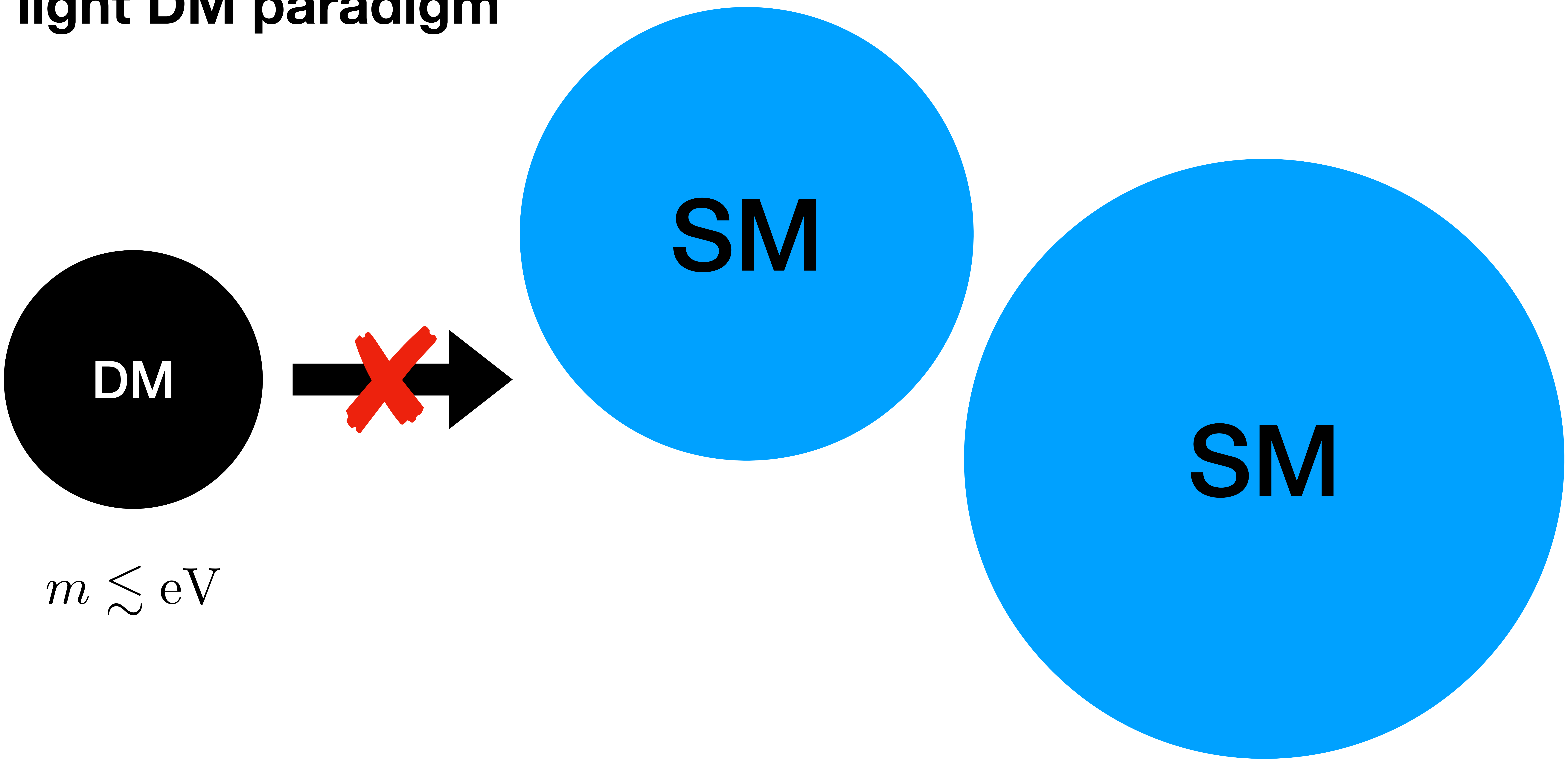
# Pushing light millicharged dark matter to its limits

## [2102.08394] with Joerg Jaeckel

Sebastian Schenk (IPPP Durham), 5 March 2021

# Pushing light millicharged dark matter to its limits

## The very light DM paradigm




$m \lesssim \mathrm{eV}$

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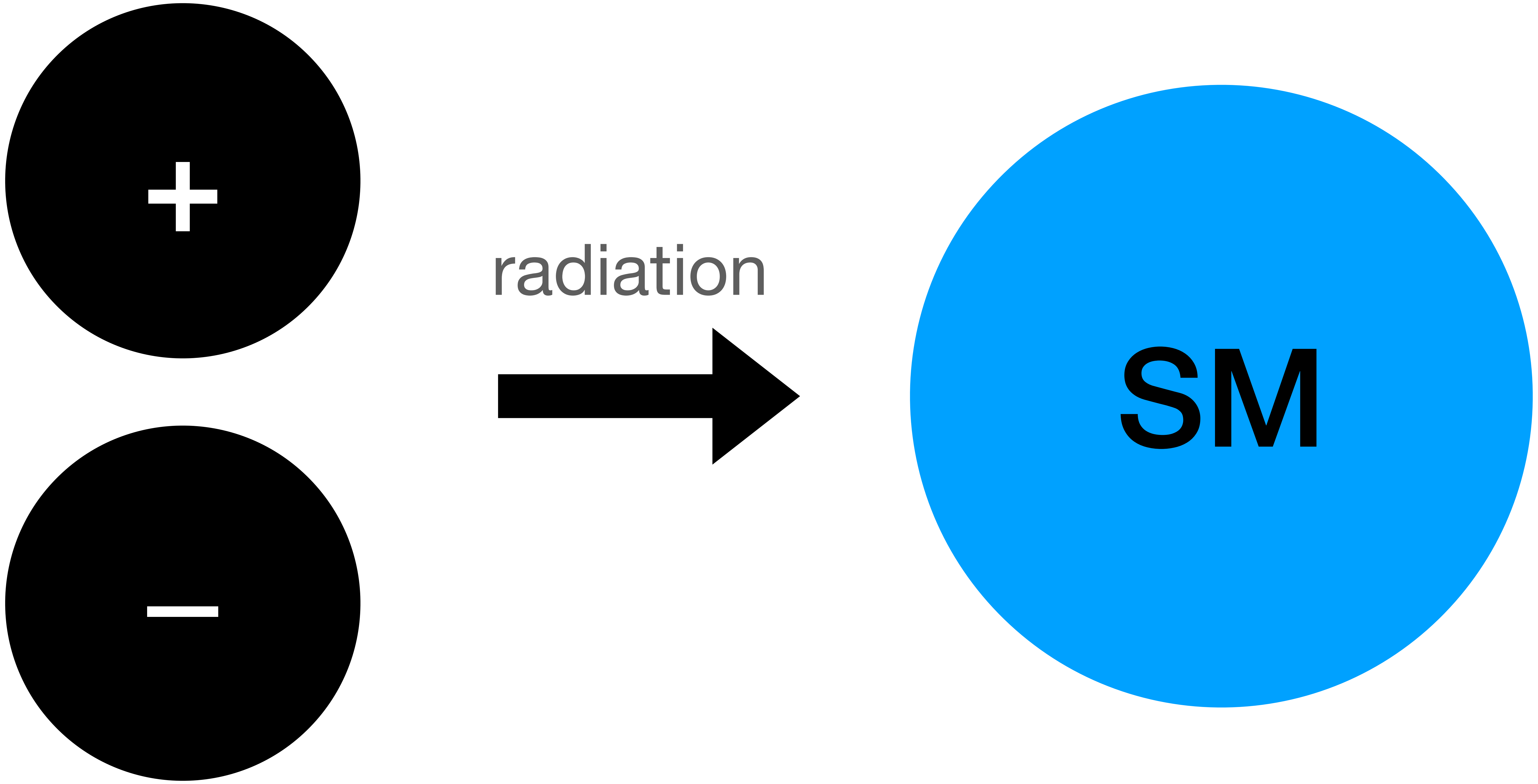
## The very light DM paradigm




