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# Phenomenology of GeV-scale dark matter near *p*-wave resonance

*(Based on arXiv:2401.02513)*

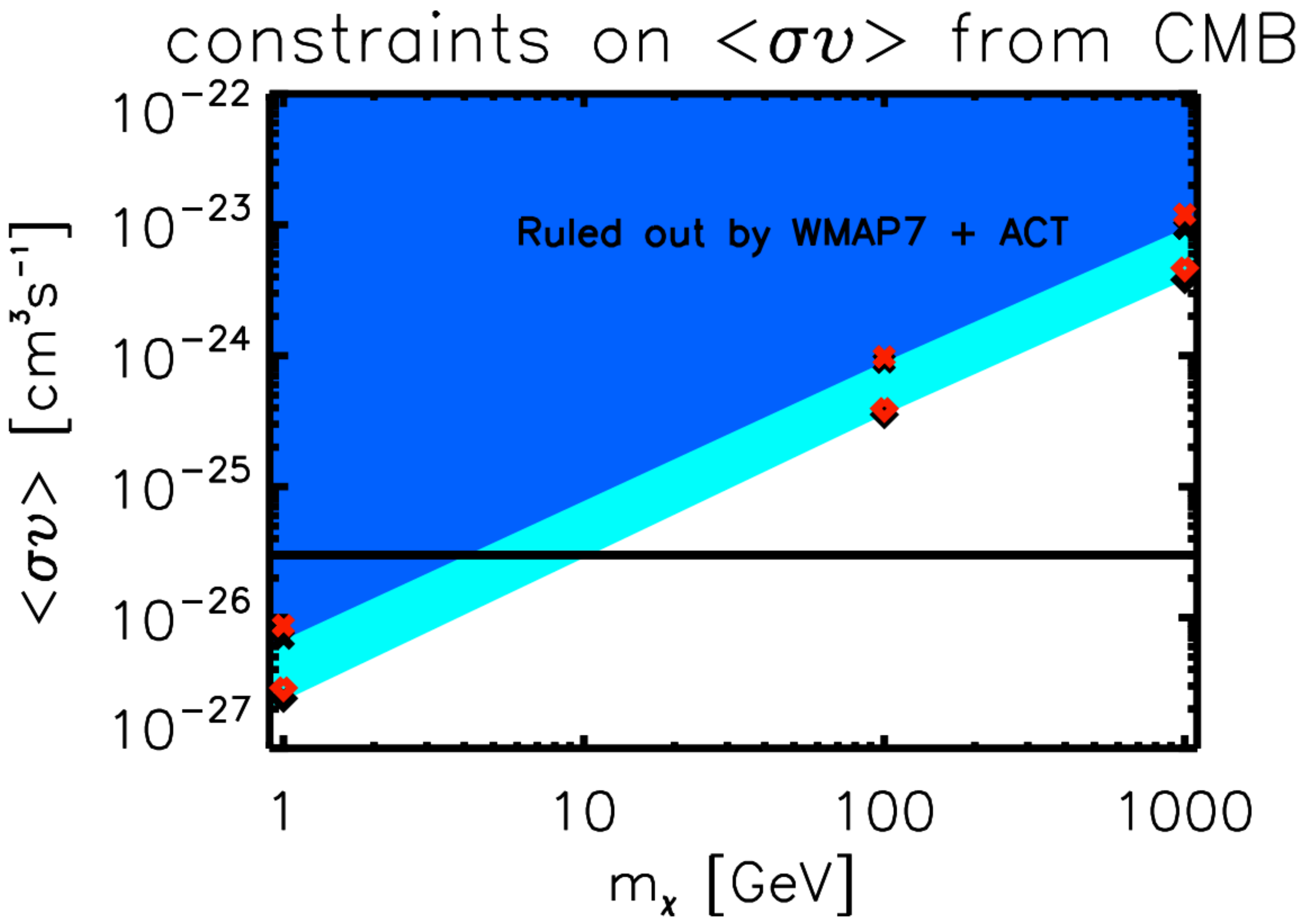

**Sreemanti Chakraborti**
**IPPP, Durham University**

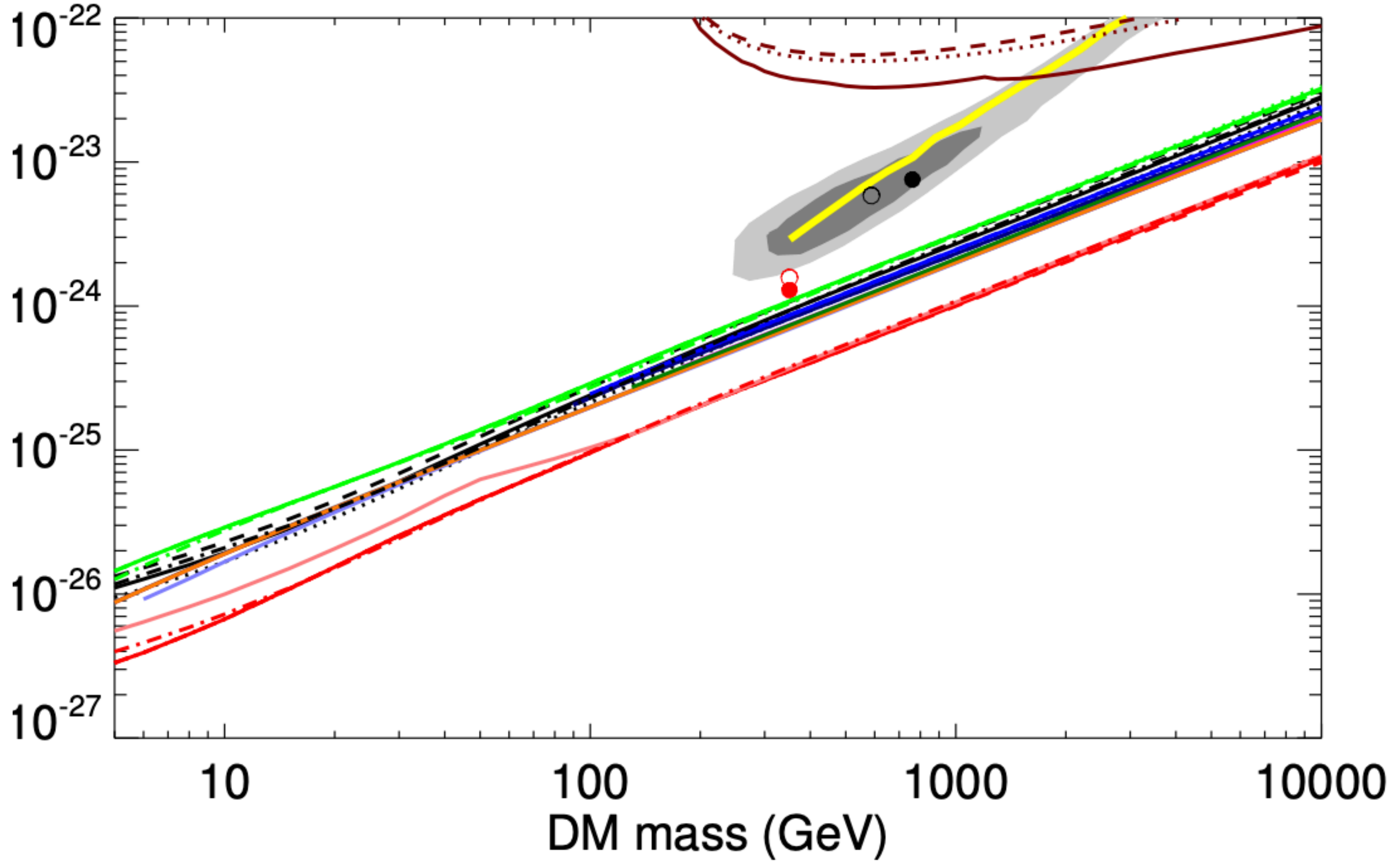

**Collaborators: G. Bélanger, Y. Génolini and P. Salati**

# Challenges

DM of mass range 100 MeV-a few GeV → stringent CMB limits !!!

PHYSICAL REVIEW D **84**, 027302 (2011)




T. Slatyer, Phys. Rev. D 93, 023527 (2016)

# Ways around

Velocity-dependent annihilation cross-section ??

- *p*-wave?
- BW resonance?

... why not have both ??

