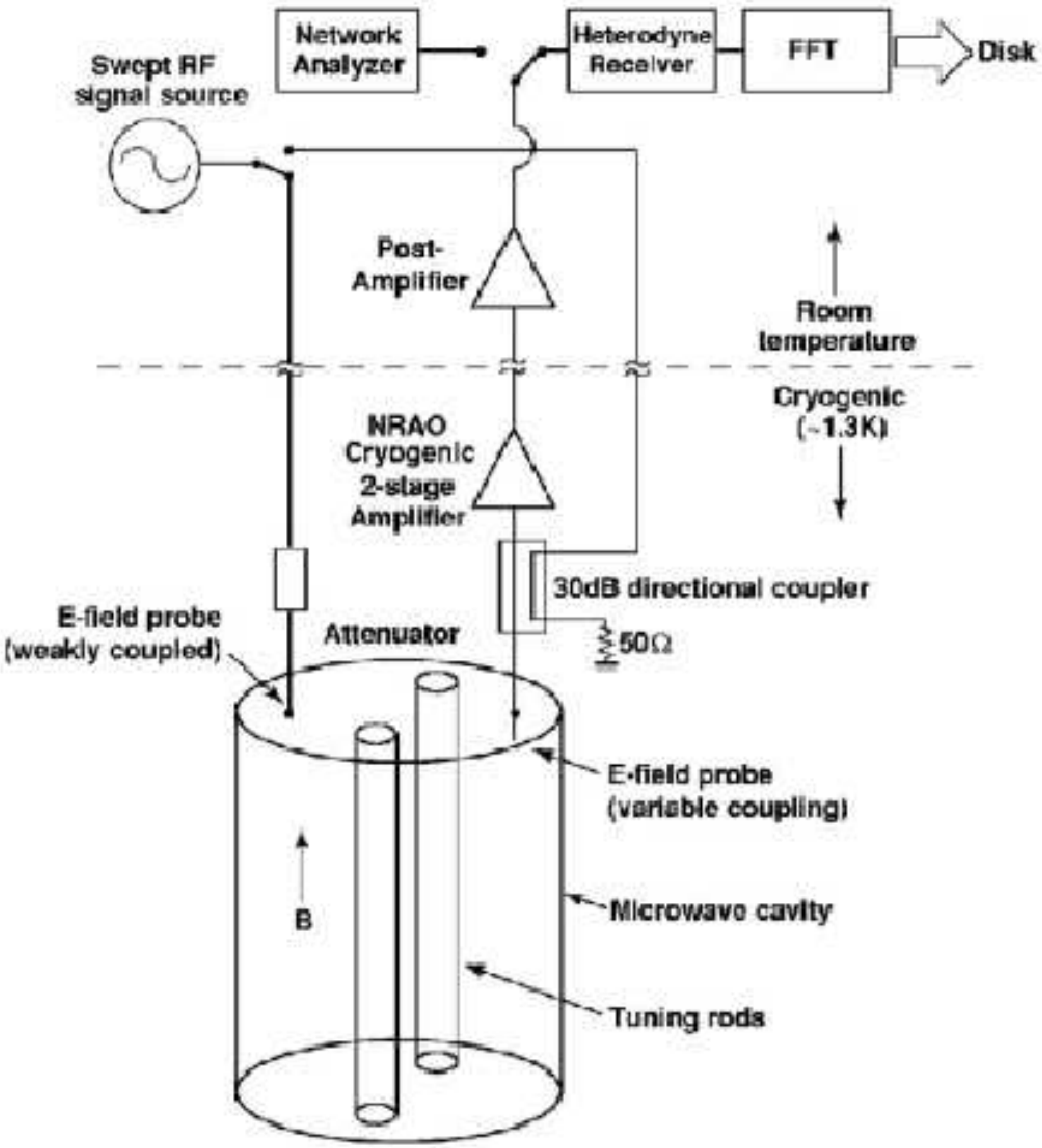
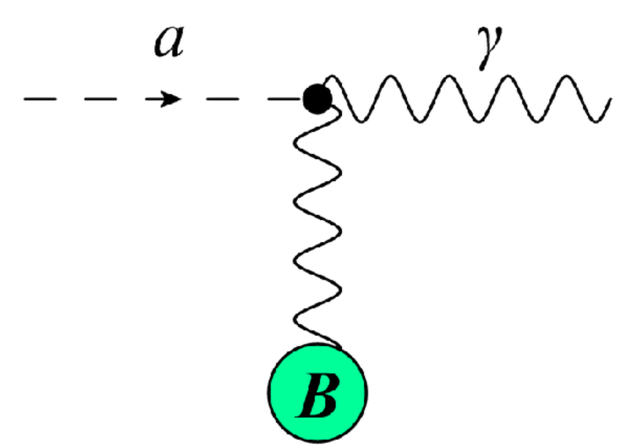


Let's examine the case of a 10^{-18} solar mass halo that is 1000 times more dense than CDM

Resonant Axion Searches



ADMX



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

Harmonic oscillator analog:

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

Effects on Earth-bound experiments

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

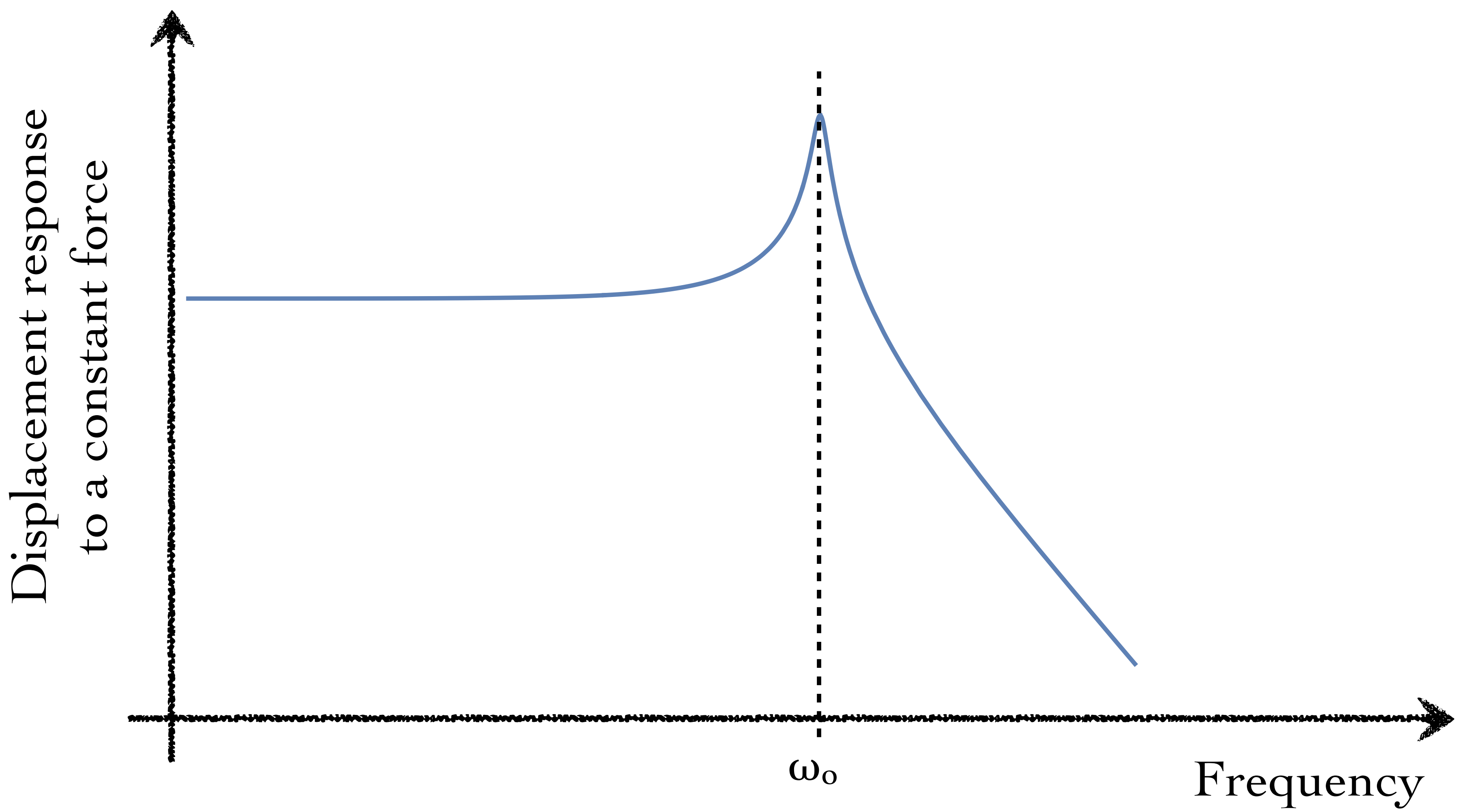
- Every ~3 years, power goes up by the over-density factor for approximately 6 hours