$m \lesssim \mathrm{eV}$

[Preskill, Wise, Wilczek; 1983]
[Abbott, Sikivie; 1983]
[Dine, Fischler; 1983]
[Nelson, Scholtz; 2011]
[Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald, 2012]

# Producing very light dark matter

## The misalignment mechanism

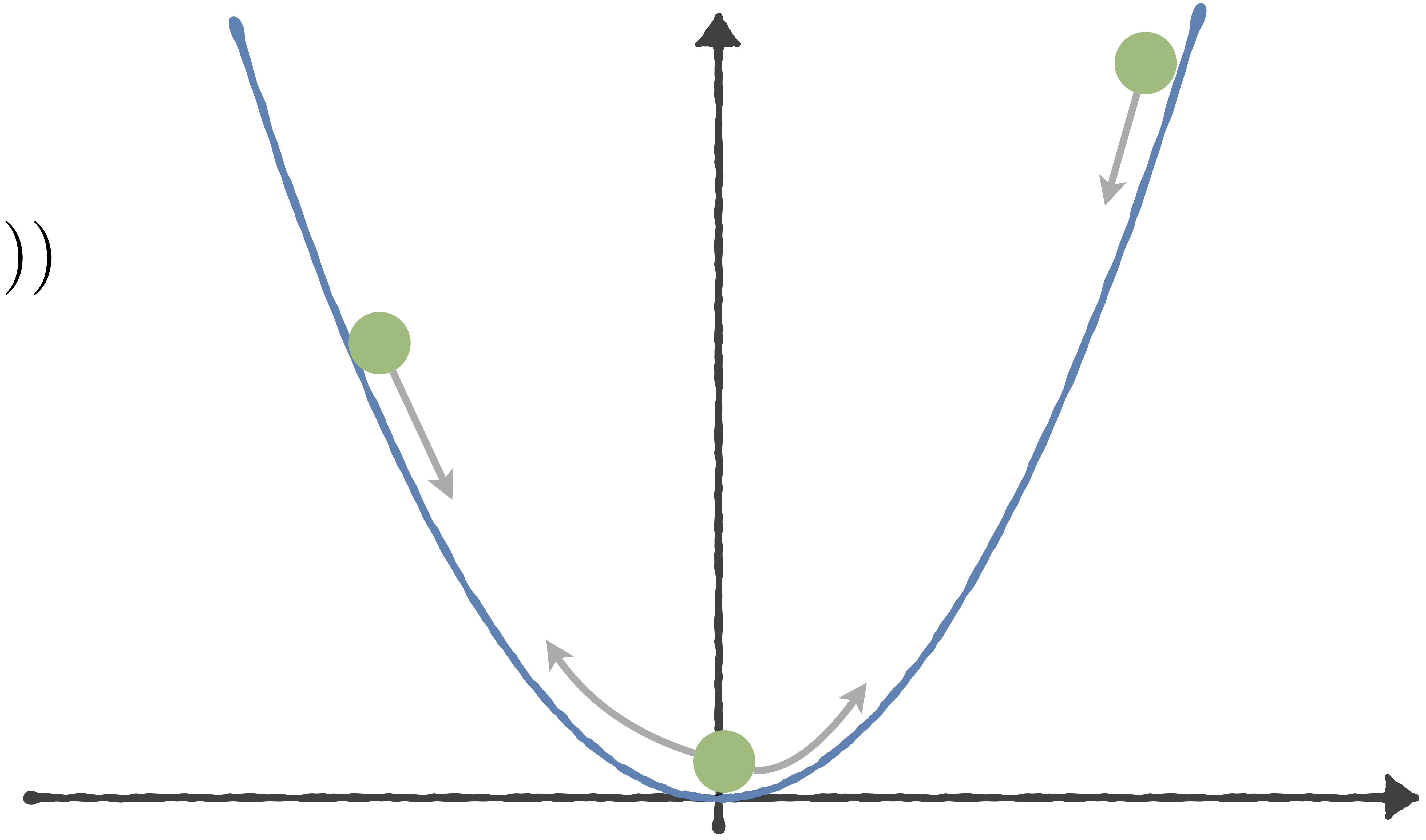
$$V(\varphi) = \frac{m^2}{2}\varphi^2 \quad \rightsquigarrow \quad \ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$$

Harmonic oscillations

$$\varphi(t) = \varphi_0 \left(\frac{a_0}{a}\right)^{\frac{3}{2}} \cos\left(m\left(t - t_0\right)\right)$$
$$= \Phi(t)\cos\left(m\left(t - t_0\right)\right)$$

DM energy density

$$\langle\rho\rangle \sim \frac{1}{2}m^2\Phi^2(t) \propto a^{-3}$$



# Resonant depletion of millicharged DM

# Resonant depletion of millicharged DM

## Scalar QED as a toy theory

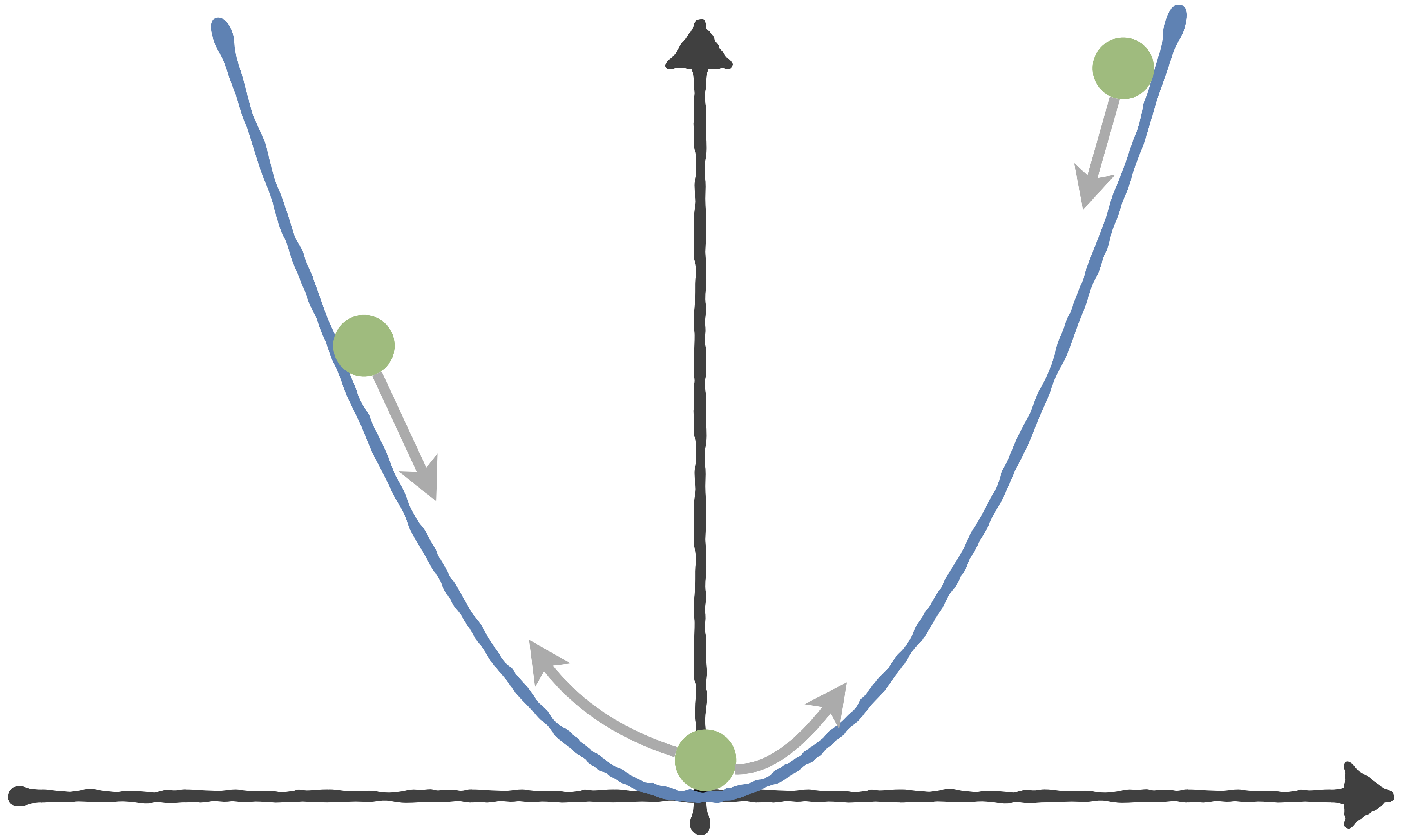
$$\mathcal{L} = -\frac{1}{4}F^2 + (D_\mu\phi)^\dagger D^\mu\phi - m^2\phi^\dagger\phi$$