**New particles**

- Scalar : $\phi, Z_2$ odd → **DM**
- Dark photon : $X$ → mediator

$$\mathscr{L} \supset -\left\{ X_\mu J^\mu_\phi \equiv i g_x X^\mu \left( \phi^\dagger \partial_\mu \phi - \partial_\mu \phi^\dagger \phi \right) \right\} - \epsilon\, e Q_f \bar{f} \not{X} f$$

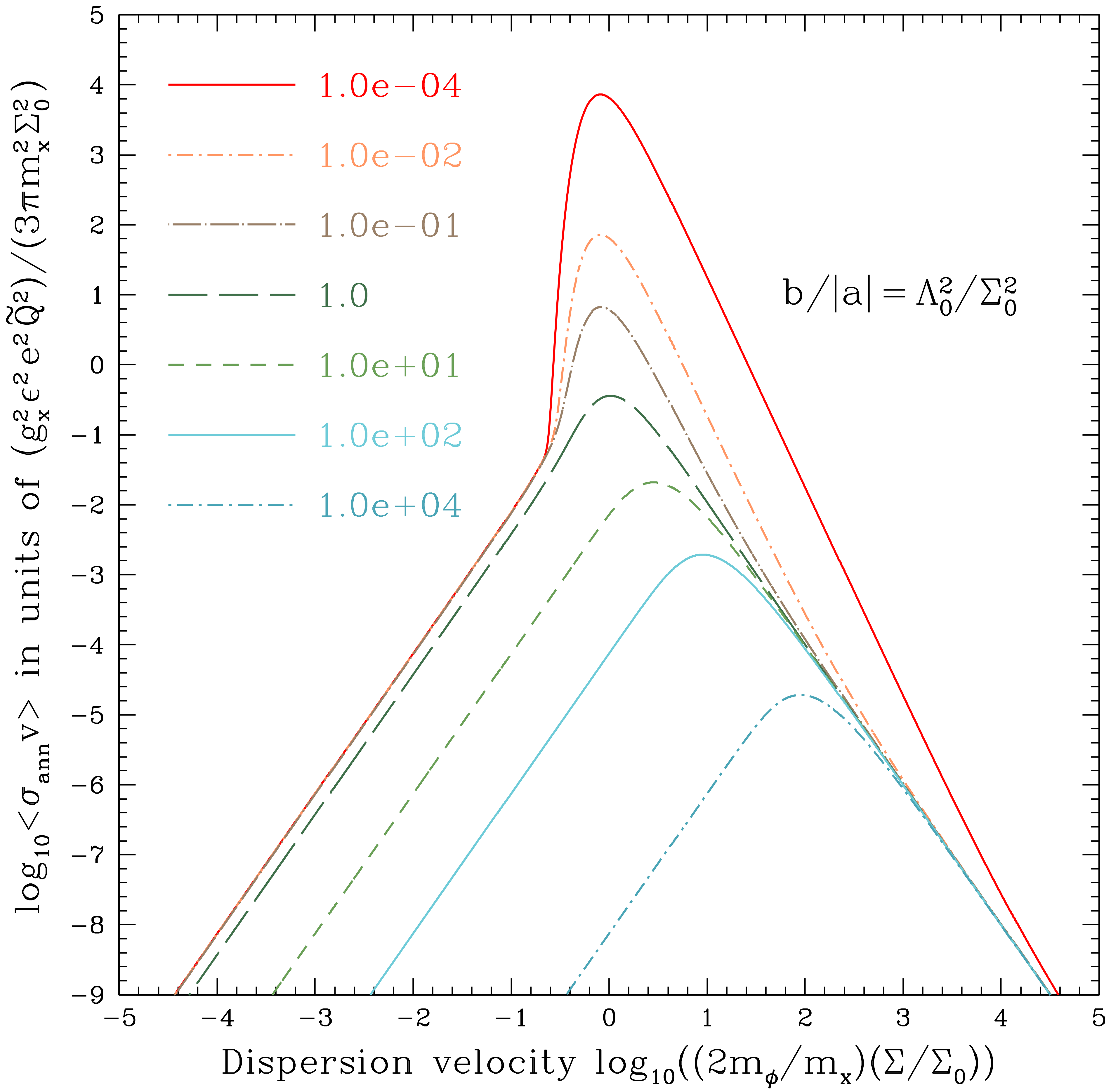
$$a = -\left\{ \frac{m_x^2}{4m_\phi^2} \right\} \left\{ \frac{\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2}{\Sigma^2} \right\}$$

$$b = \left\{ \frac{m_x^2}{4m_\phi^2} \right\} \left\{ \frac{\Lambda_0^2 \equiv \Gamma_x/m_x}{\Sigma^2} \right\}$$

$$\Gamma_x = \frac{m_x}{12\pi} \left\{ \frac{g_x^2}{4} \Sigma_0^3 + \epsilon^2 e^2 Q'^2 \right\}$$

$$Q'^2 = \sum_f \left\{ 1 - \frac{4m_f^2}{m_x^2} \right\}^{1/2} \left\{ 1 + \frac{2m_f^2}{m_x^2} \right\} Q_f^2$$

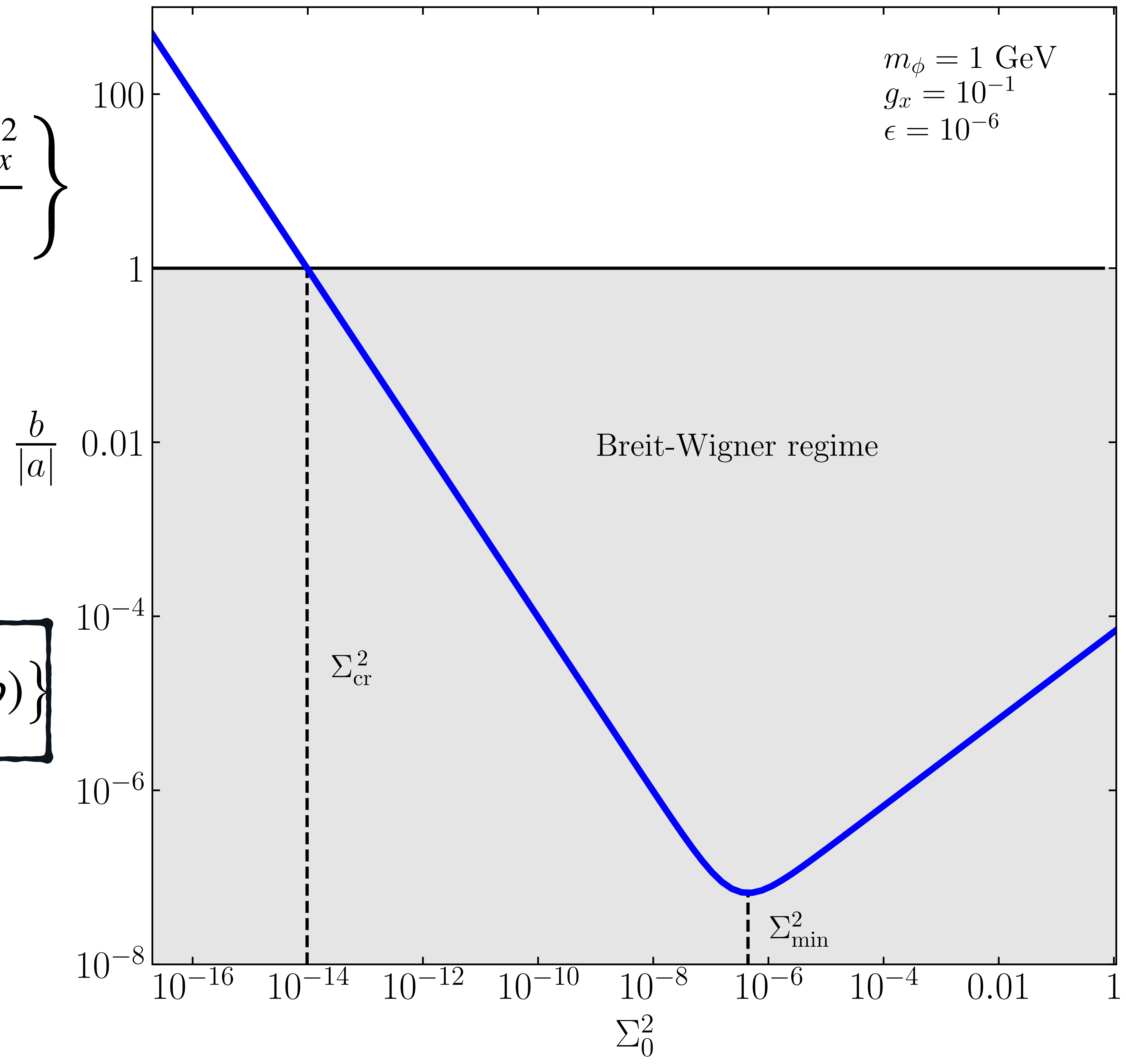
$$\boxed{m_\phi, \Sigma_0^2, g_x, \epsilon}$$




$$a = -\left\{\frac{m_x^2}{4m_\phi^2}\right\}\left\{\frac{\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2}{\Sigma^2}\right\}$$

$$b = \left\{\frac{m_x^2}{4m_\phi^2}\right\}\left\{\frac{\Lambda_0^2 \equiv \Gamma_x/m_x}{\Sigma^2}\right\}$$