- 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



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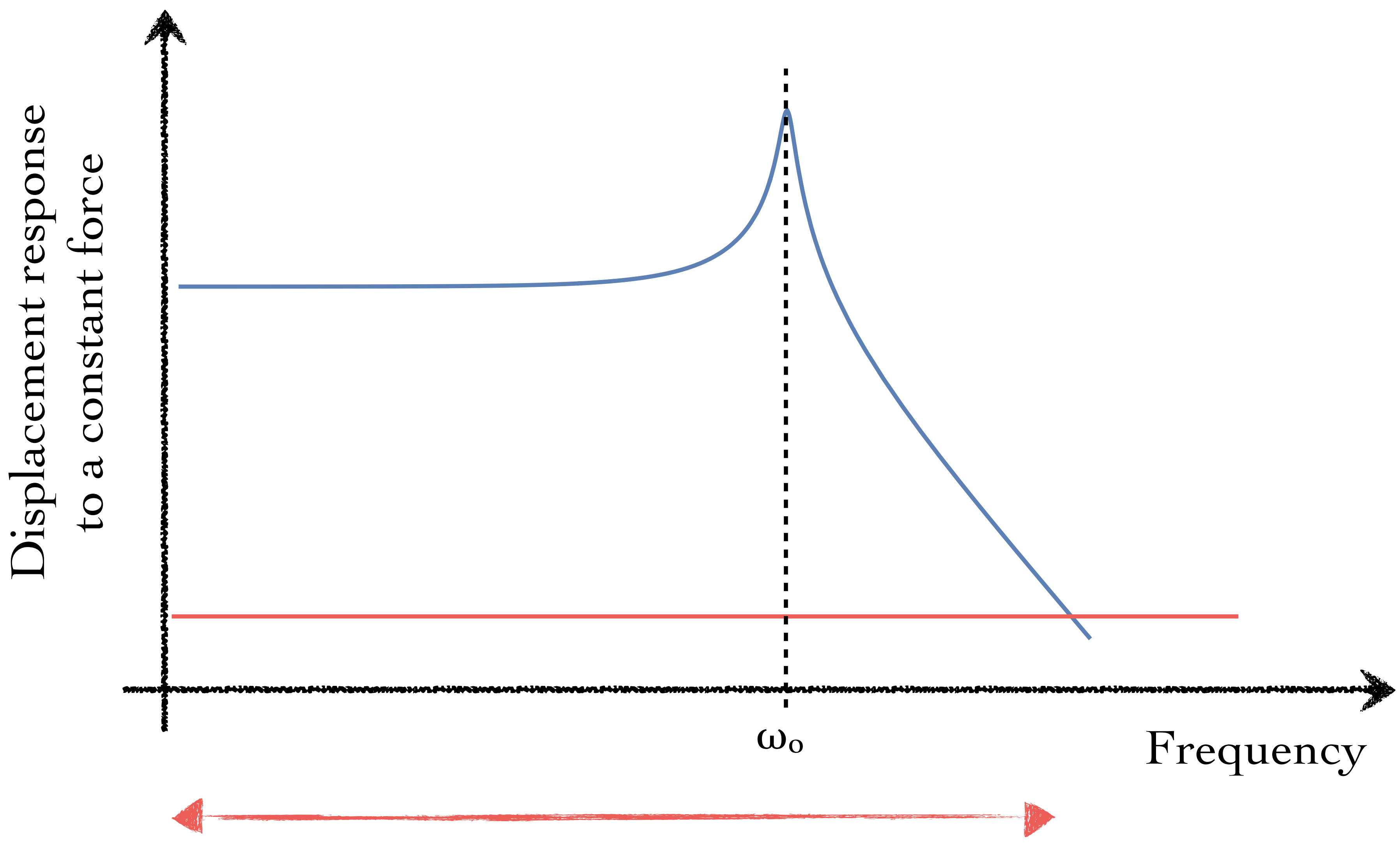

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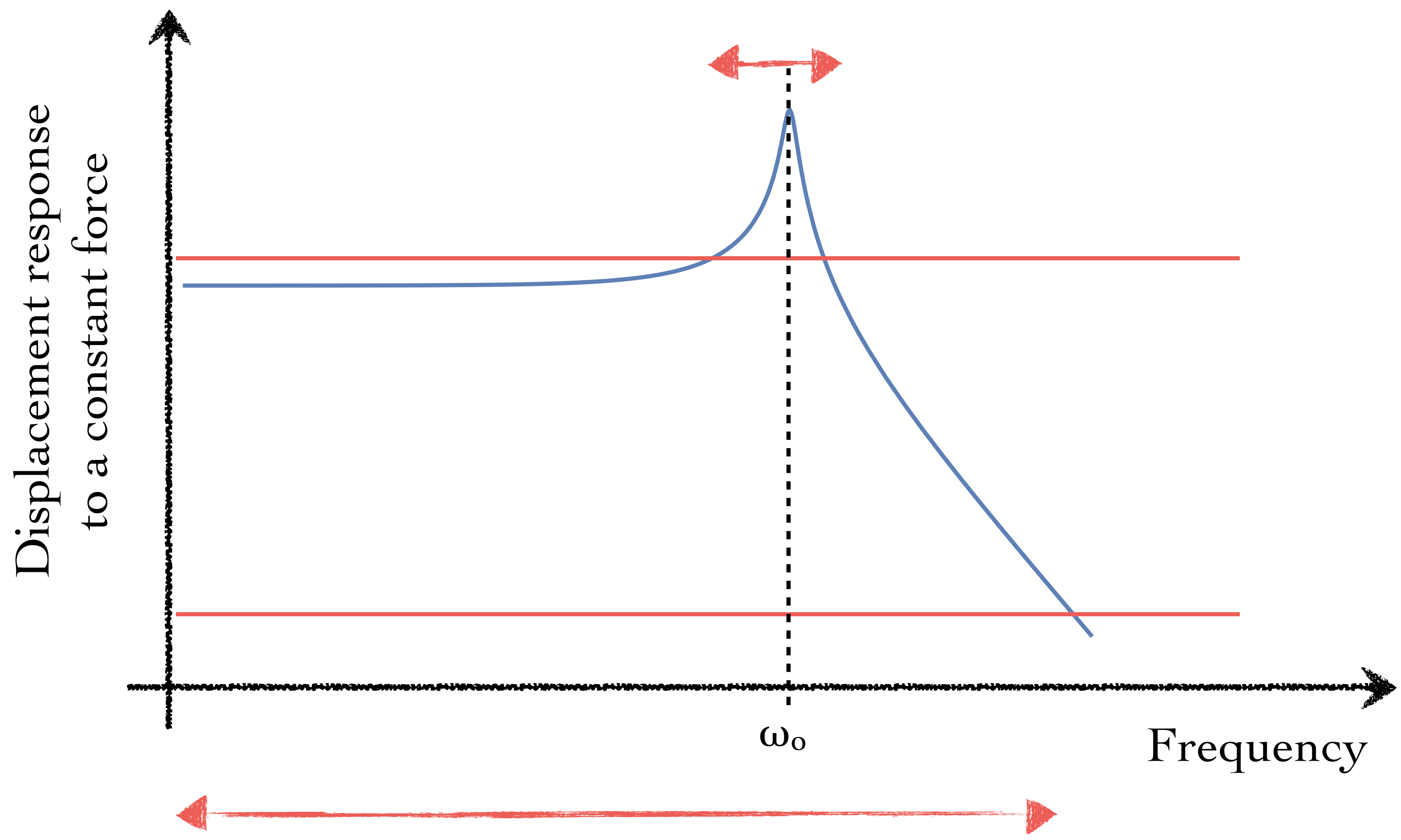