Annihilation channels are open

$$\phi\phi \to AA$$

Electric charge q should be tiny

$$\ddot{A} + H\dot{A} + \left(\frac{k^2}{a^2} + q^2\varphi^2\right)A = 0$$



# Parametric resonance

## Instabilities of the Mathieu equation

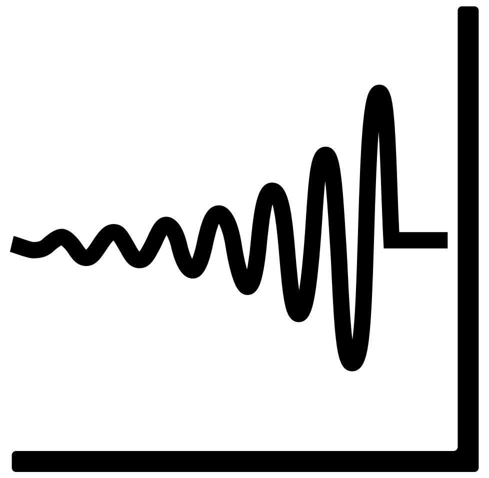
Mathieu equation

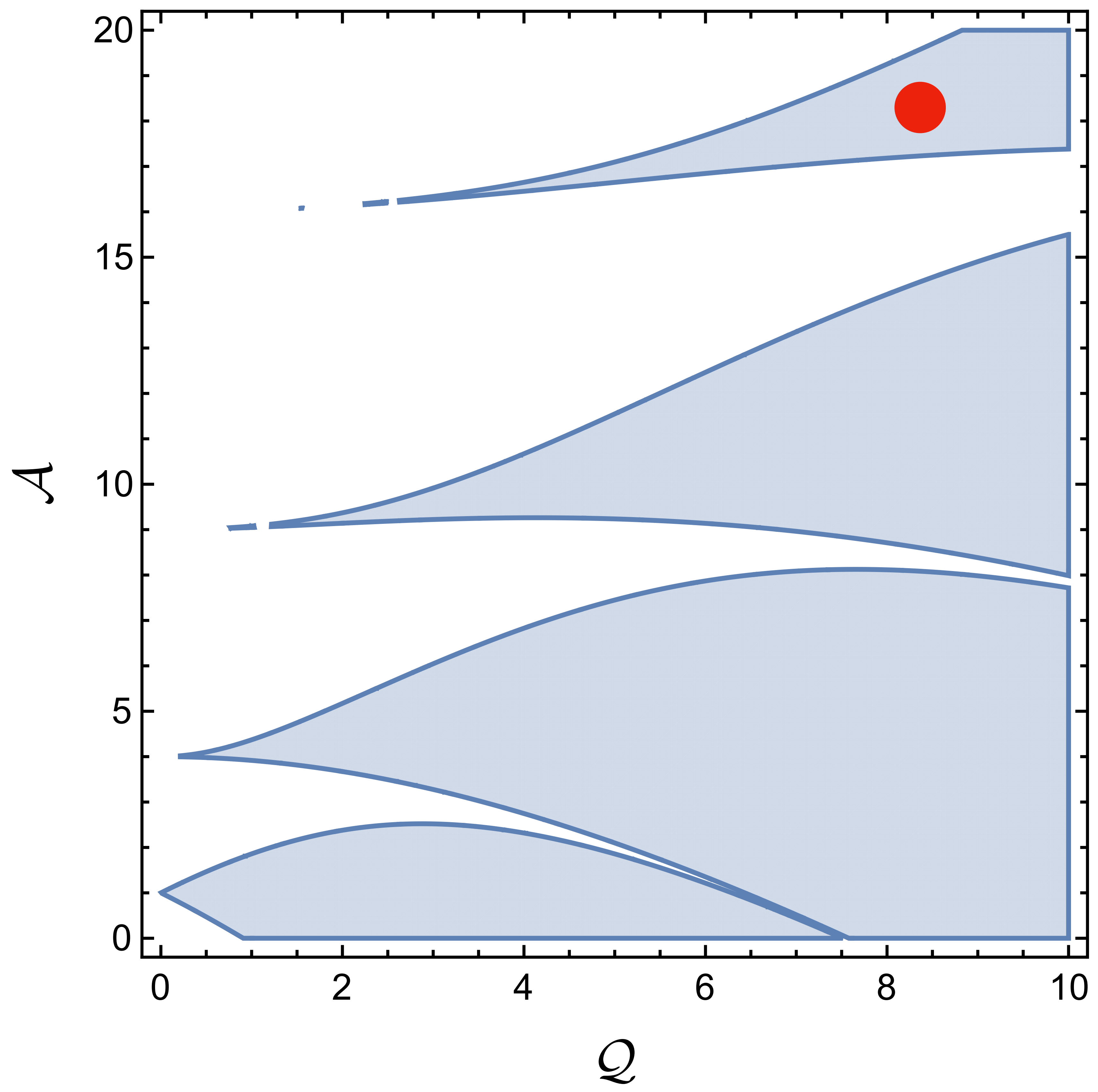
$$\frac{d^2}{dx^2}A + \left(\mathcal{A}_k - 2\mathcal{Q}\cos\left(2x\right)\right)A = 0$$

$$\mathcal{A}_k = \frac{k^2}{a^2m^2} + \frac{3}{4}\frac{H^2}{m^2} + 2\mathcal{Q} \qquad \mathcal{Q} = \frac{q^2\Phi^2}{4m^2}$$

Solutions have an exponential part

$$A \propto \exp\left(\mu_k m t\right)$$





# Parametric resonance

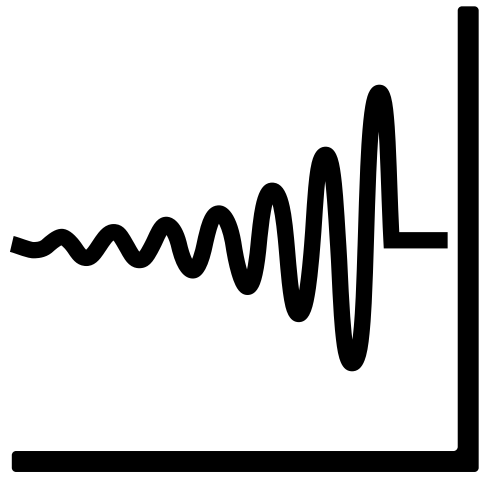
## Instabilities of the Mathieu equation