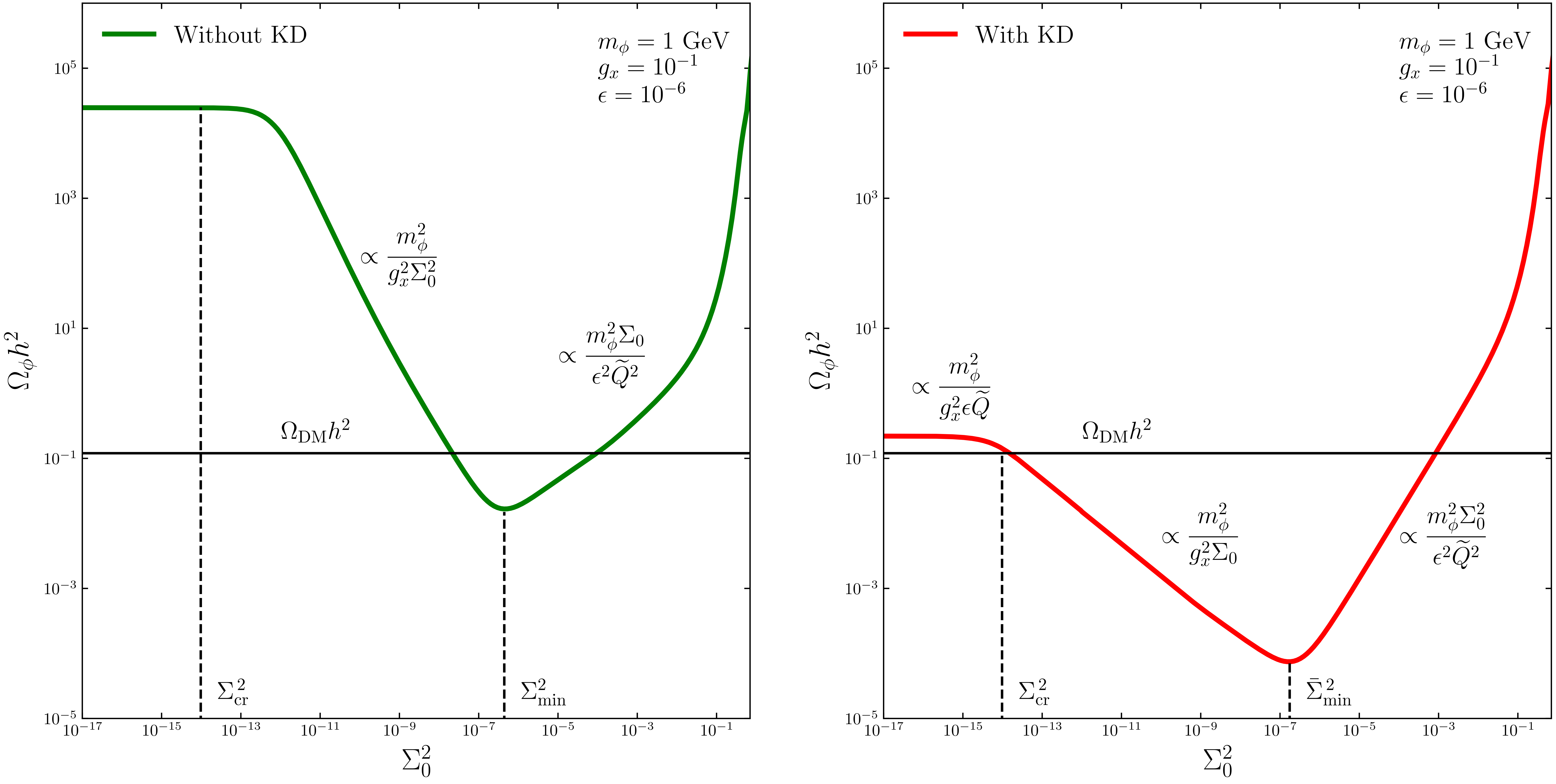
$$\langle\sigma_{\rm ann} v\rangle = \frac{g_x^2 \epsilon^2 e^2 \tilde{Q}^2}{3\pi m_x^2 \Sigma_0^2} \times \left\{|a|\,J(a,b)\right\}$$




- When $\Lambda_0$ is smaller than $\Sigma_0$, the cross-section is enhanced by a Breit-Wigner resonance.
- Above a velocity of order $\Sigma_0$, where its peak value is reached, $\langle\sigma_{\rm ann} v\rangle$ drops like $\Sigma^{-3}$ to reach the asymptotic behavior $\Sigma^{-2}$.
- Below the peak, the *p*-wave annihilation regime sets in and $\langle\sigma_{\rm ann} v\rangle$ is proportional to $\Sigma^2$. For large values of $\Lambda_0$ with respect to $\Sigma_0$, the two asymptotic regimes only appear.

# Kinetic decoupling

- Thermalization of DM occurs primarily through an exchange of energy due to collisions with the SM plasma
- For small $\epsilon$, kinetic equilibrium is not always maintained, and DM can decouple from the thermal bath earlier than usual
- We assume that $\phi$ and $\bar{\phi}$ reach thermal equilibrium through mutual collisions at a temperature $T_\phi$ which is different from the plasma temperature $T$ after kinetic decoupling has occurred.
- When DM decouples thermally from the primordial plasma, its temperature drops faster than usual. $T_\phi$ decreases as $a^{-2}$, while $T$ scales approximately like $a^{-1}$. As DM cools down, the annihilation cross-section $\langle \sigma v_{ann} \rangle$ increases, and hence relic density drops. $\langle \sigma v_{ann} \rangle$ peaks at the DM dispersion velocity $\Sigma_M$, where most of the annihilation takes place.




For each $(g_x, \epsilon)$, there could be two values of $\Sigma_0^2$ yielding the observed relic

✓ Left-branch solution : $\Sigma_0^2 < \bar{\Sigma}^2_{\rm min}$ → Exists only if the plateau is above the relic line

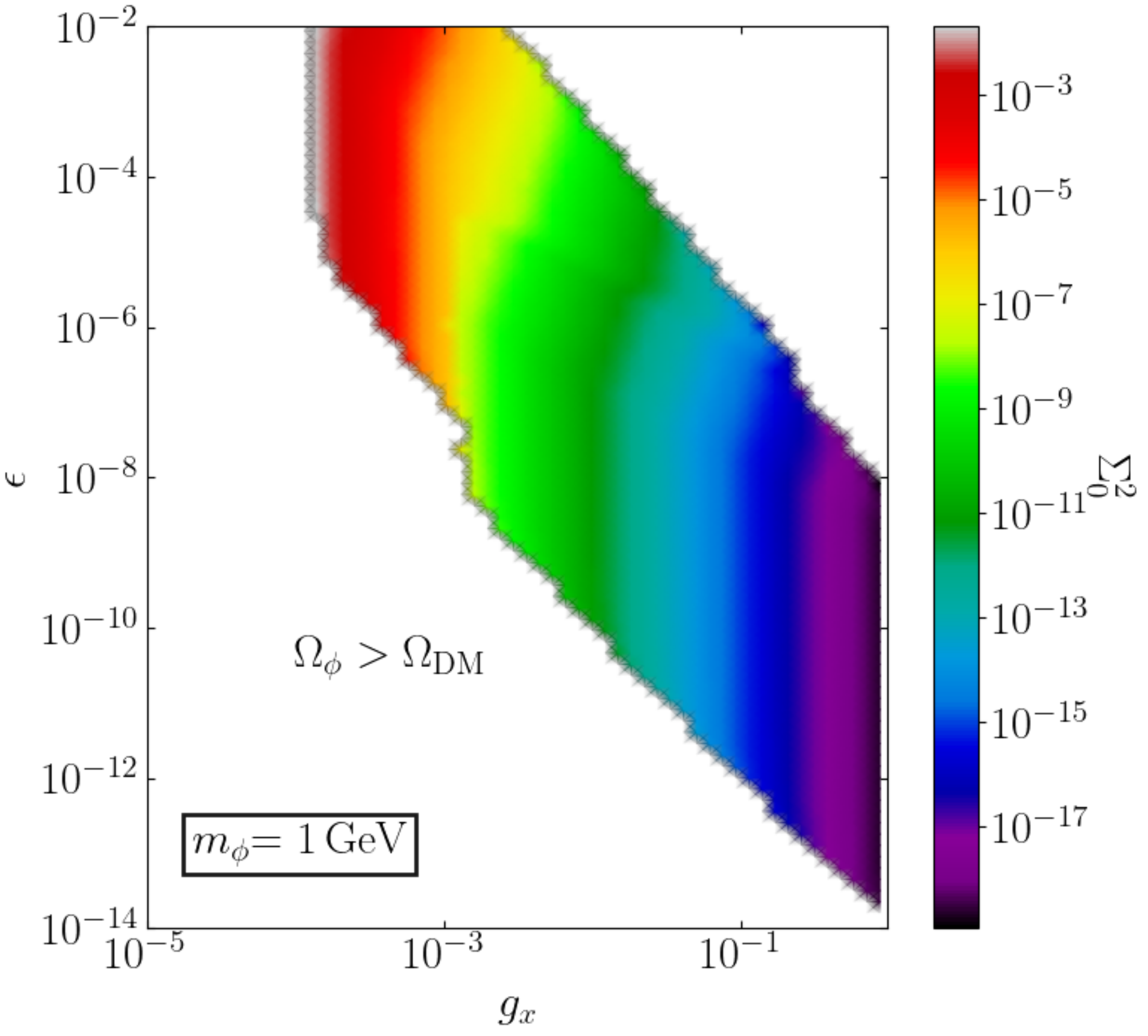
✓ Right-branch solution : $\Sigma_0^2 > \bar{\Sigma}^2_{\rm min}$