The bandwidth is determined by the detector sensitivity for displacement

Effects on Earth-bound DM Searches

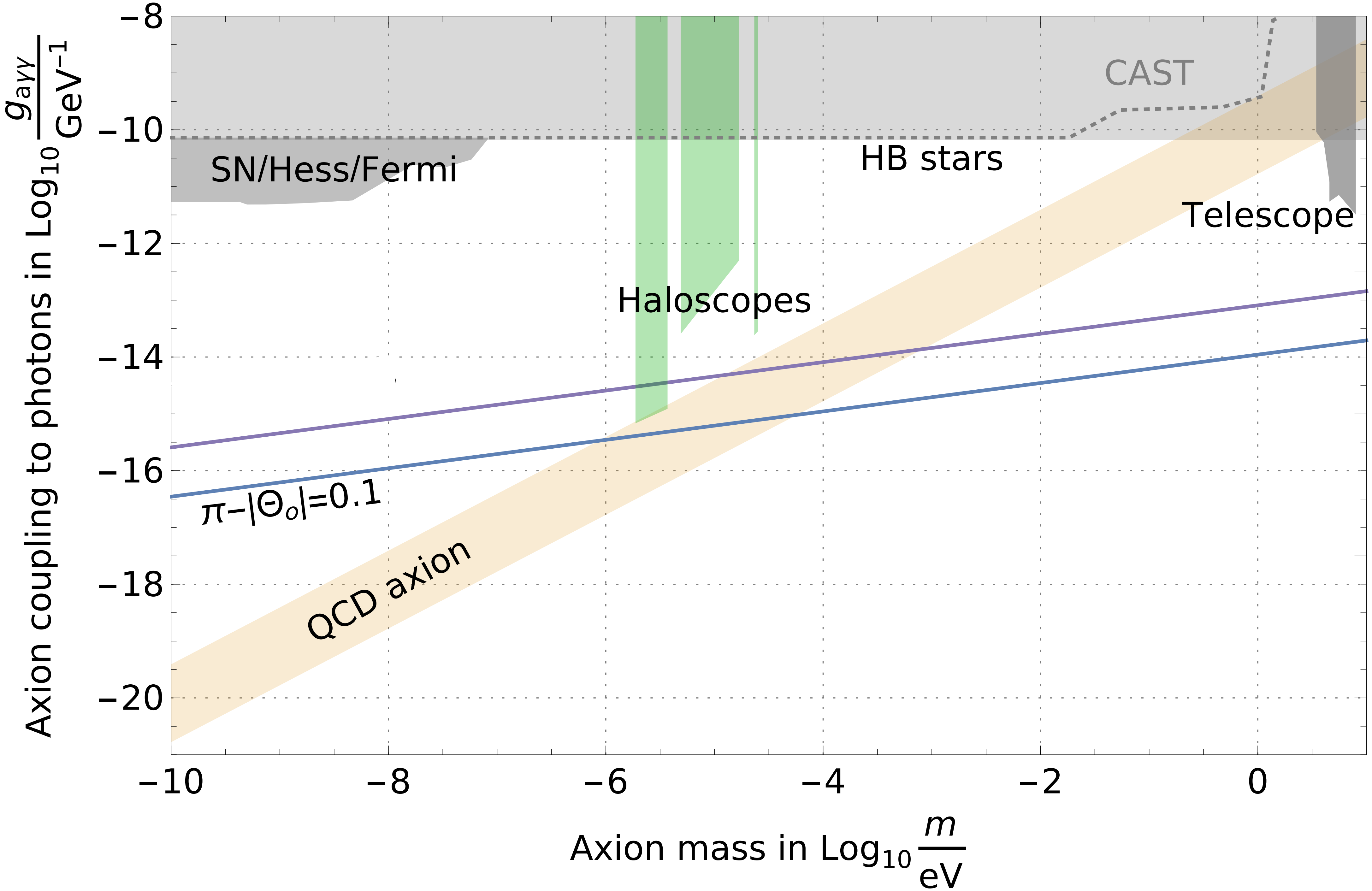
Ex. 10^{-18} solar mass halo

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
- $Q_{\text{DM in clump}} >> Q_{\text{DM-diffuse}}$

Summary of effects on earth-bound experiments



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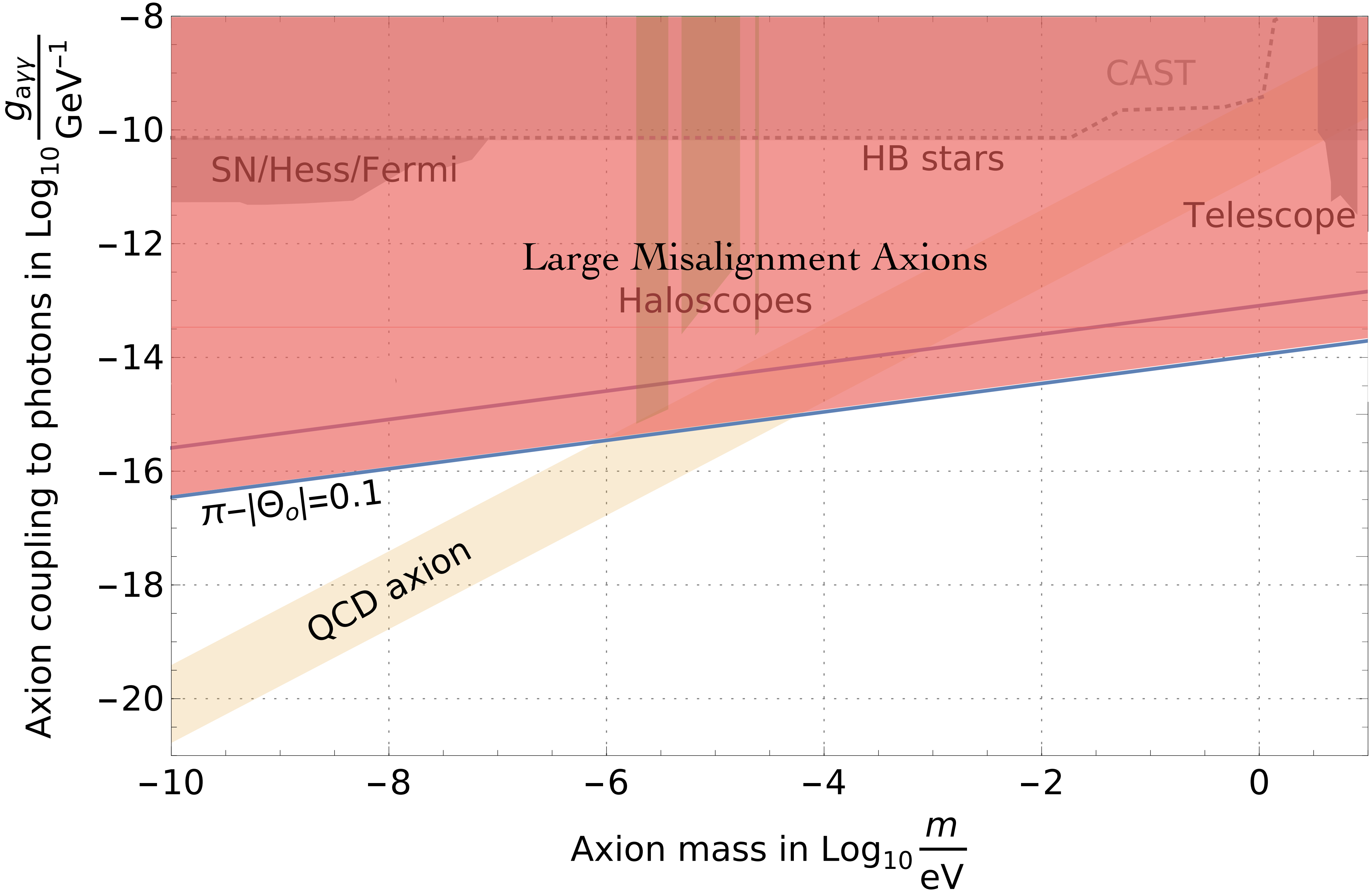


Need to reconsider existing bounds and search strategies

What about the QCD axion?