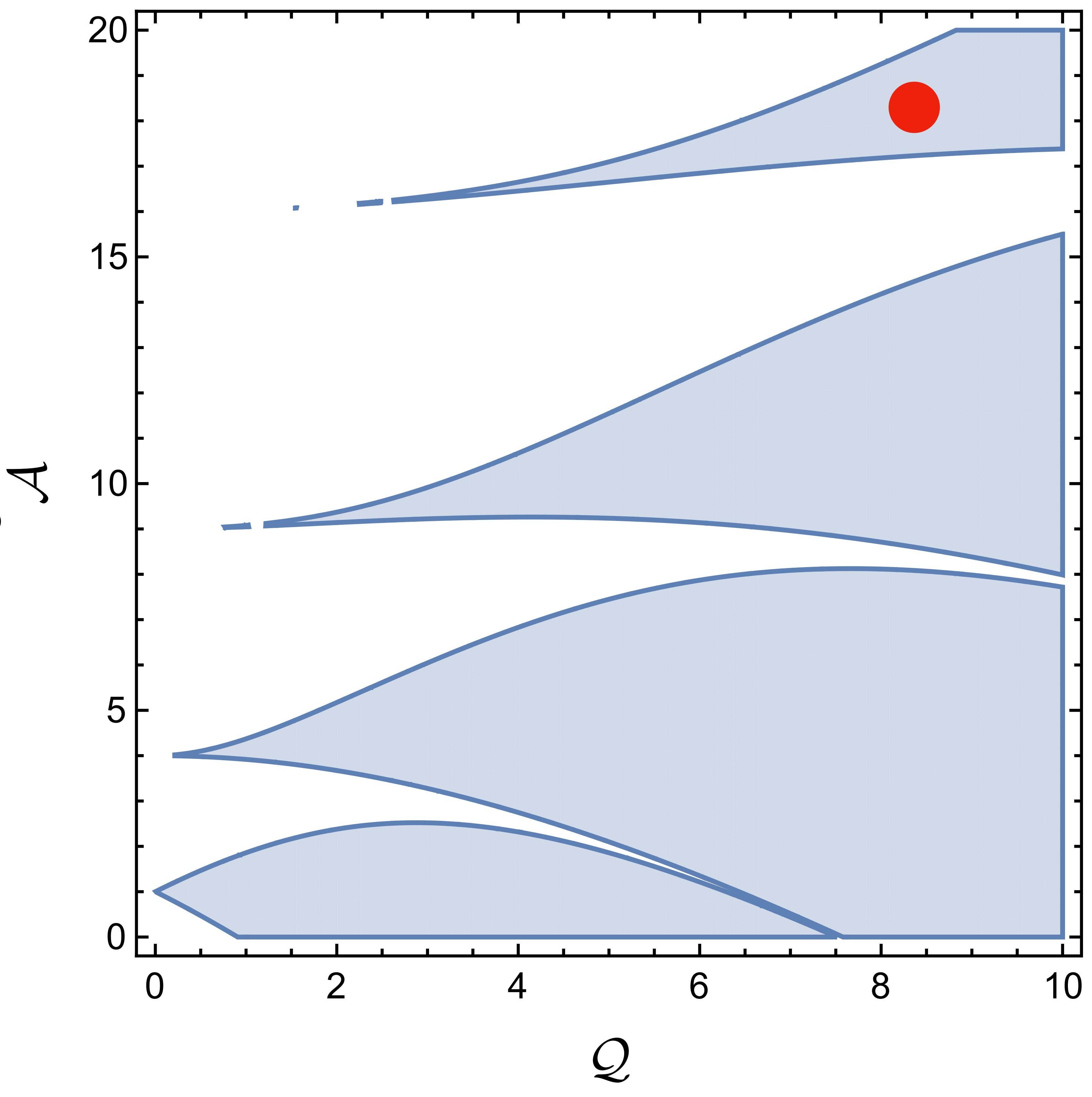
Mode functions determine occupation number

$$n_k = \frac{\omega_k}{2}\left(\frac{|\dot{A}|^2}{\omega_k^2} + |A|^2\right)$$

Unstable solutions = rapid productions of photons

$$n_k \propto \exp\left(2\mu_k m t\right)$$





# What about the expansion of the Universe?

# Including the expansion of the Universe

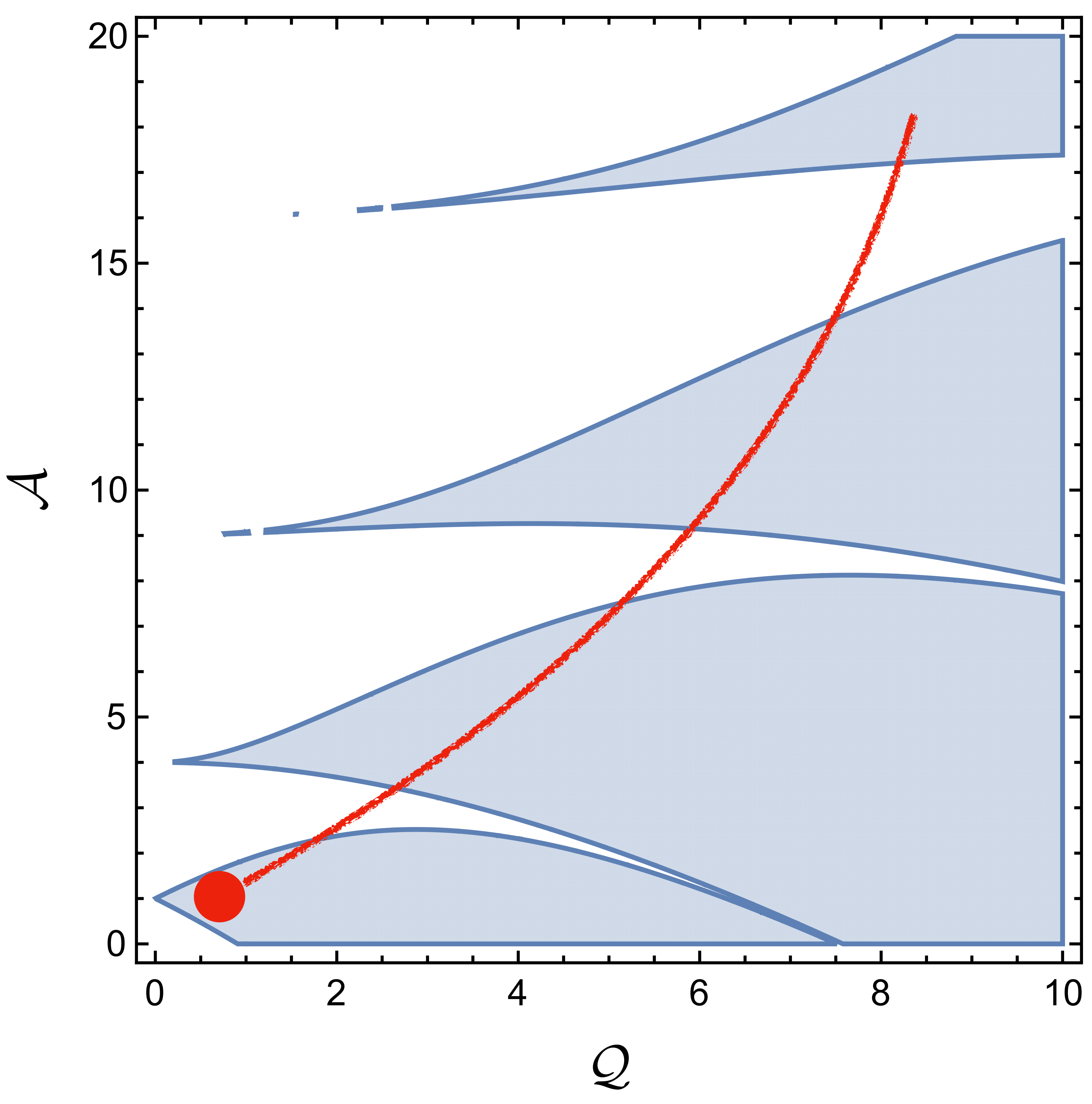
Photons get redshifted

$$\frac{\delta k}{k} \simeq H\delta t$$

Trajectory in the instability chart $(\mathcal{A}_k(t),\ \mathcal{Q}(t))$

Exponential growth vs redshift

$$\delta t_{\rm exp} \simeq \frac{1}{2\mu_k m} \qquad \delta t_{\rm redshift} \simeq \frac{1}{H}\frac{\delta k}{k}$$