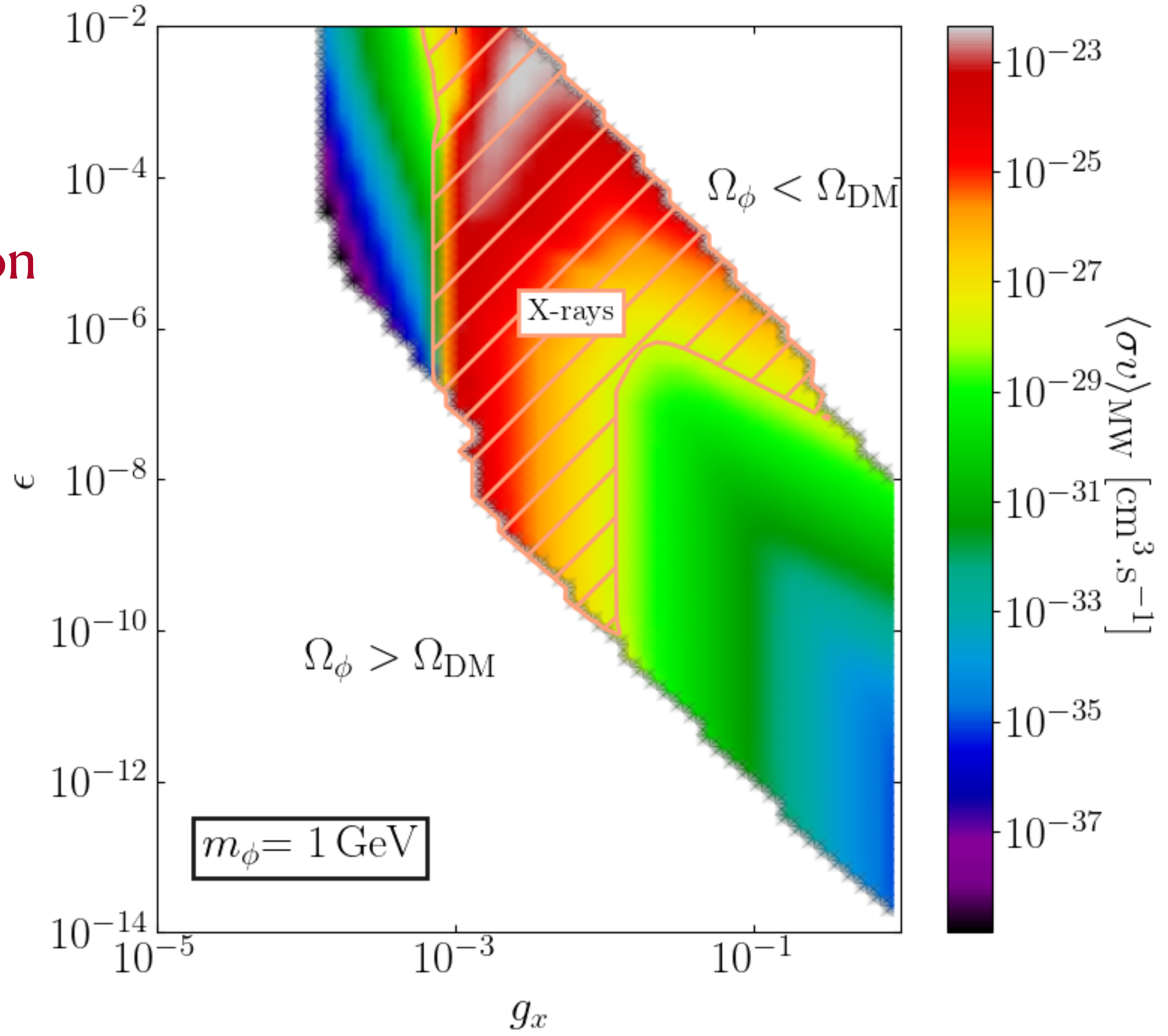
# Constraints on DM annihilation

- The model can be constrained by limiting annihilation at different DM velocities owing to the non-trivial velocity dependence
- In the $g_x$ vs. $\epsilon$ parameter space, the velocity dependence can be tuned by choosing $\Sigma_0^2$, because the BW peak accordingly shifts