The QCD axion

Temperature dependent mass

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

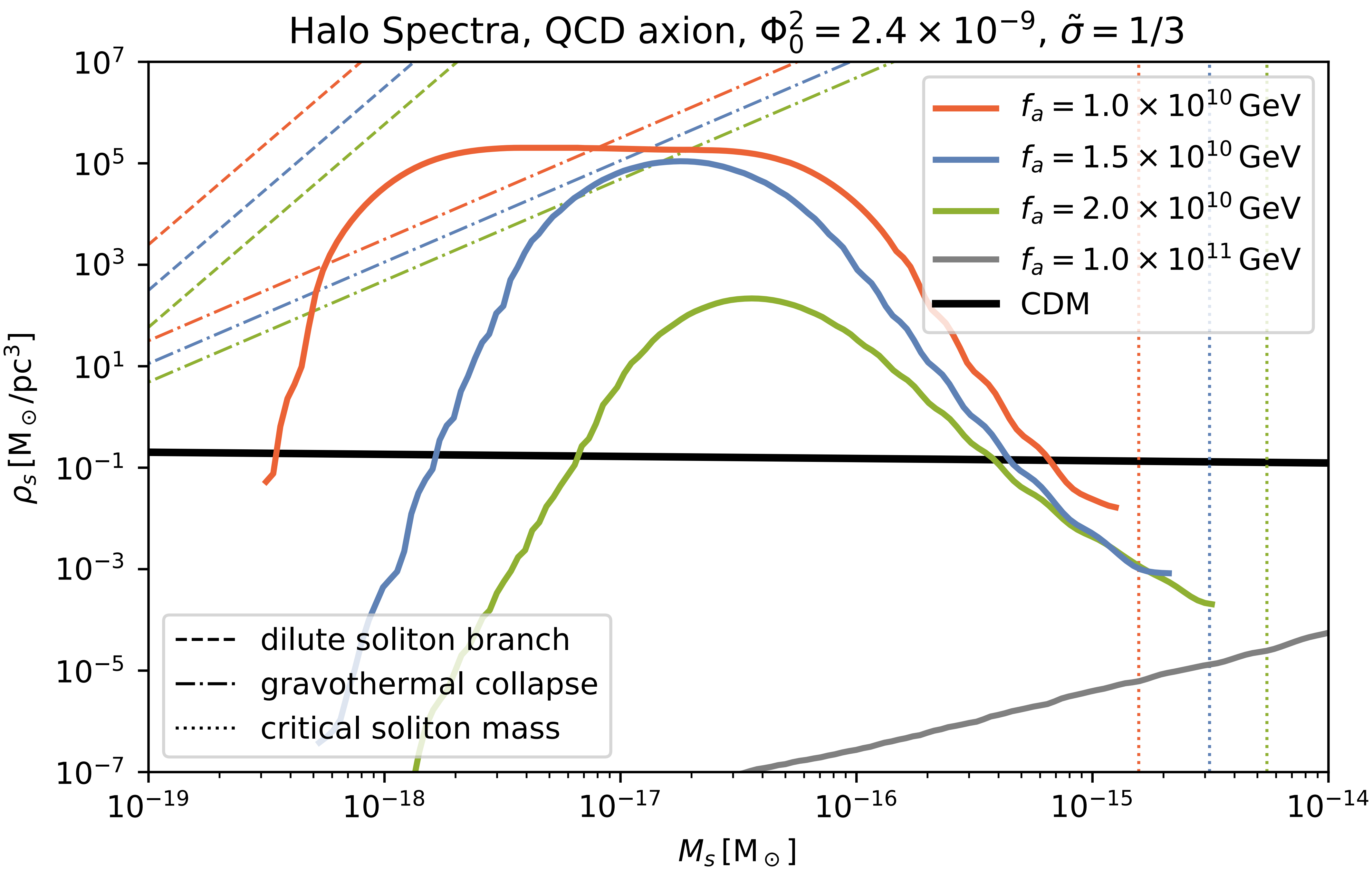
with

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

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)

Other lessons learned from the large misalignment mechanism

- Produces axions stars, miniclusters or oscillons of mass:

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

- Cannot produce dense axion stars without overclosing the universe with Dark Matter

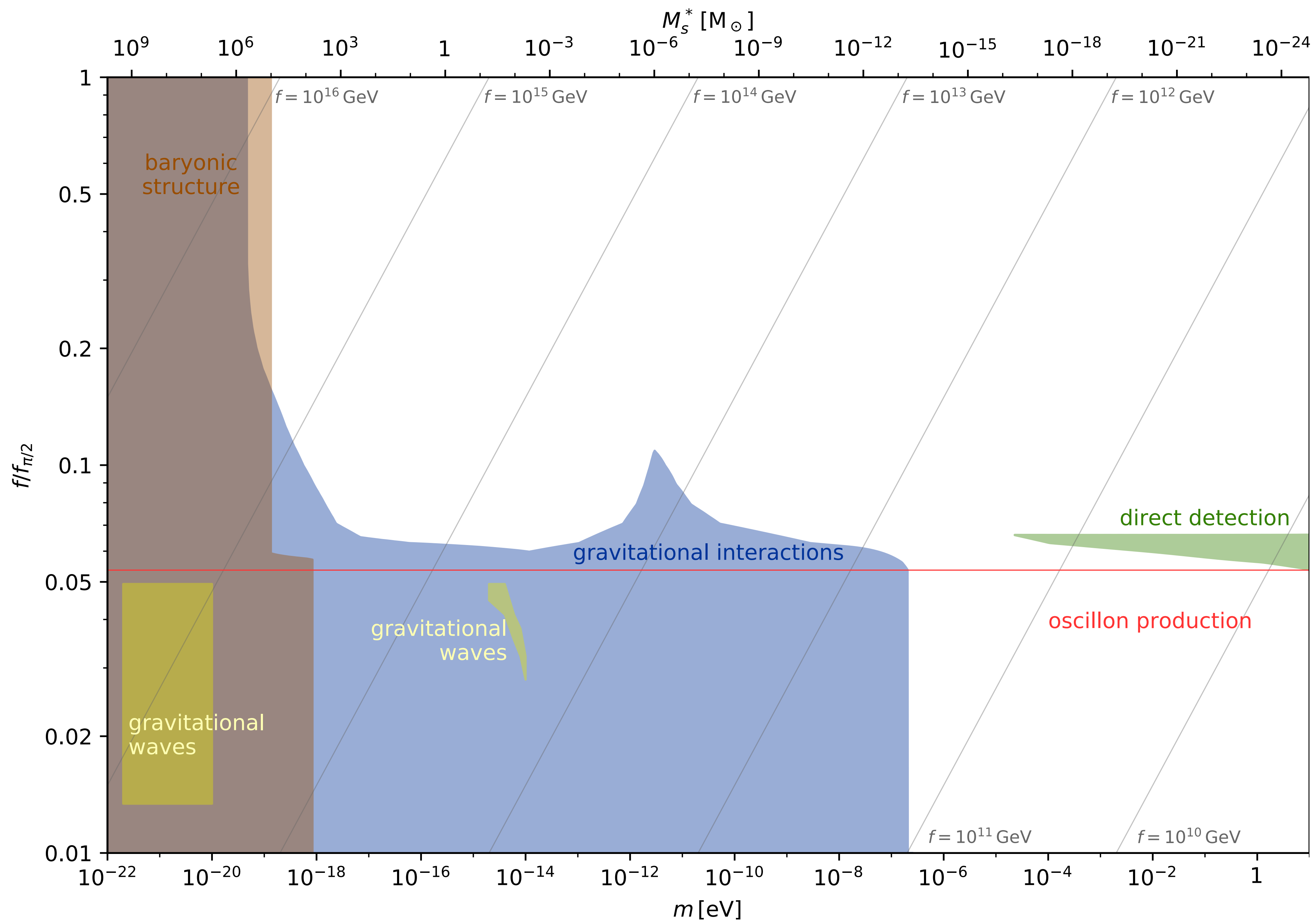
- For earth-bound experiments the relevant frequency range is that of ADMX and higher

- Oscillons DM should be a possibility but exact mechanism of longevity or appropriate potential has yet to be identified

Open Questions

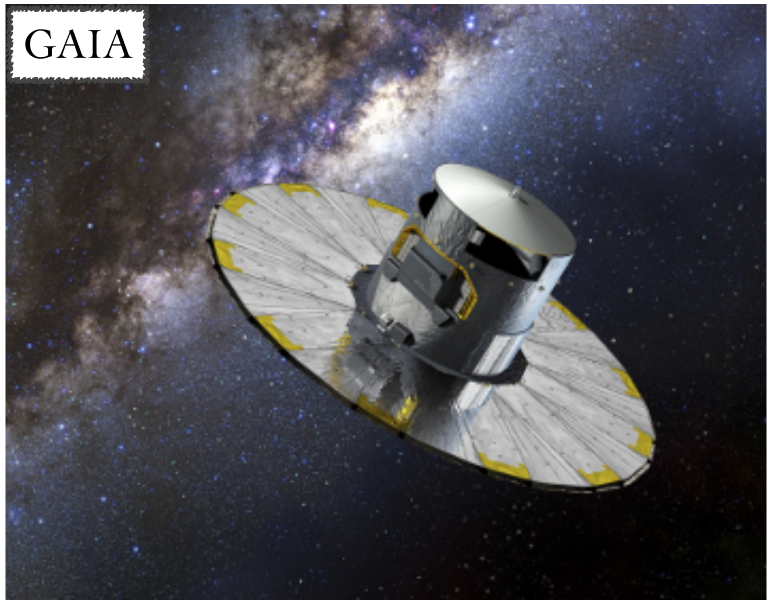
- How much can we really tell about star formation?
- Are there non gravitational probes of large DM halos?
- What fraction of DM is in these halos?
  What are the optimal strategies for laboratory DM searches?

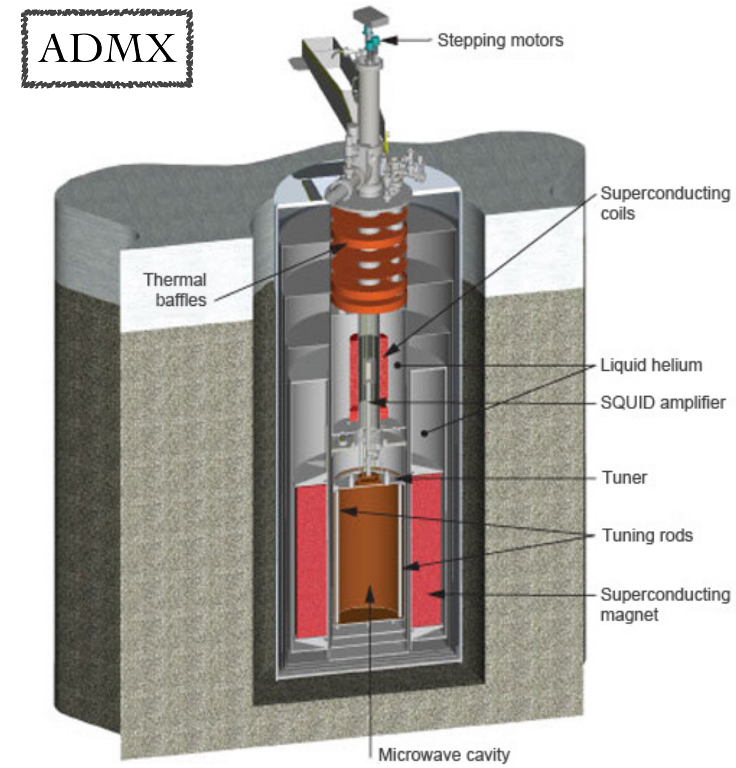
Signatures of the large misalignment mechanism