# Including the expansion of the Universe

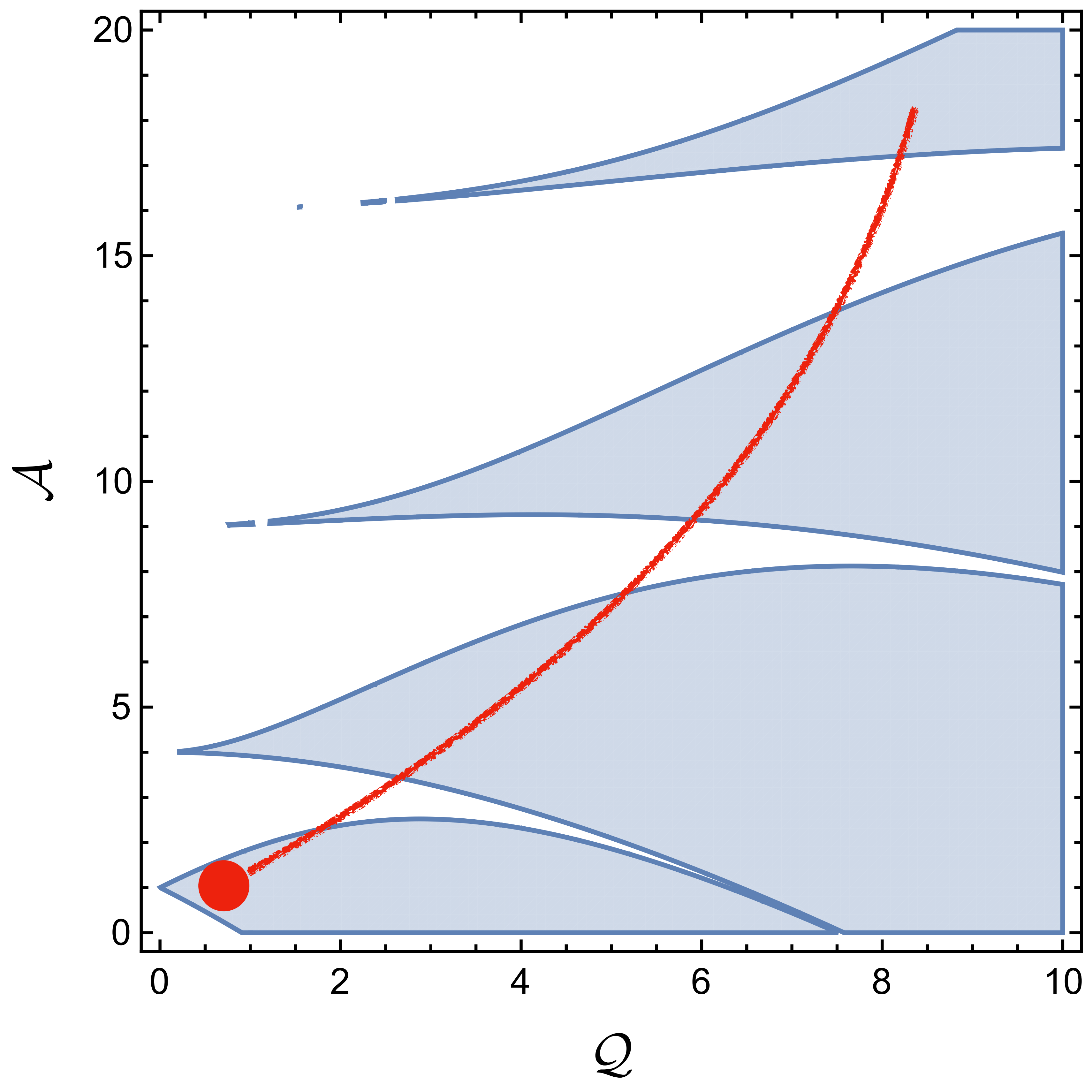
In order to avoid a fragmentation of the DM

$$\frac{1}{2\mu_k m} \gtrsim \frac{1}{H}\frac{\delta k}{k}$$

Can be translated into a condition on the charge

Consider different regimes

$$\mathcal{Q} \ll 1 \qquad\qquad \mathcal{Q} \gg 1$$



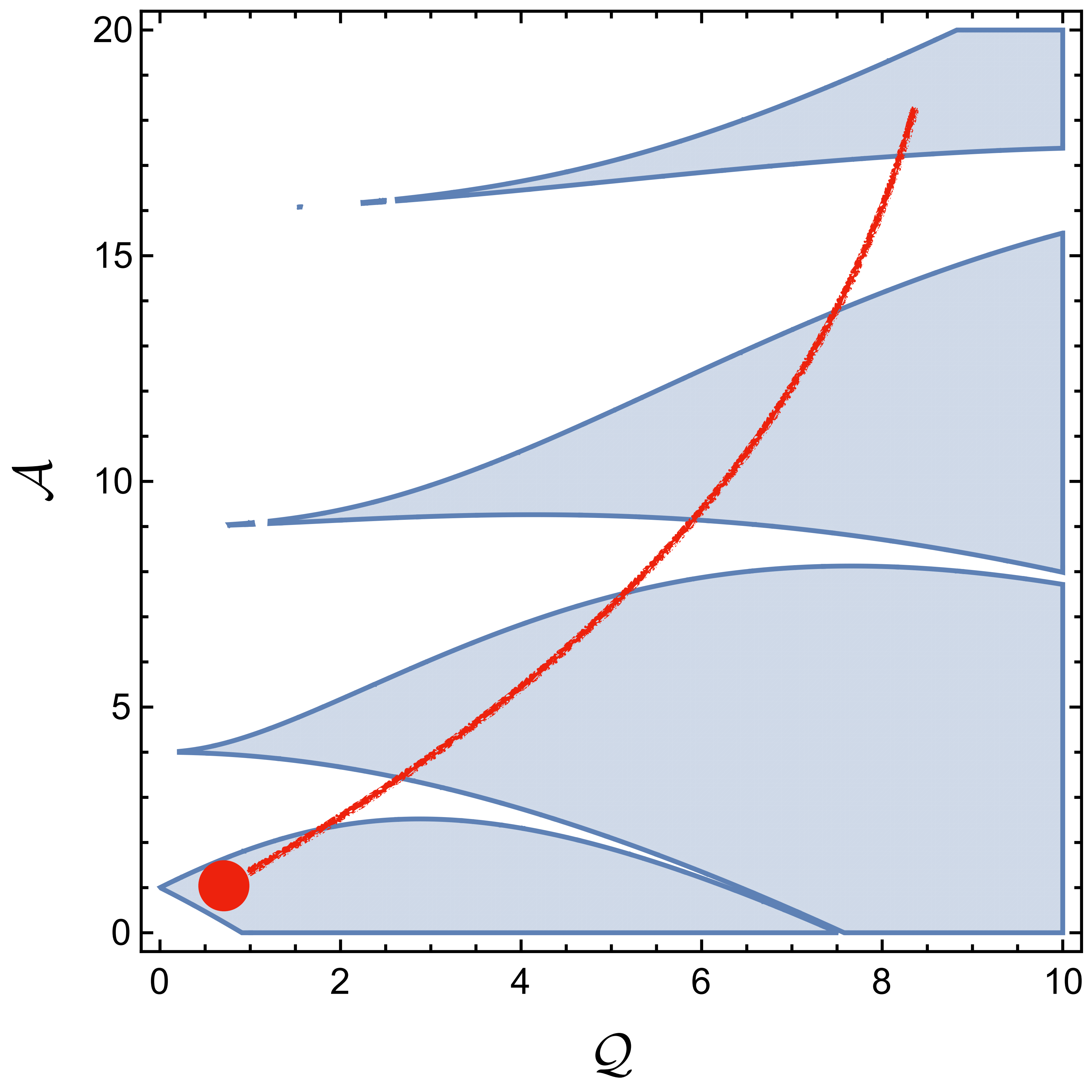
# Including the expansion of the Universe