# Relic density and annihilation in the galaxies

Left-branch solution

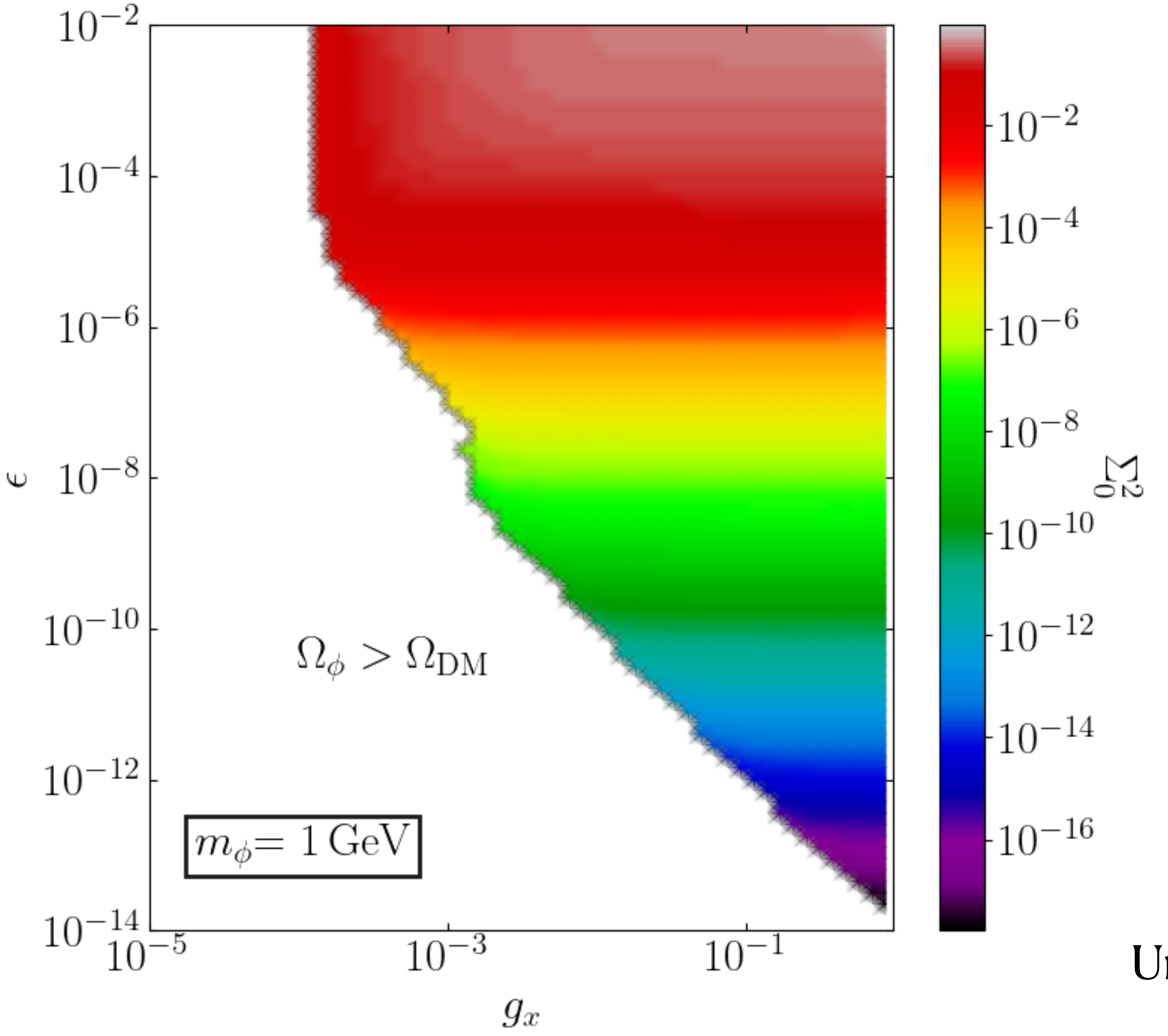


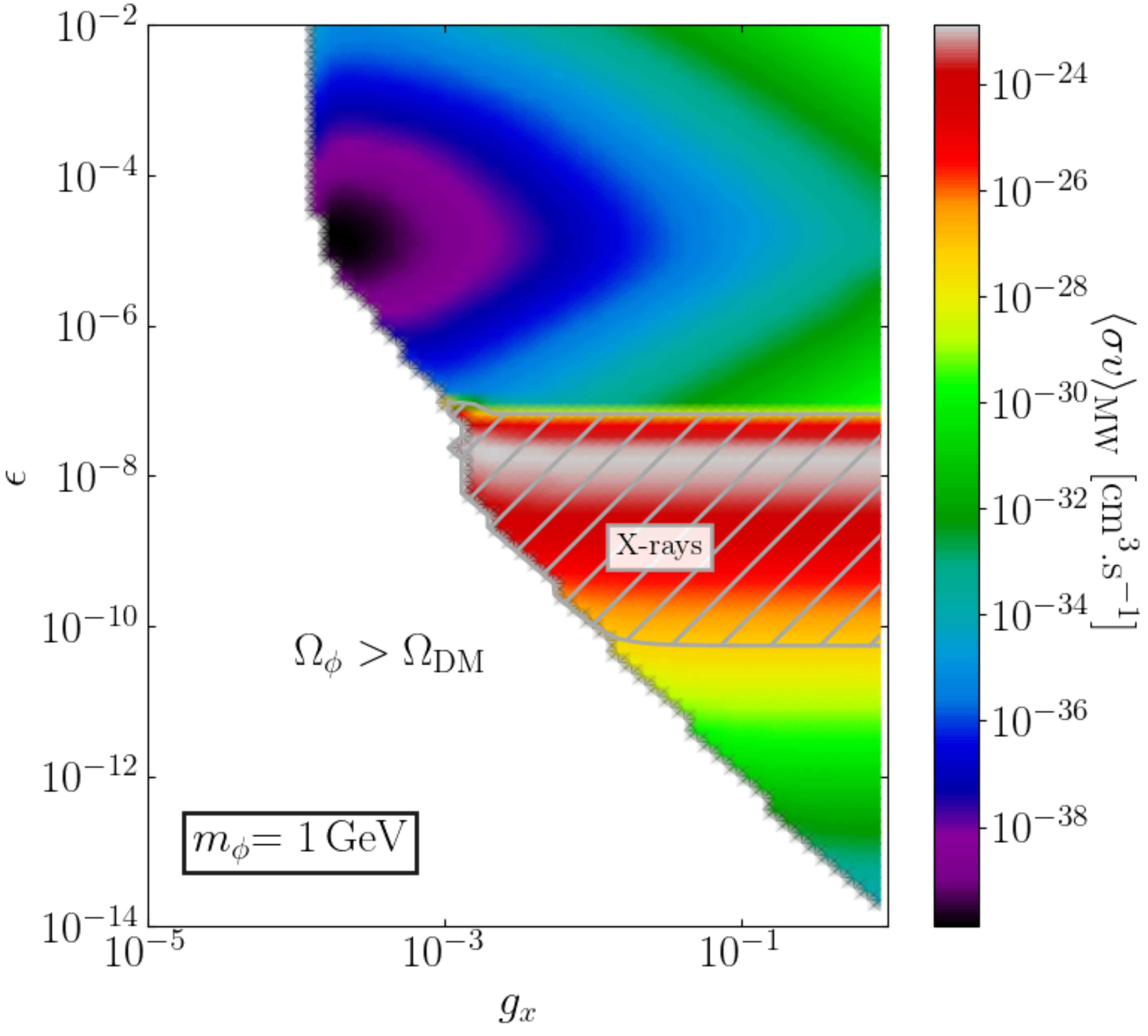




$\Sigma^2_{MW} \sim 3 \times 10^{-7}$

# Relic density and annihilation in the galaxies

Right-branch solution



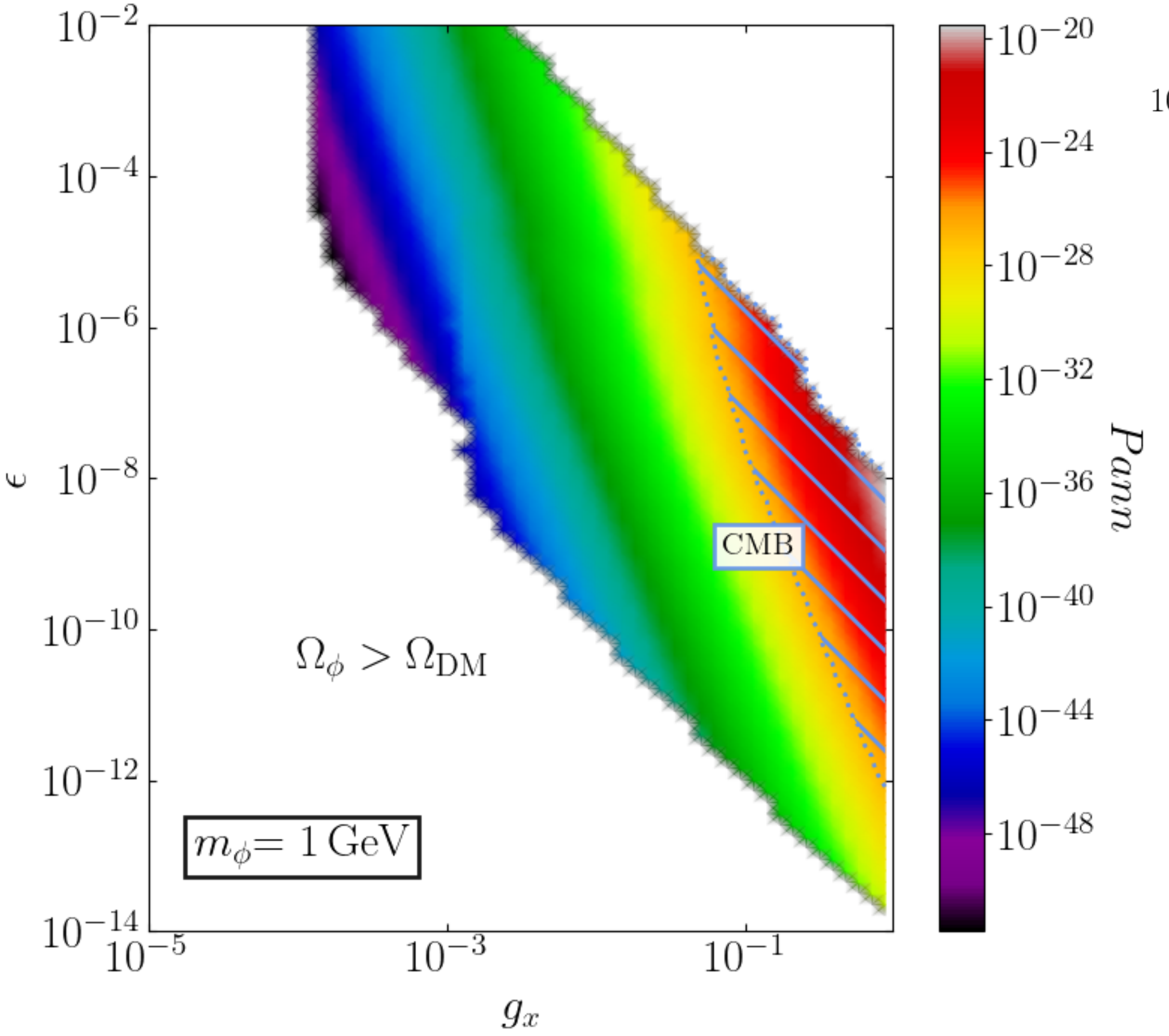

$\Sigma_{MW}^2 \sim 3 \times 10^{-7}$

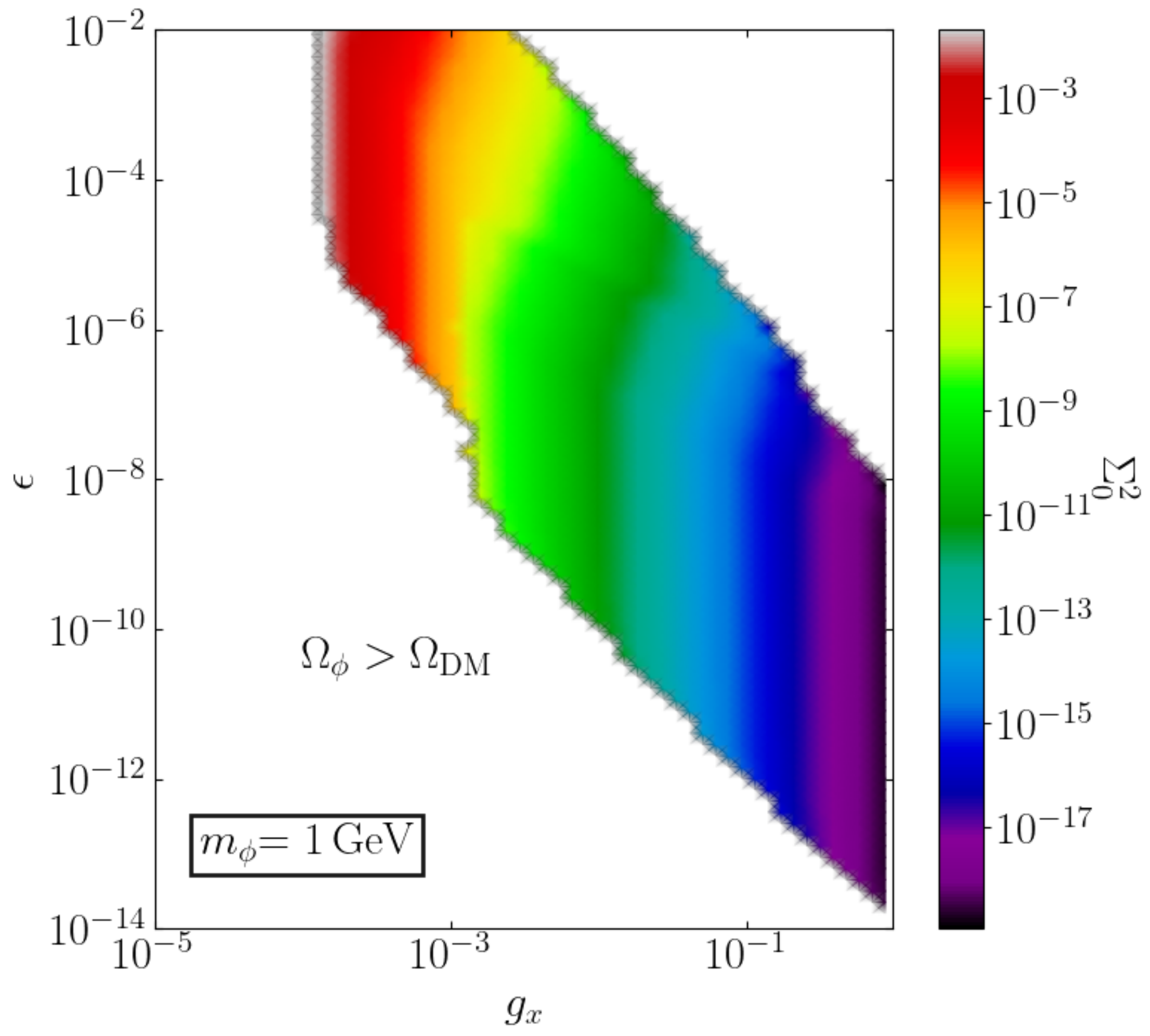
Unlike the left-branch solution, here one can always find $\Sigma_0^2$ that will give the right relic