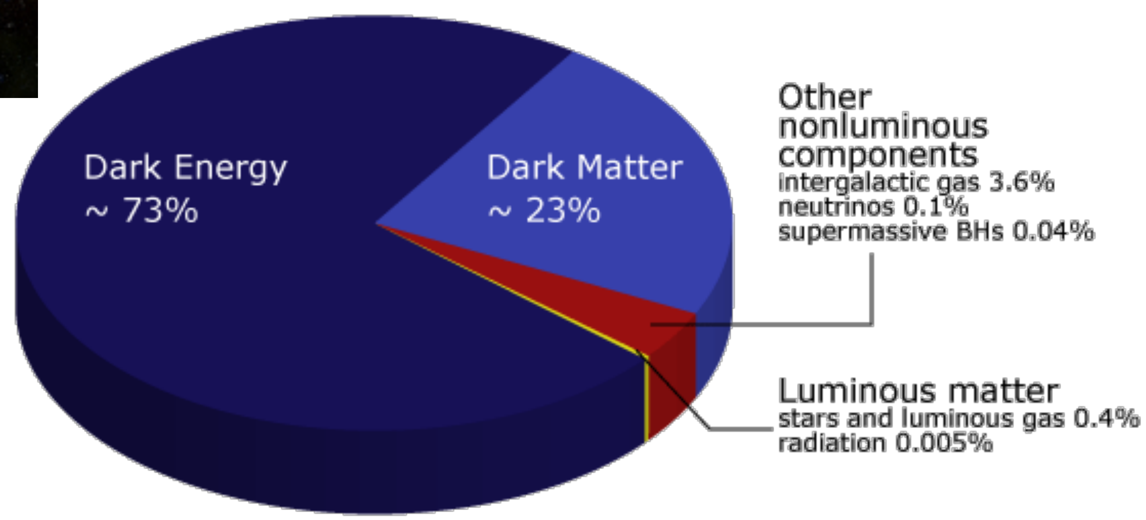


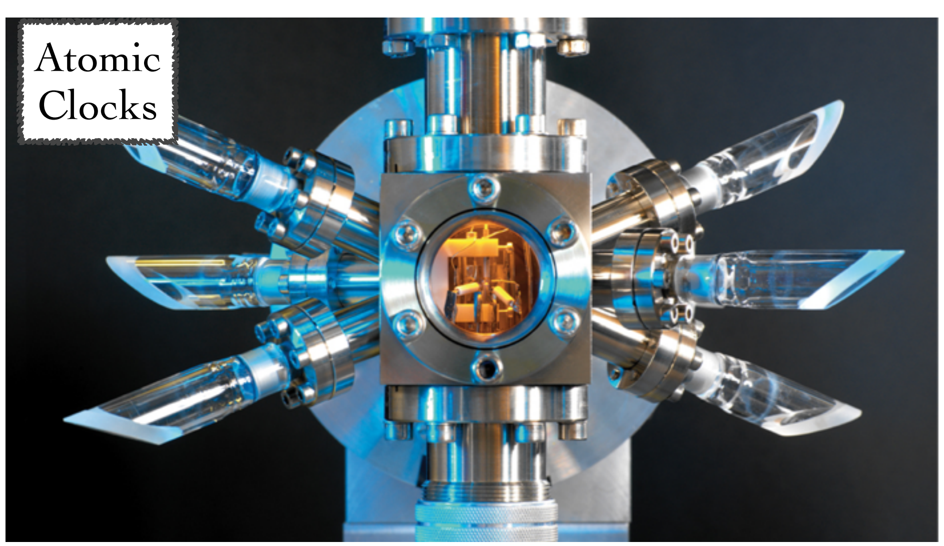
$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))$$

Shining Light on Dark Matter





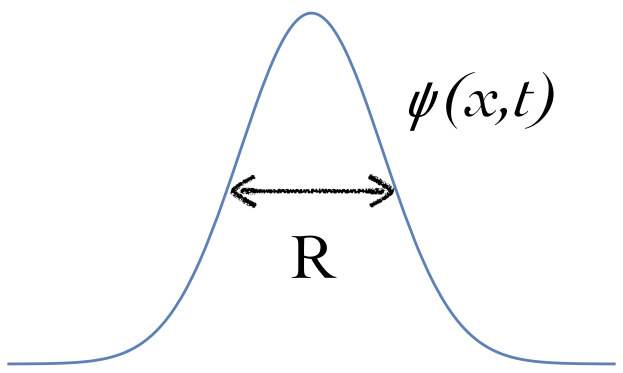




Back-up slides

What are solitons?
What are oscillons?

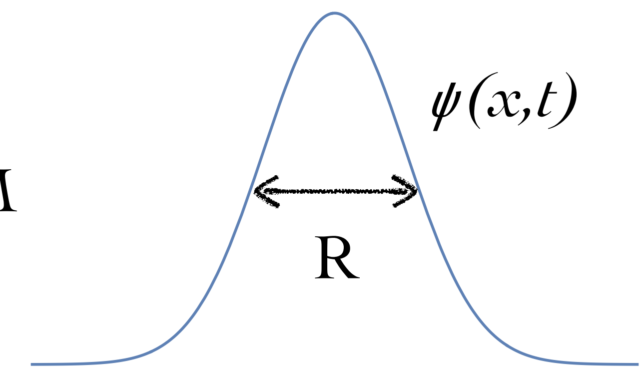
Scalar field configuration of size R and total mass M



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

What are solitons?
What are oscillons?

Scalar field configuration of size R and total mass M



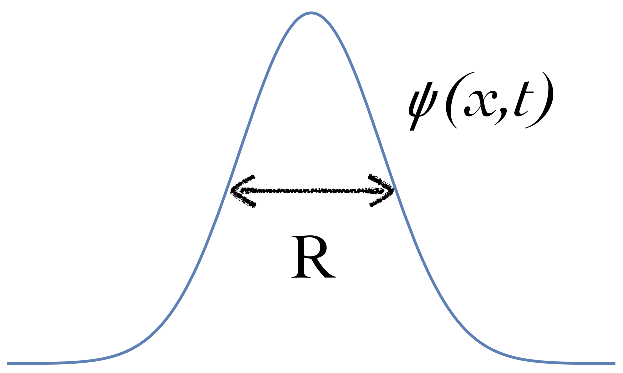
$$\text{Hamiltonian energy density} = \frac{|\nabla\psi|^2}{2m} + V_{grav}(\psi) - \lambda|\psi|^4 + \lambda'|\psi|^6$$

Integrate over volume

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

What are solitons?
What are oscillons?

Scalar field configuration of size R and total mass M



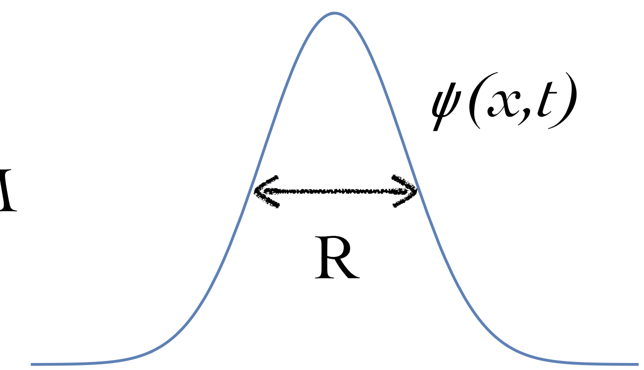
$$\text{Hamiltonian energy density} = \frac{|\nabla\psi|^2}{2m} + V_{grav}(\psi) - \lambda|\psi|^4 + \lambda'|\psi|^6$$

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

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

What are solitons?
What are oscillons?