Narrow resonance

$$\log\left(\frac{1}{n_0}\sqrt{\frac{m}{H}}\frac{\Phi}{qm}\right) \gtrsim \frac{m}{H}\left(\frac{q\Phi}{2m}\right)^4 \sim a^{-4}$$

Broad resonance

$$\log\left(\frac{1}{n_0}\sqrt{\frac{m}{H}\frac{\kappa}{q^2}}\right) \gtrsim \frac{2\kappa}{3}\frac{m}{H}\left(\frac{q\Phi}{2m}\right)^{\frac{4}{3}} \sim \text{const.}$$



# The plasma mass of the photon…

## …blocks the resonant depletion

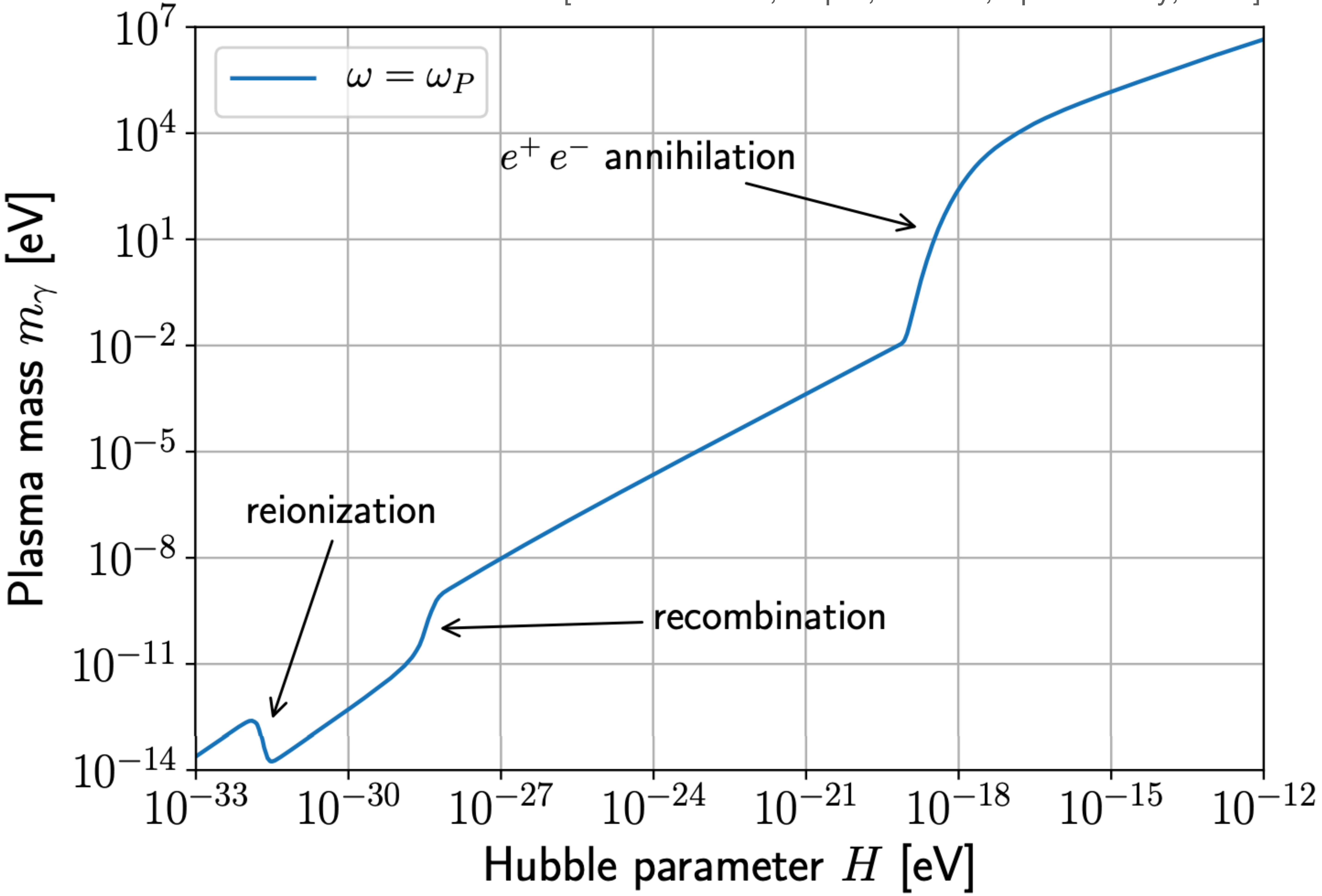
Mathieu parameter shift

$$\mathcal{A}_k \propto \frac{k^2}{a^2} \to \frac{k^2}{a^2} + m_\gamma^2$$

Resonance becomes inefficient

$$m_\gamma^2 \gtrsim m^2$$

[Alonso-Alvarez, Gupta, Jaeckel, Spannowsky; 2019]