# CMB

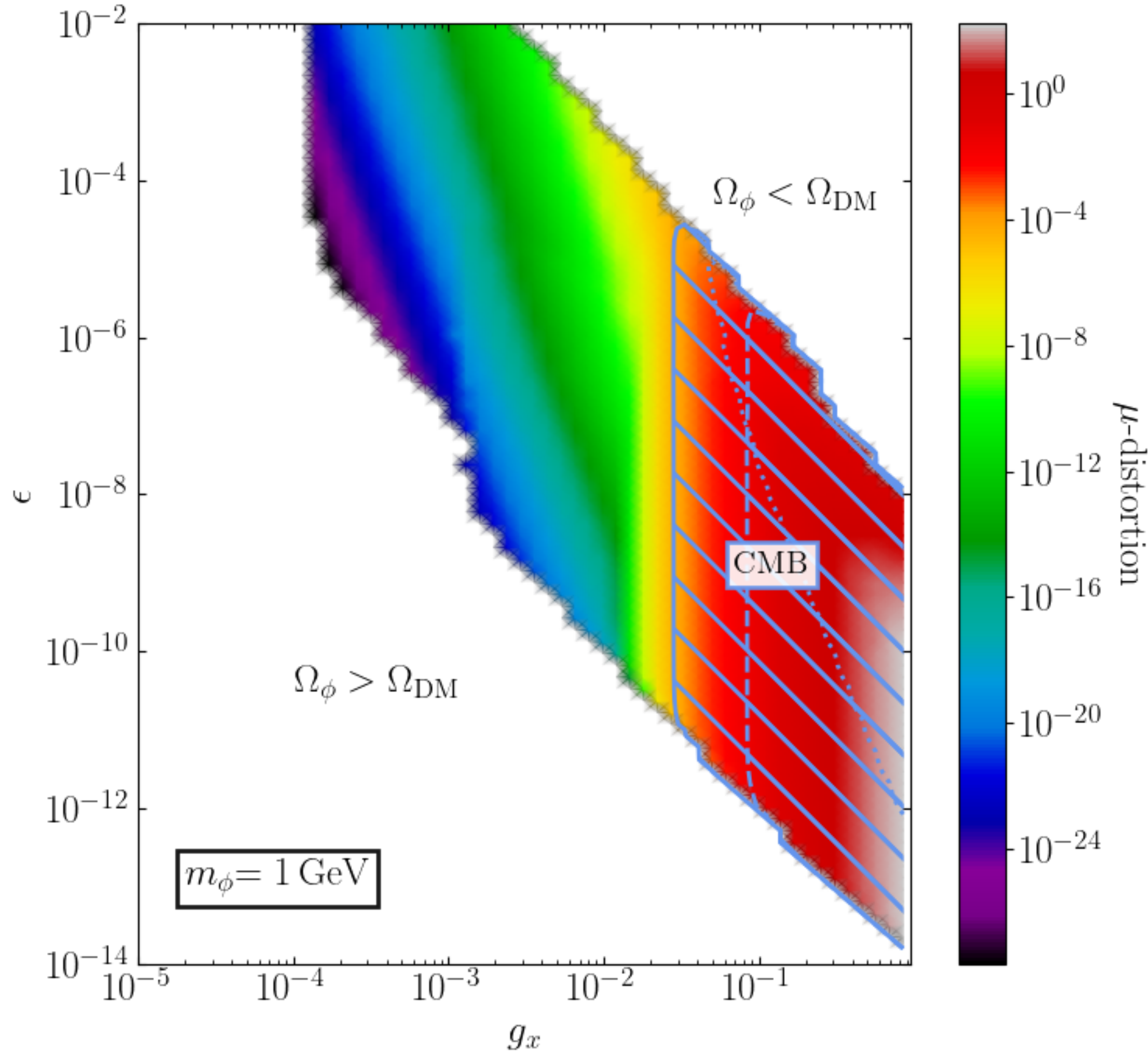
Left-branch solution

$$p_{\rm ann} = \frac{R^2}{2} f_{\rm em} \frac{\langle \sigma_{\rm ann} v \rangle_{\rm CMB}}{m_\phi}\,, \text{ where } R \equiv \frac{n_\phi({\rm CMB})}{n_\phi({\rm today})}$$



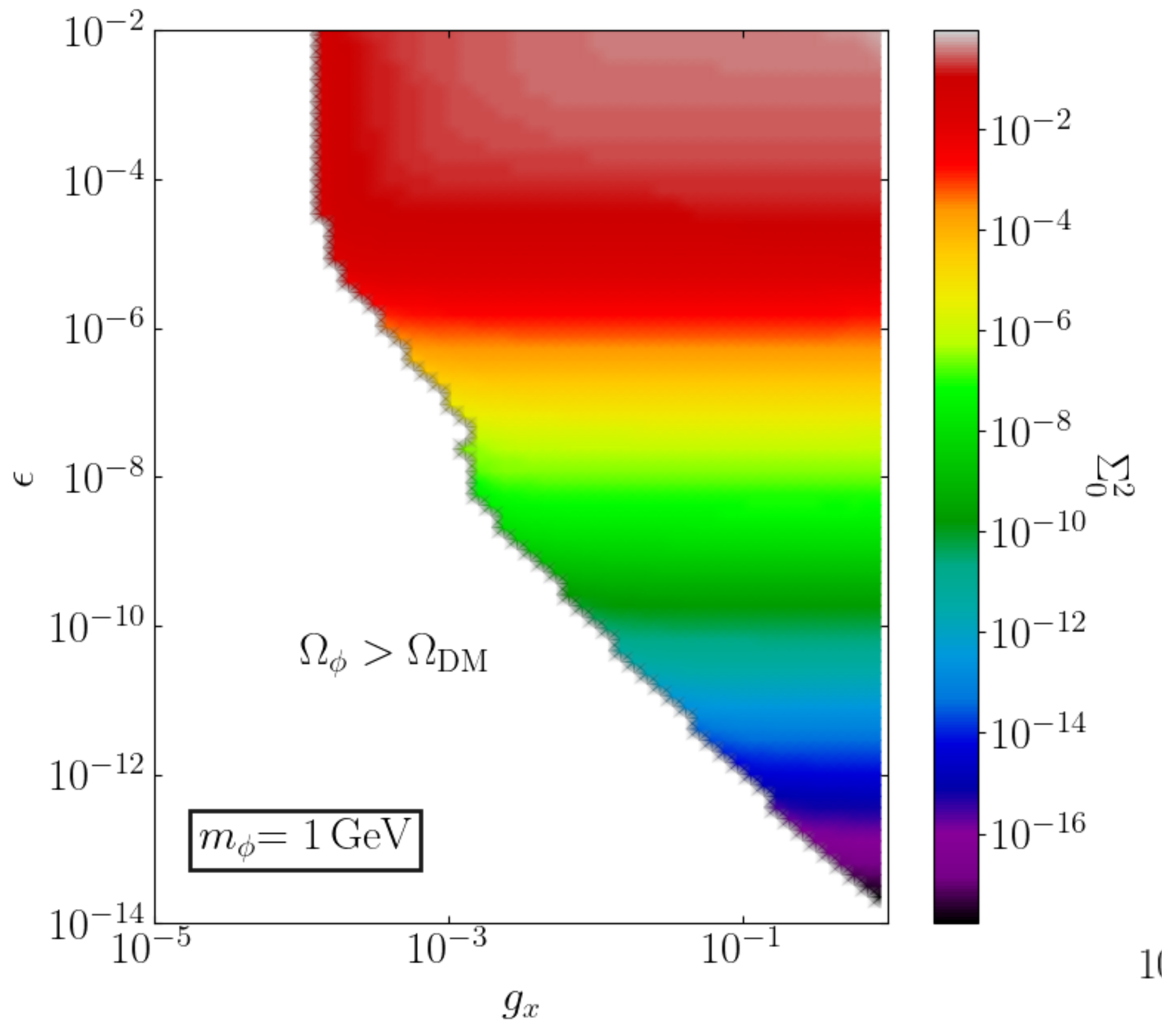

- ✓ CMB power spectrum
- ✓ CMB spectral distortions




- Significant constraints only at very small velocities, *ie*, small $\Sigma_0^2$
- $p_{ann}$ computed at $z \sim 600$
- $\mu$-distortion occurs between $5.8 \times 10^4 \leq z \leq 1.98 \times 10^6$