Scalar field configuration of size R and total mass M



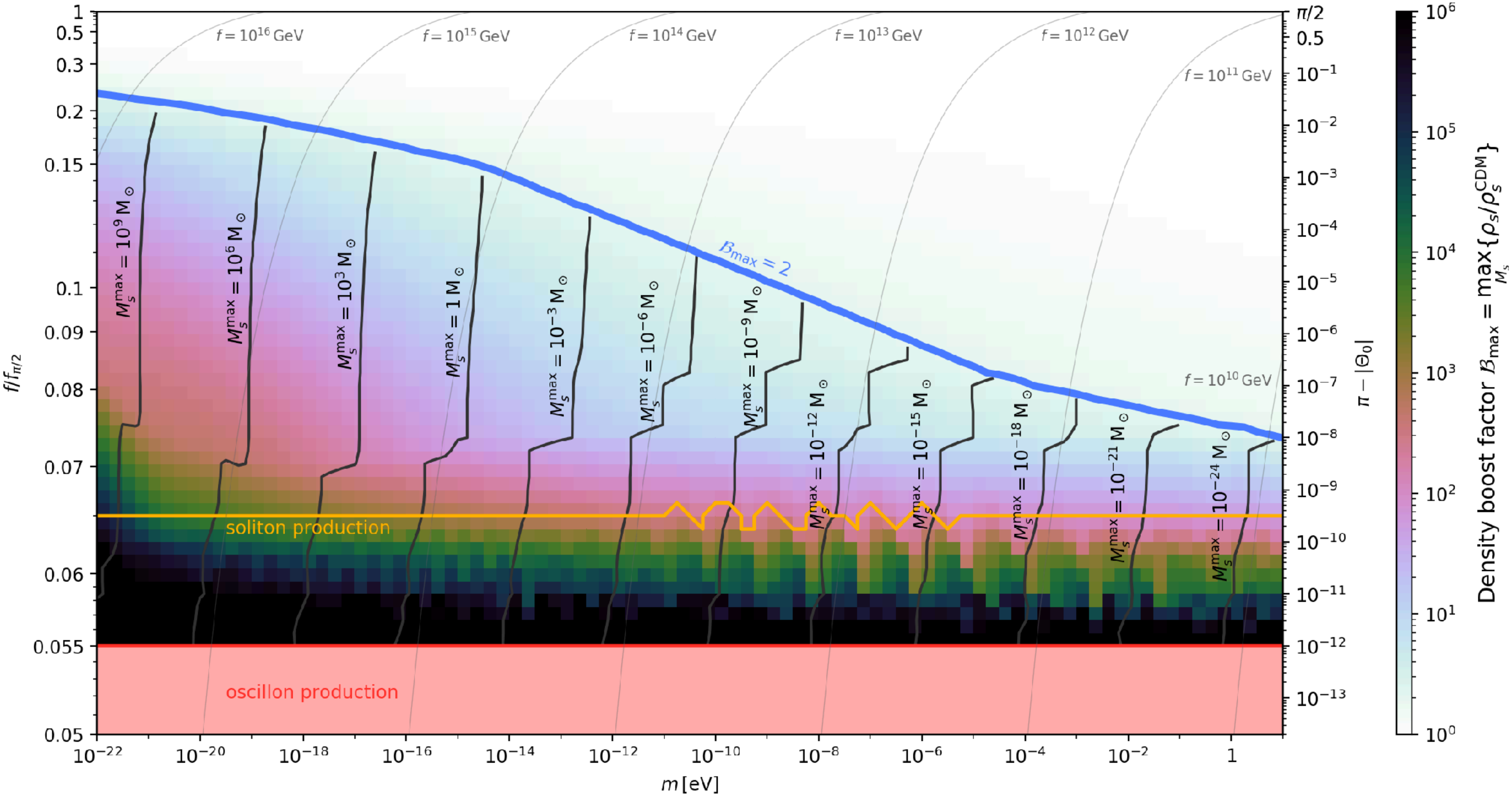
$$\text{Hamiltonian energy density} = \frac{|\nabla\psi|^2}{2m} + V_{grav}(\psi) - \lambda|\psi|^4 + \lambda'|\psi|^6$$

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

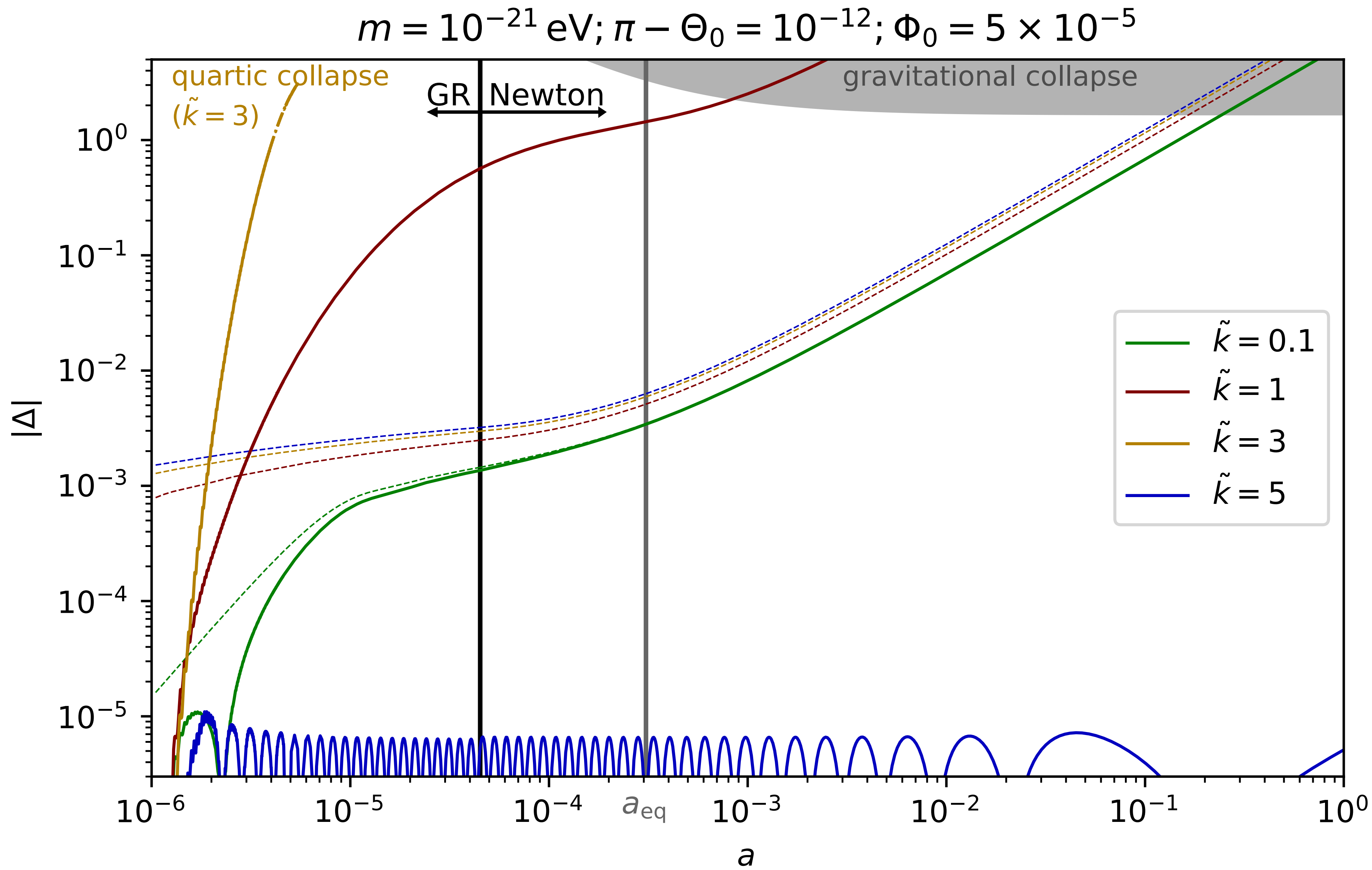
Solitons: Large (R> 1/m) scalar field configurations balancing kinetic pressure against gravity

Oscillons: Small (R~ 1/m) scalar field configurations balancing kinetic pressure against gravity