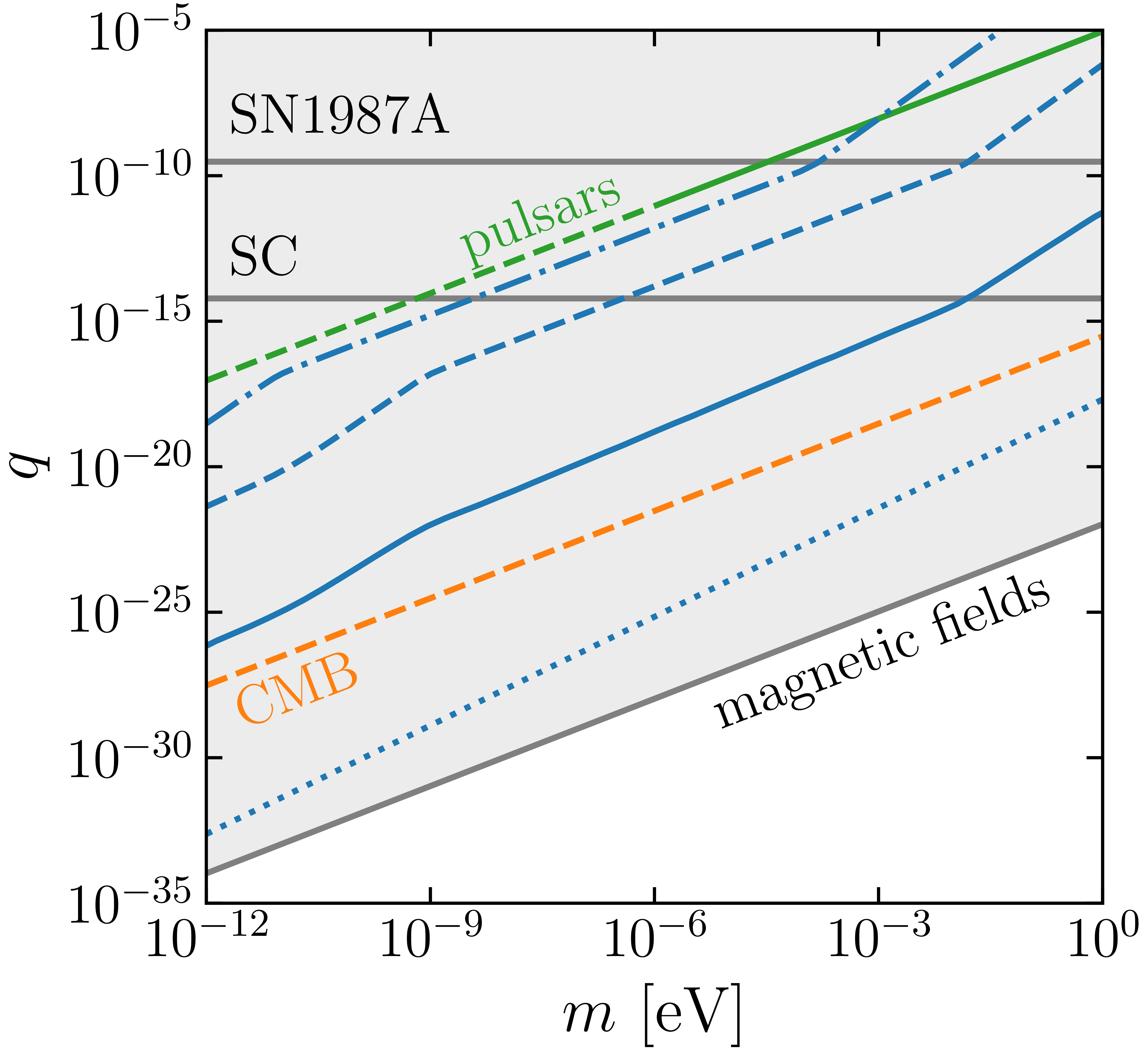
# Resonant depletion of millicharged DM

## Scalar QED toy theory

Evaluate at the earliest possible time

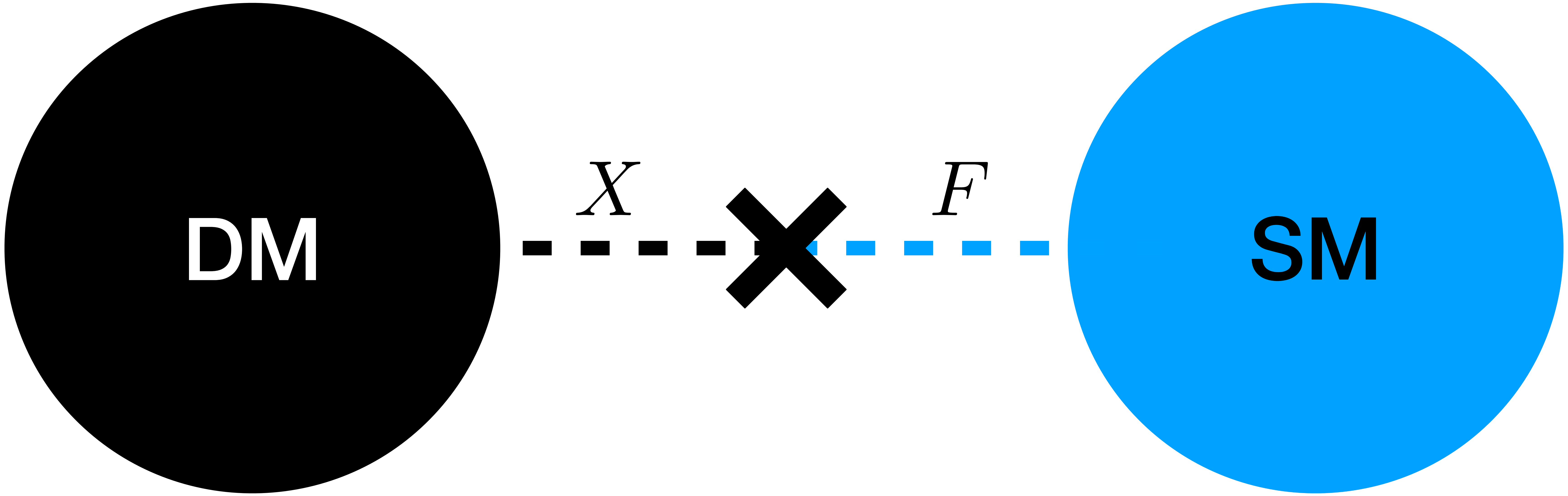
Massive photons possible

$$q \gtrsim 4\frac{m_\gamma^2}{m\Phi}$$



# Resonant depletion of millicharged DM

## Kinetic mixing with a hidden photon




$q_{\text{eff}} = \epsilon q g$

# Resonant depletion of millicharged DM

## Kinetic mixing case

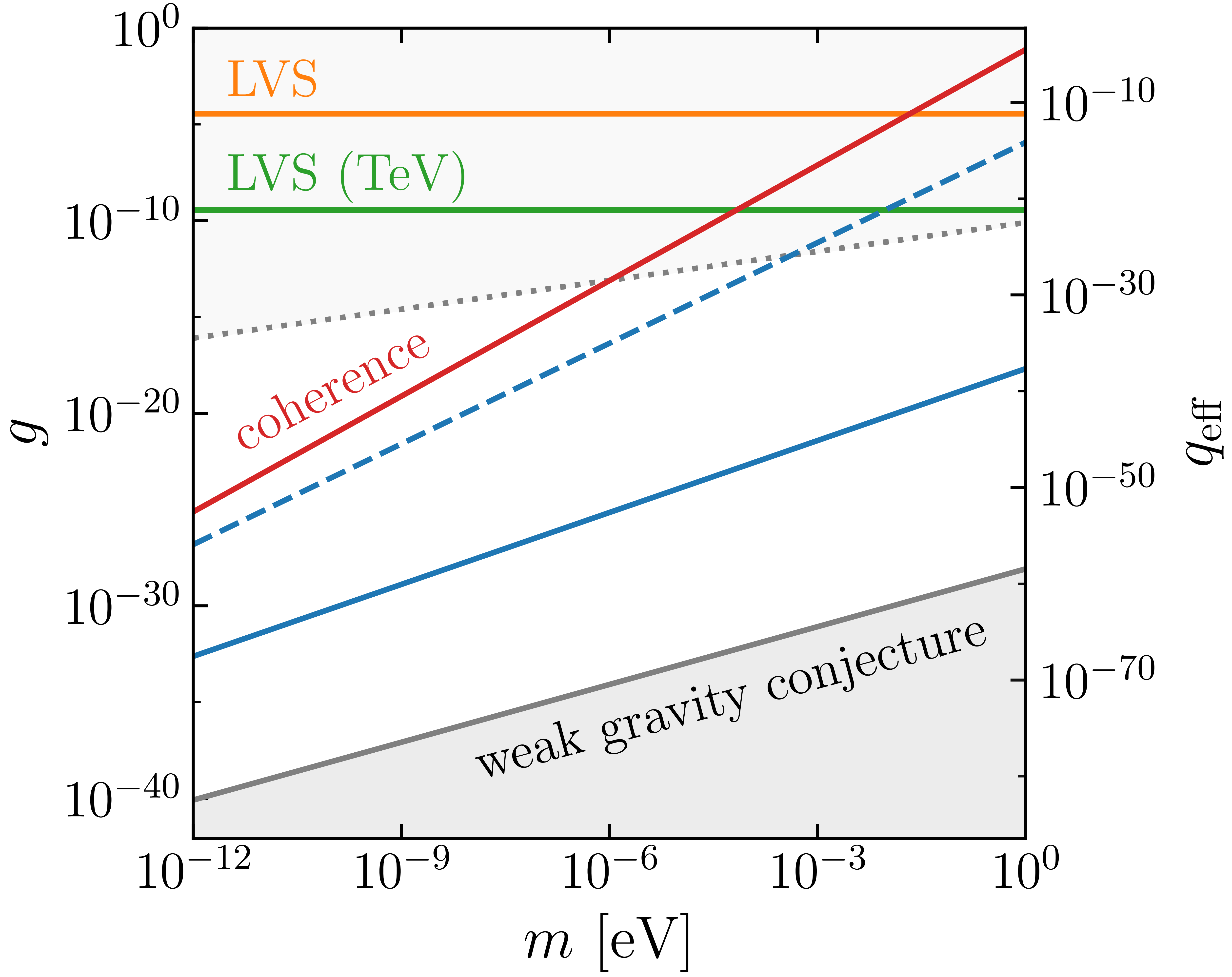
DM largely annihilates into HP

Backreaction

$$\rho_A \rightleftharpoons \rho_\phi$$