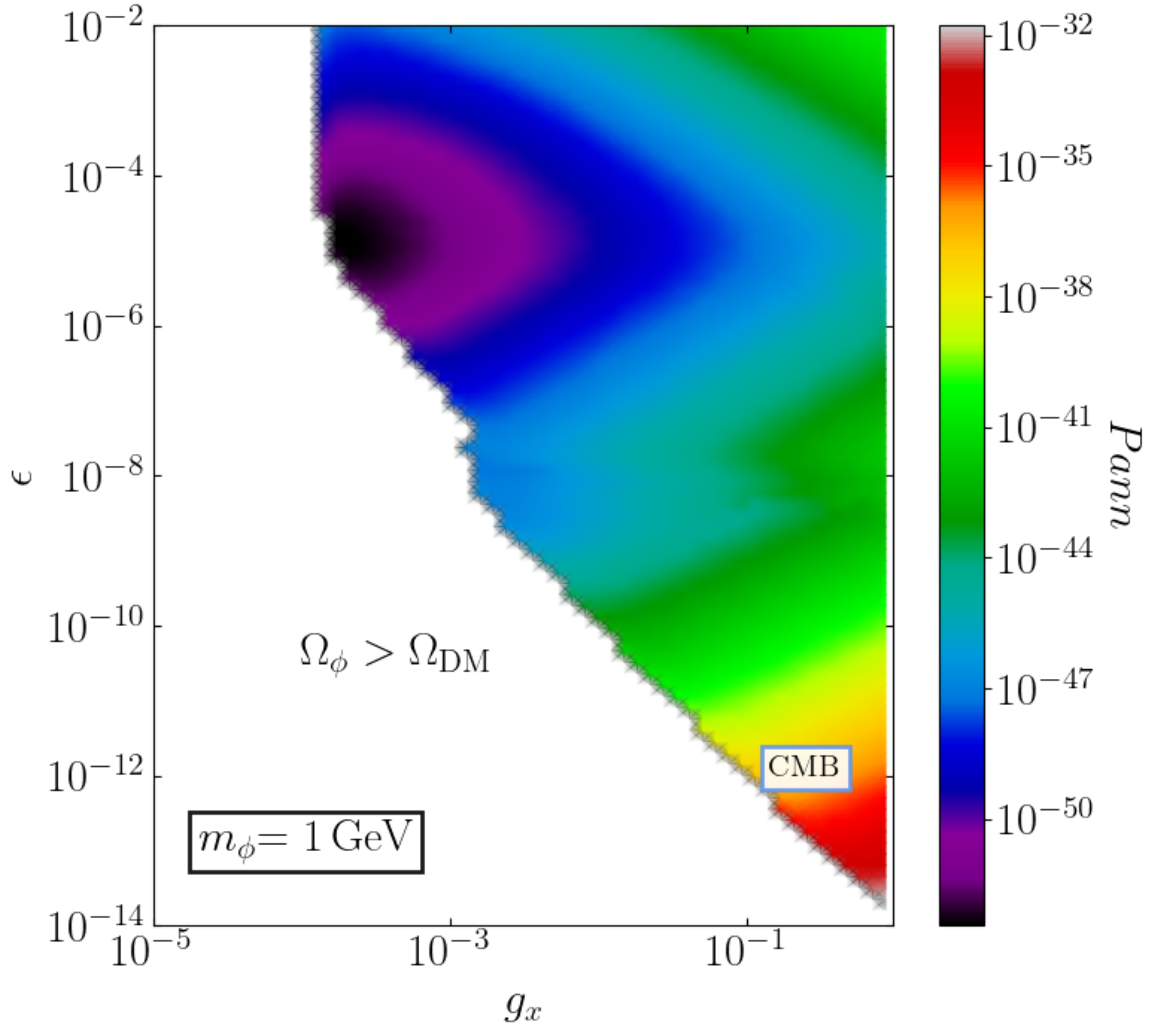
# CMB

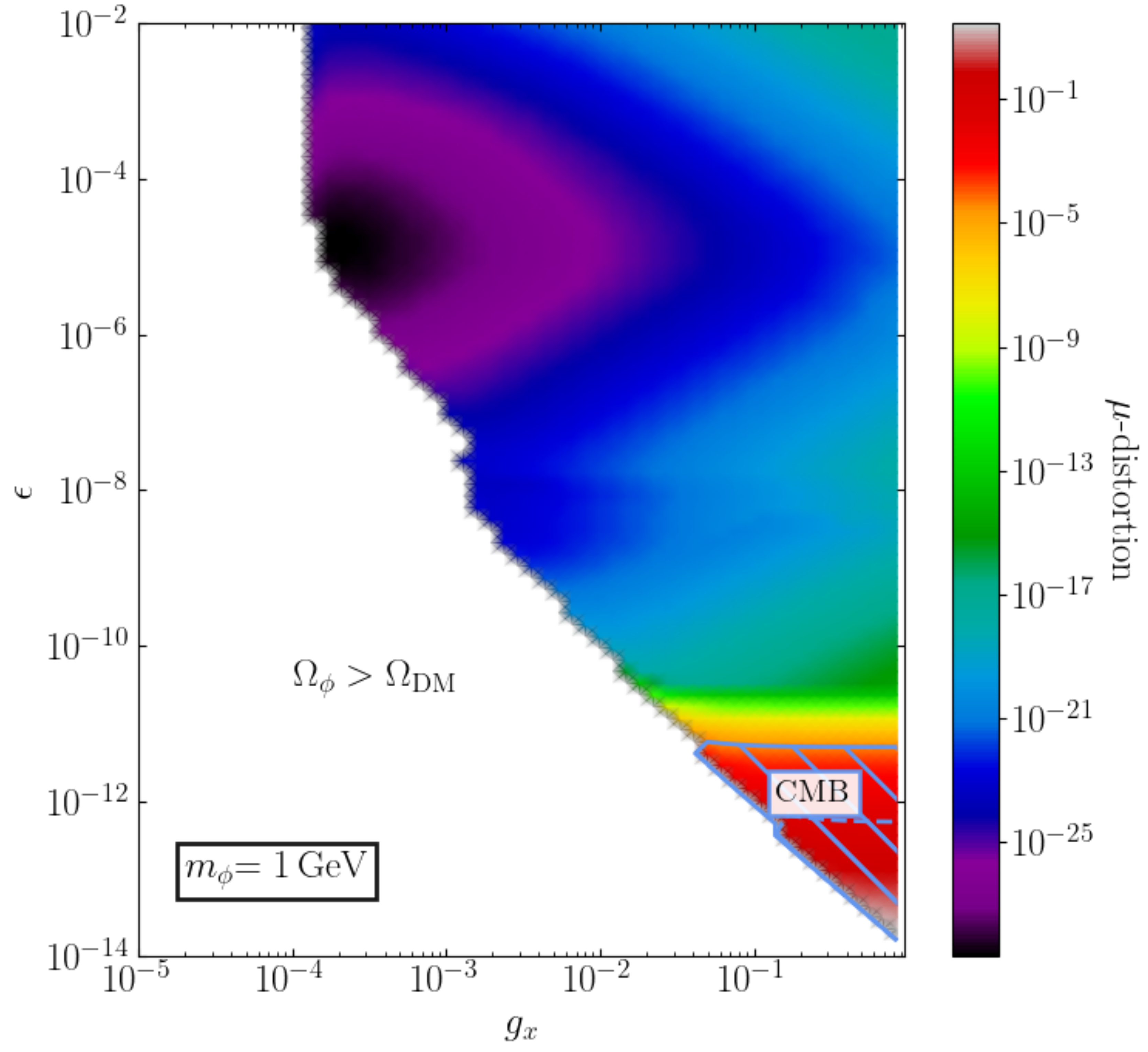
Right-branch solution




✓ CMB power spectrum

✓ CMB spectral distortions



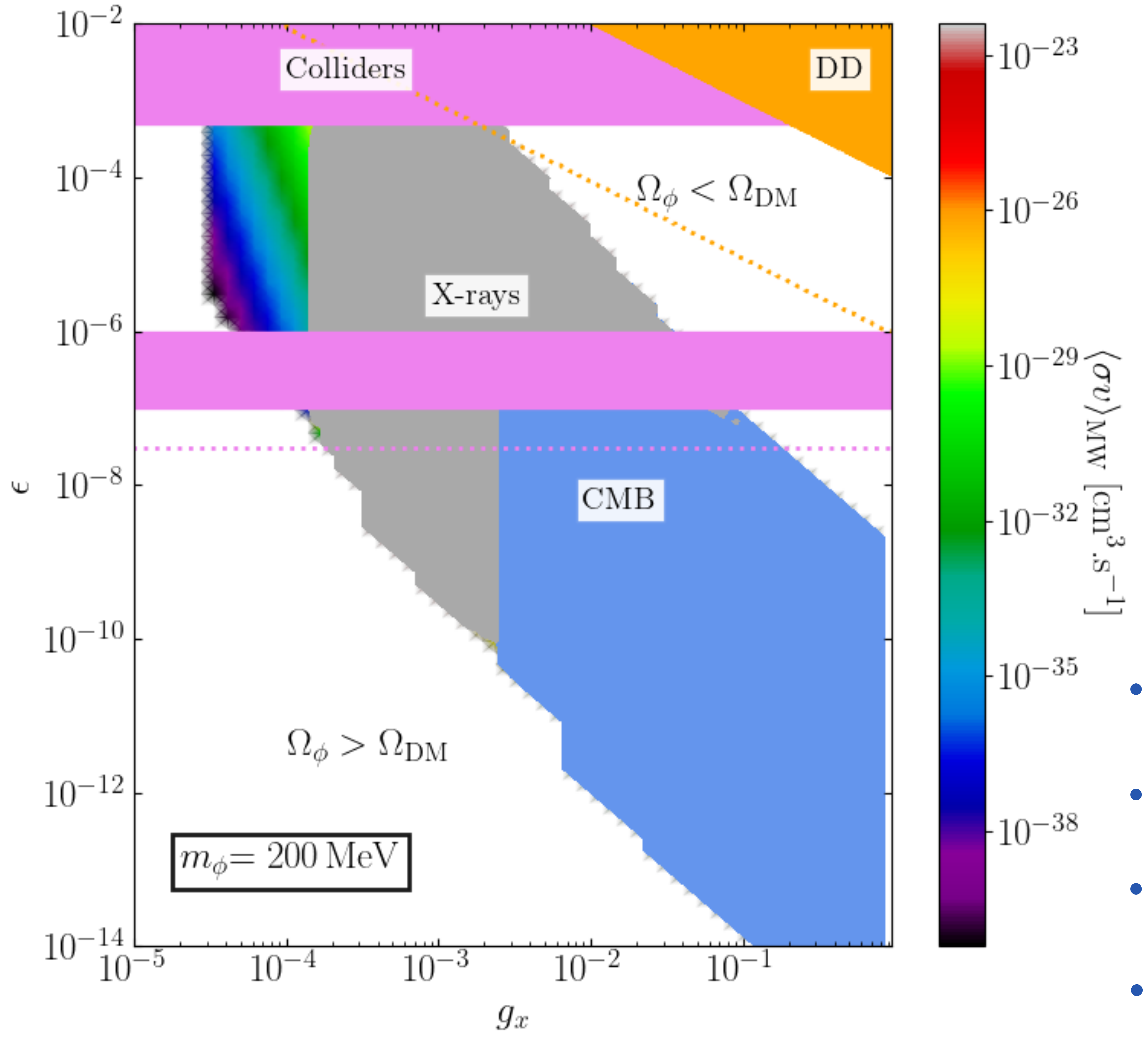
# Earth-based probes

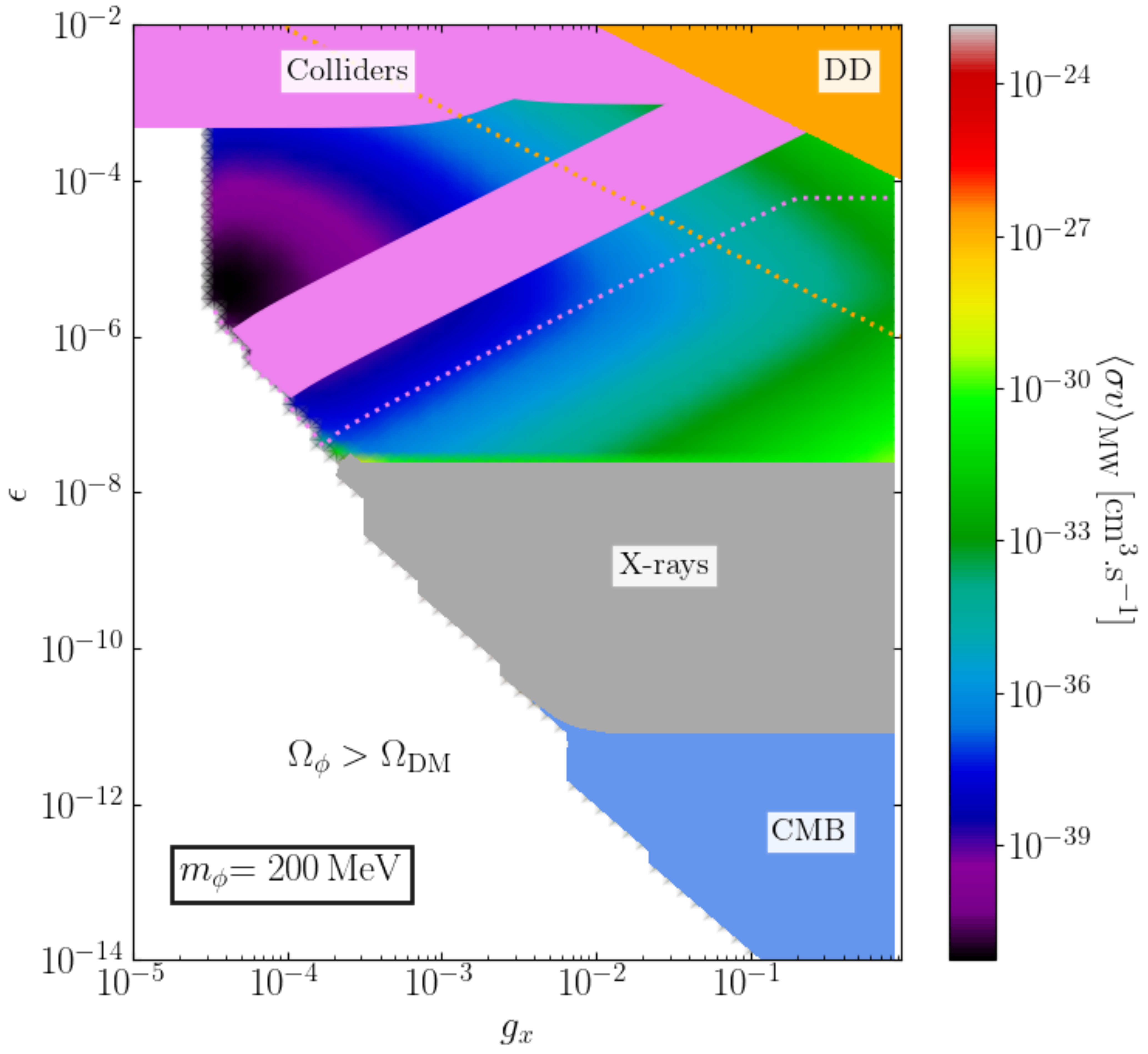
## Direct detection and accelerators

- Direct searches dedicated to light DM detection: Pandax-4T (S2+Migdal), Pandax-4T (S1+S2)
- Future projections from DARKSPHERE (NEWS-G) and SBC-1 ton