Delayed Onset of Oscillation

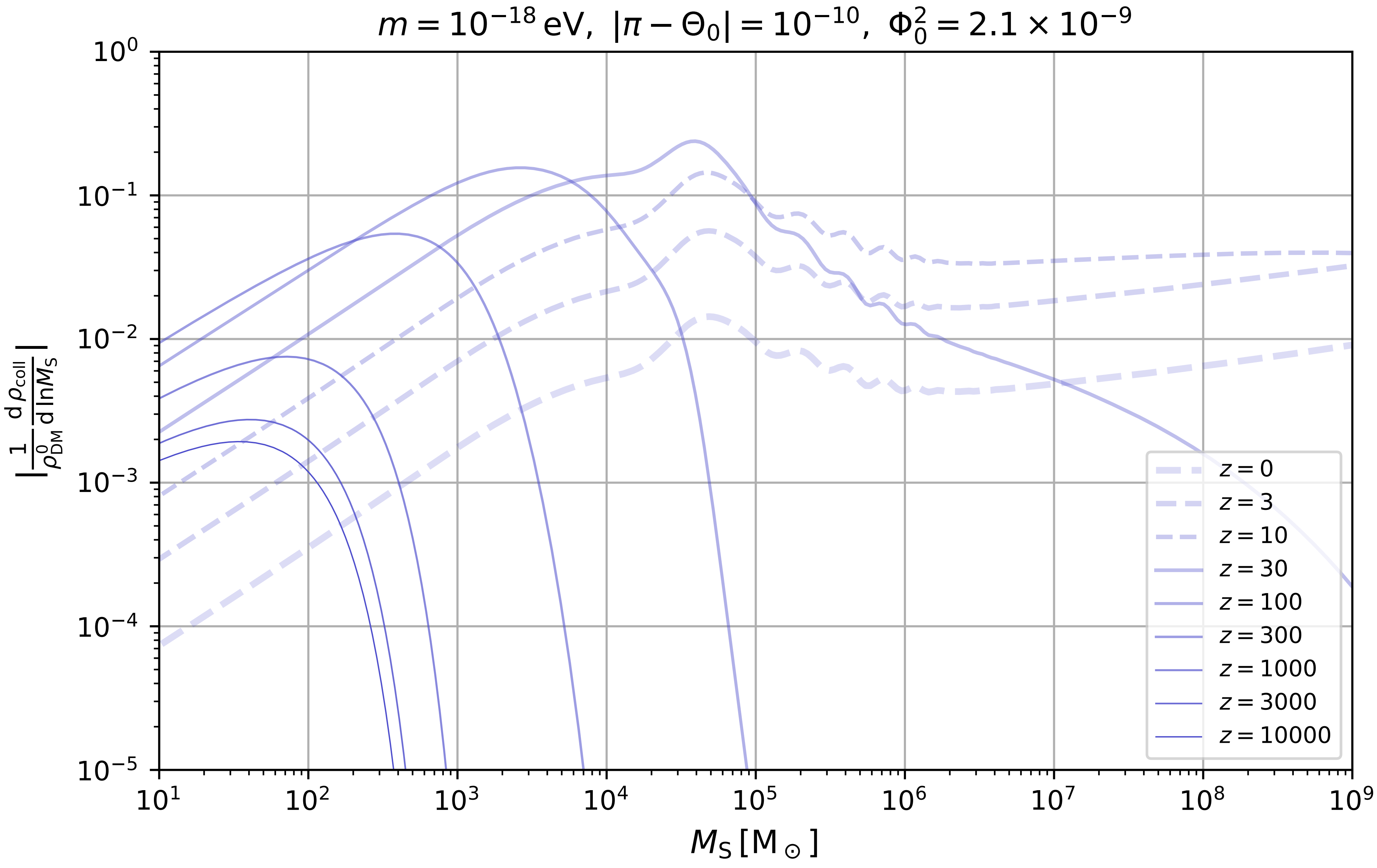


Growth of density perturbations as a function of scale and time



Initial conditions: scale invariant spectrum

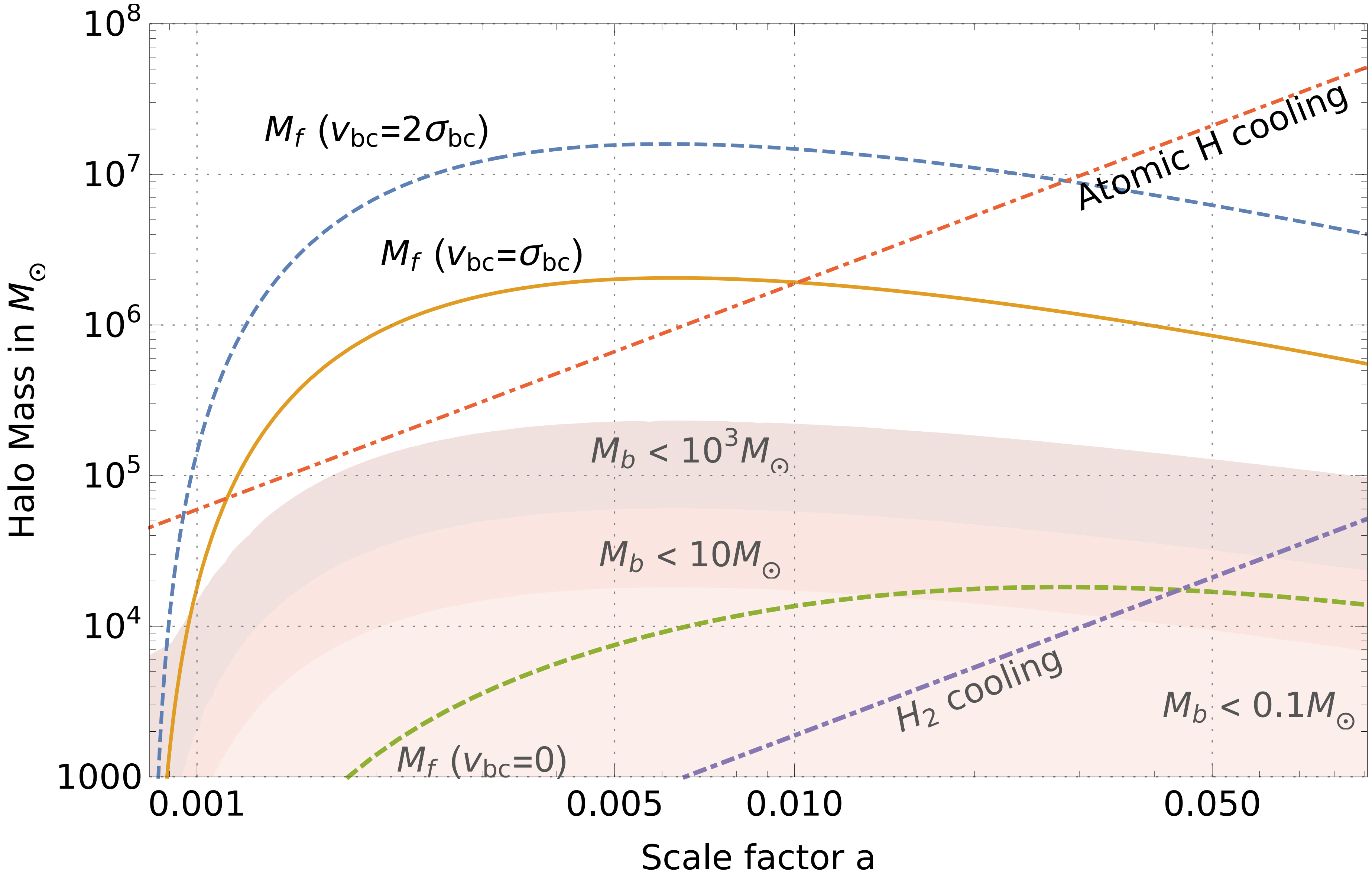
Press-Schechter



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?

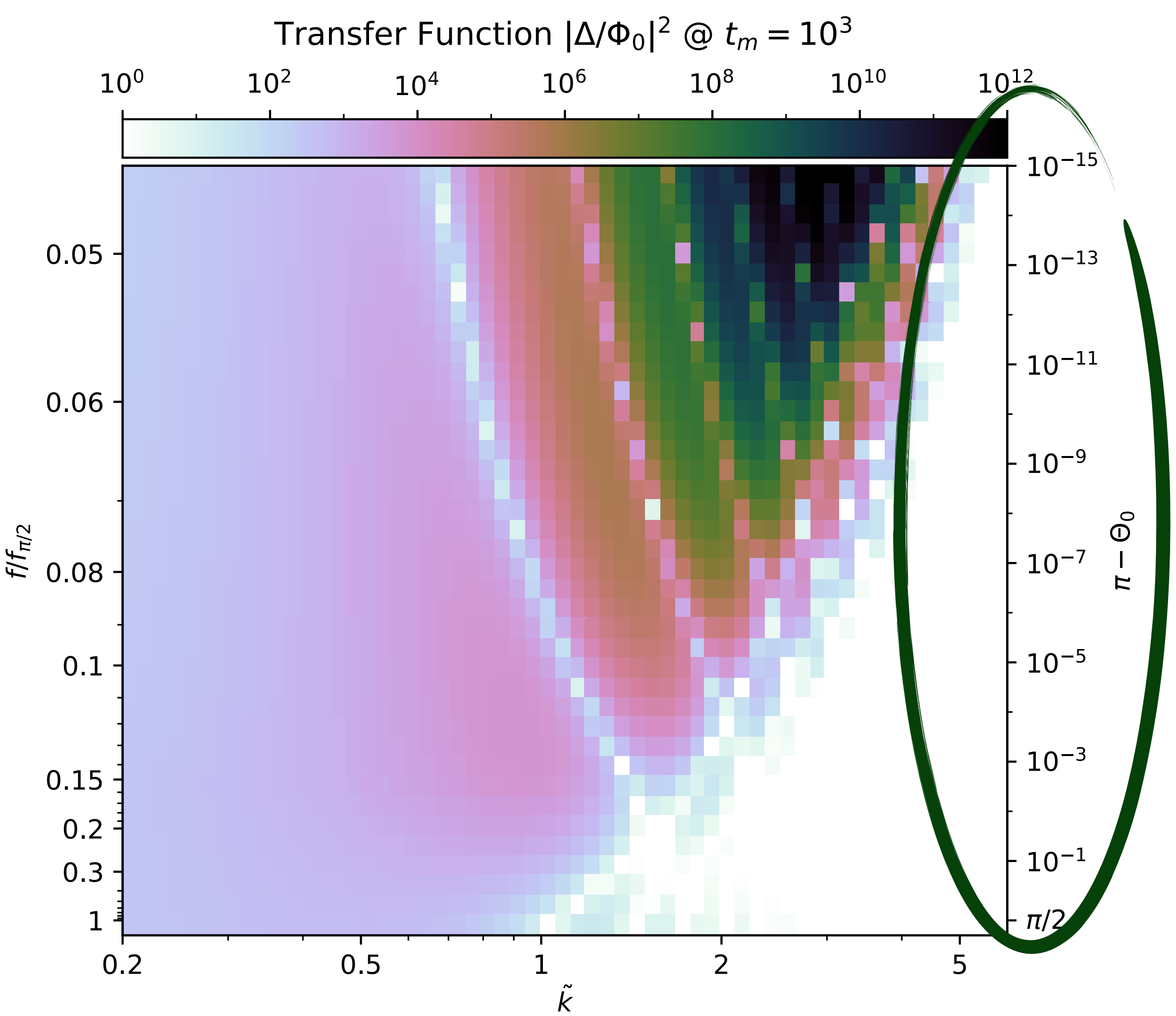
- Dynamics fixing $\Theta=\pi$ during inflation