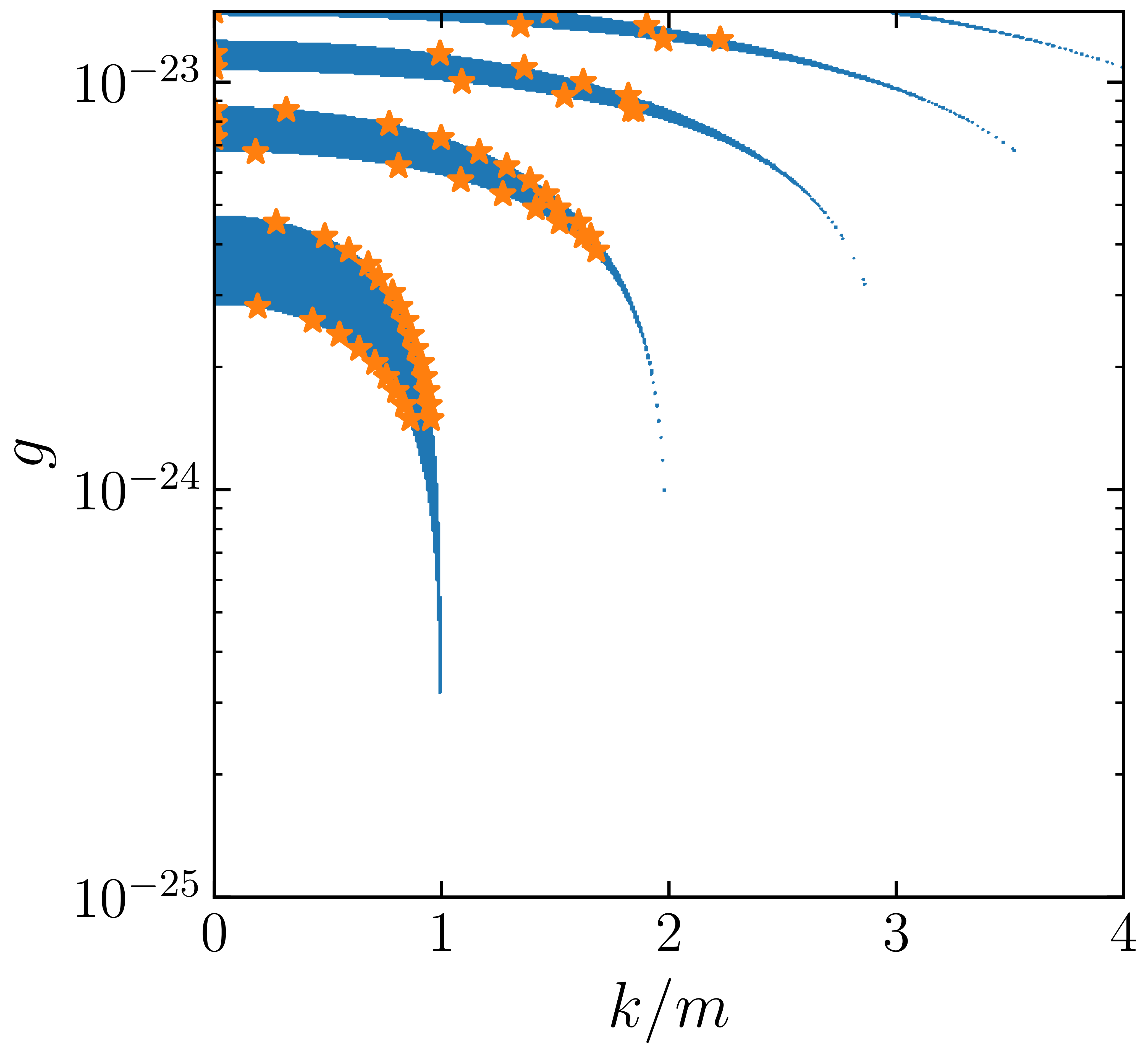
Coherence

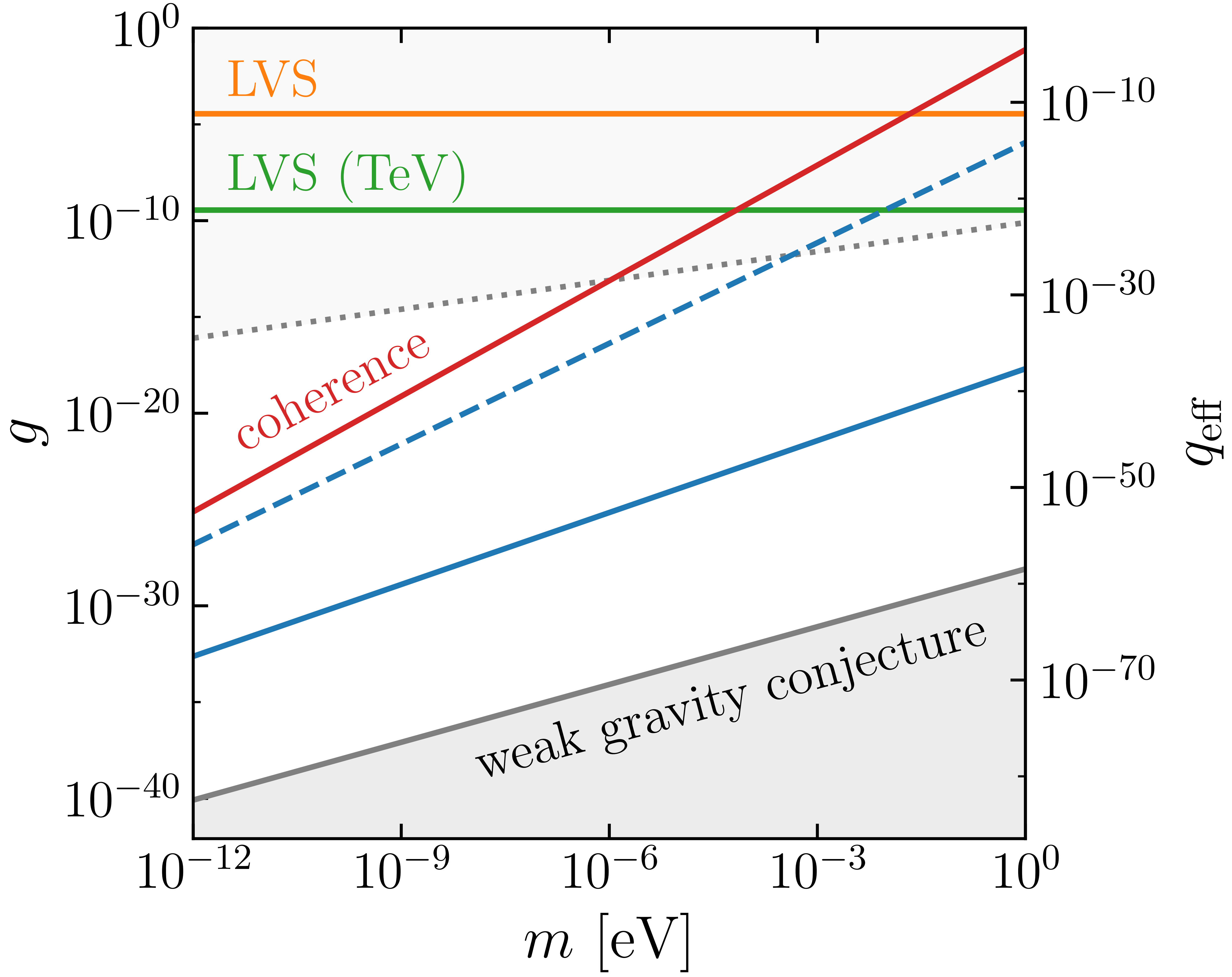
$$\Delta k \gtrsim m v_{mr} \left( \frac{a_{mr}}{a} \right)$$



# Resonant depletion of millicharged DM

## Independent of mixing parameter



# Pushling light millicharged DM to its limits
## Conclusions

High occupation number may lead to rapid production of gauge bosons

$$n_k \propto \exp\left(2\mu_k m t\right)$$

DM field transfers energy exponentially

Stability puts strong constraints on coupling

Why is there nothing left?