- Environmental selection just like the case of the QCD axion outside the traditional axion window

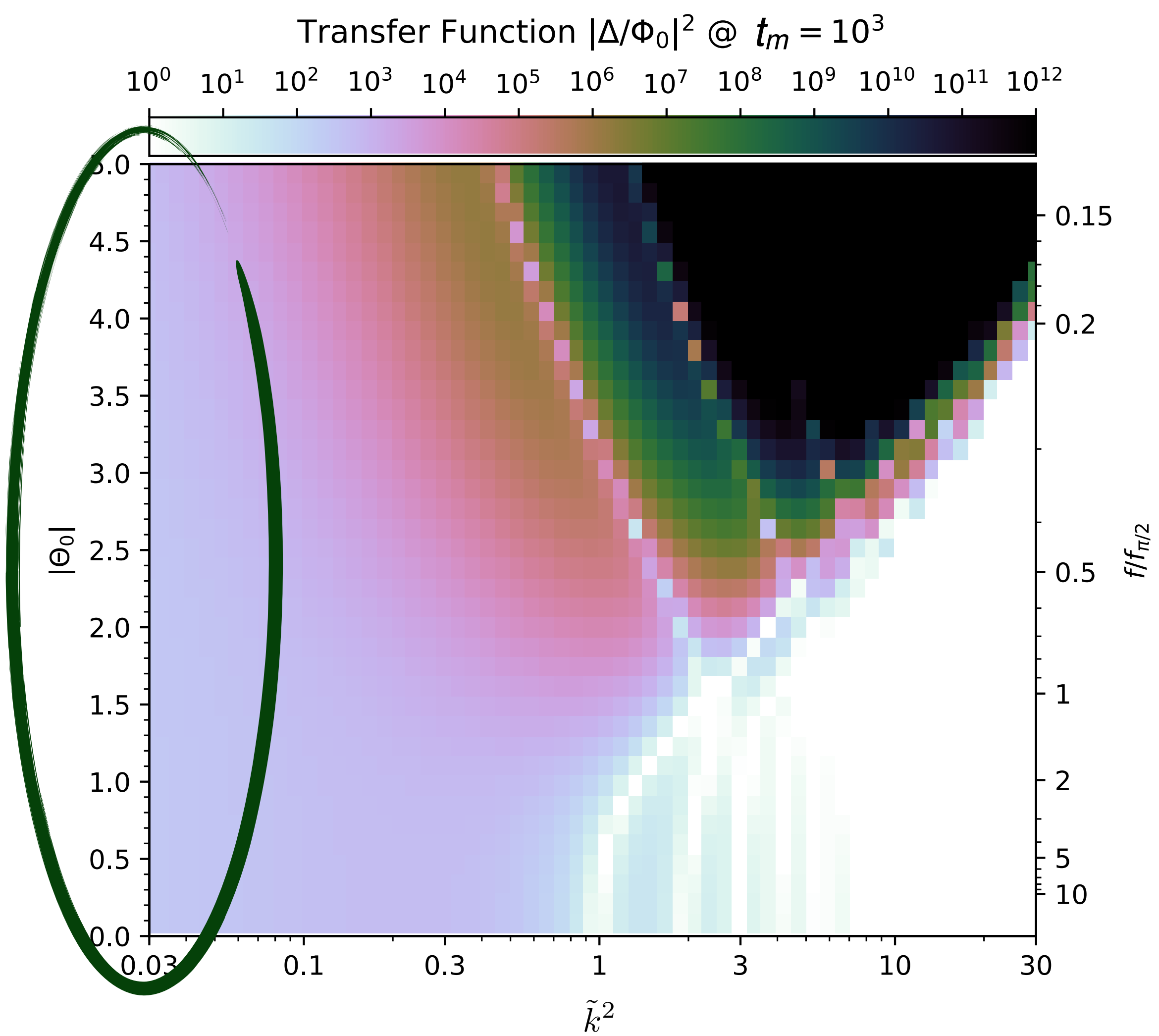
- For string axions, a cosine potential is not the only option

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

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

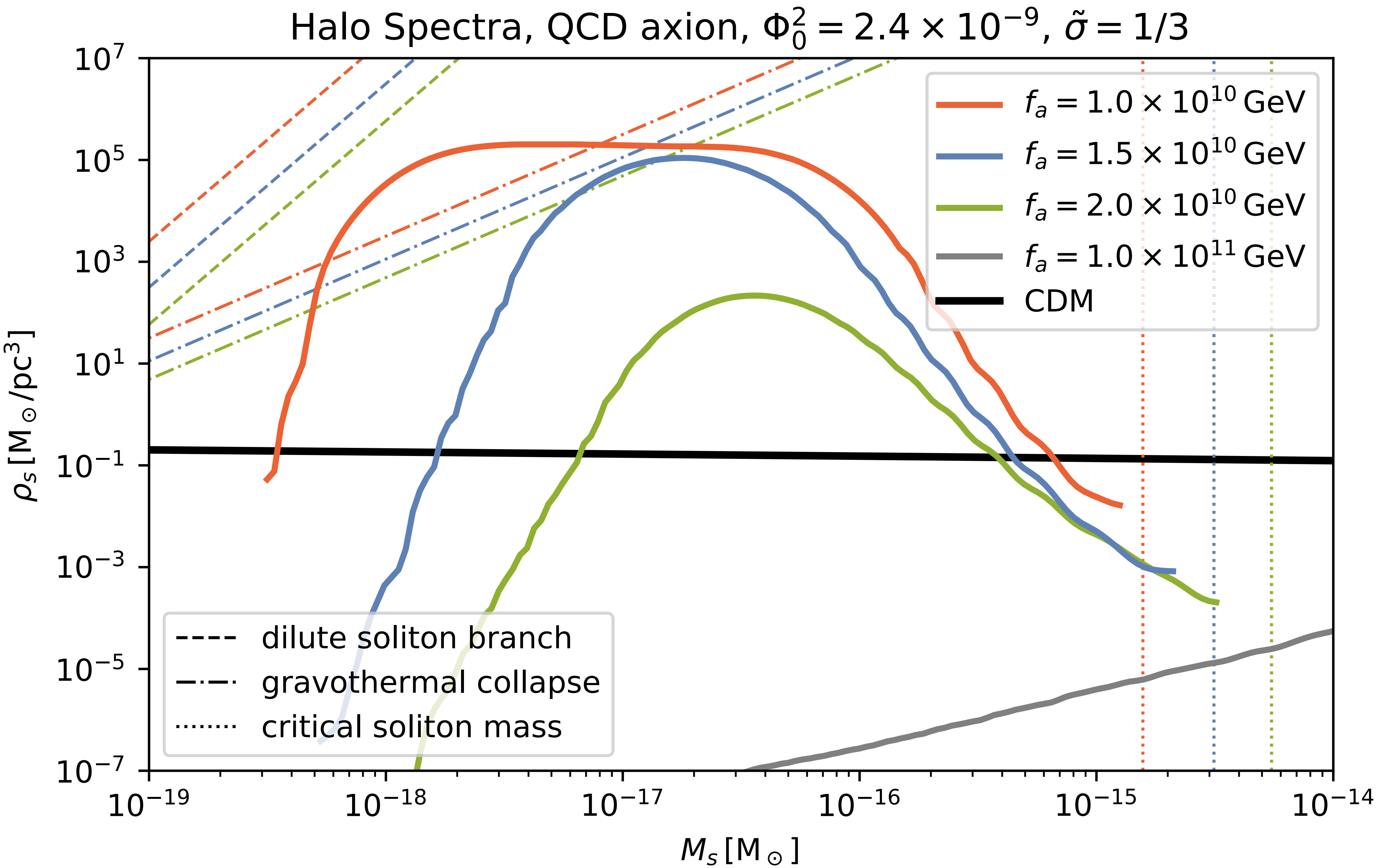
with

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

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

- Dynamics of the large misalignment mechanism
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