- Accelerators can probe both visible and invisible decays of the mediator
- For dark photon mass $\lesssim$ 600 MeV, the visible decay searches put limits on both *prompt* and *displaced* searches. The best limits are obtained from di-muon searches of LHCb (prompt), BaBar for large $\epsilon$ and CHARM, E137 for small $\epsilon$
- BaBar and LEP provide the best limits for invisible decay searches for ~ $\mathcal{O}$ (GeV) dark photon

# Summary plots

## 200 MeV



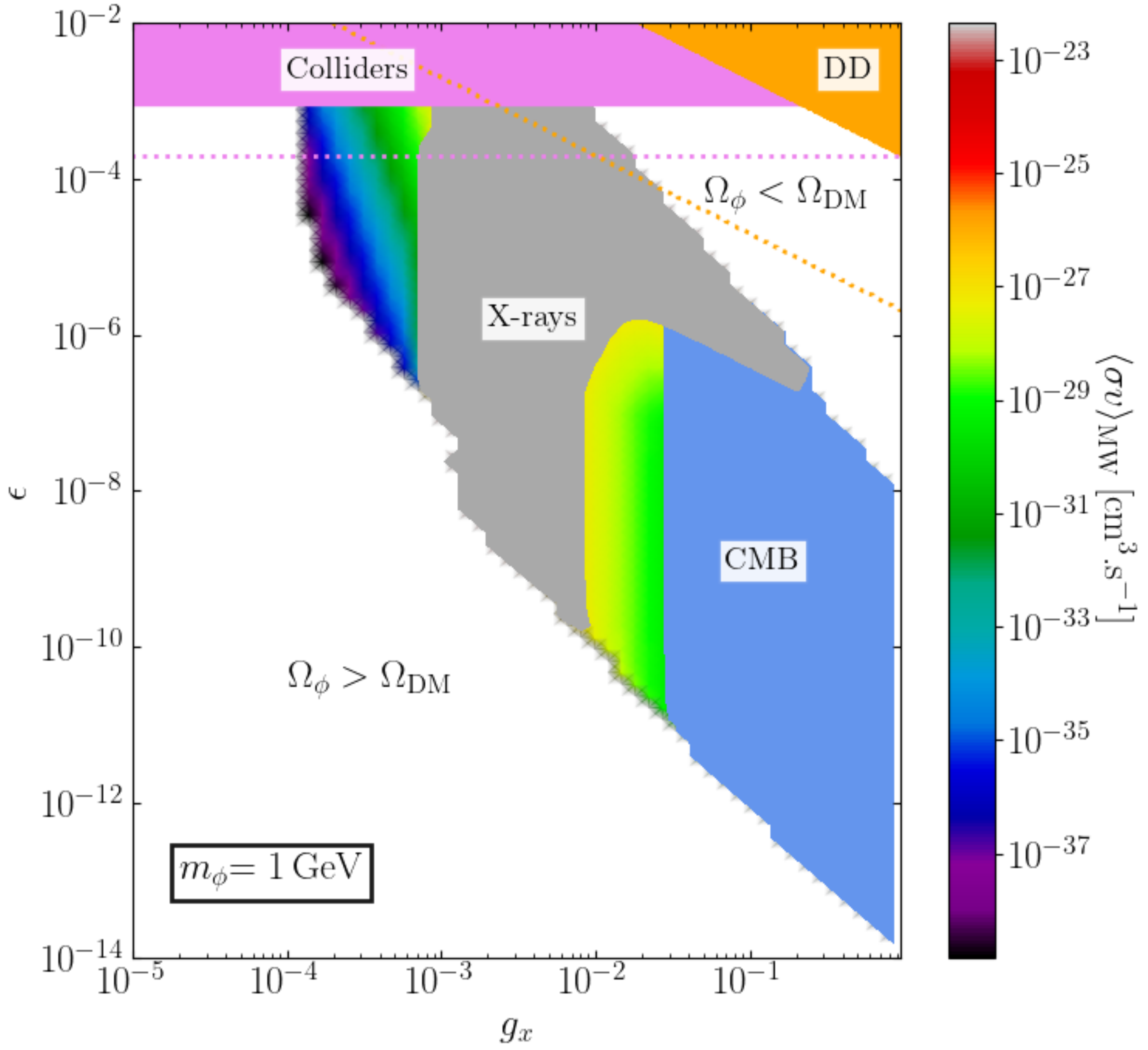



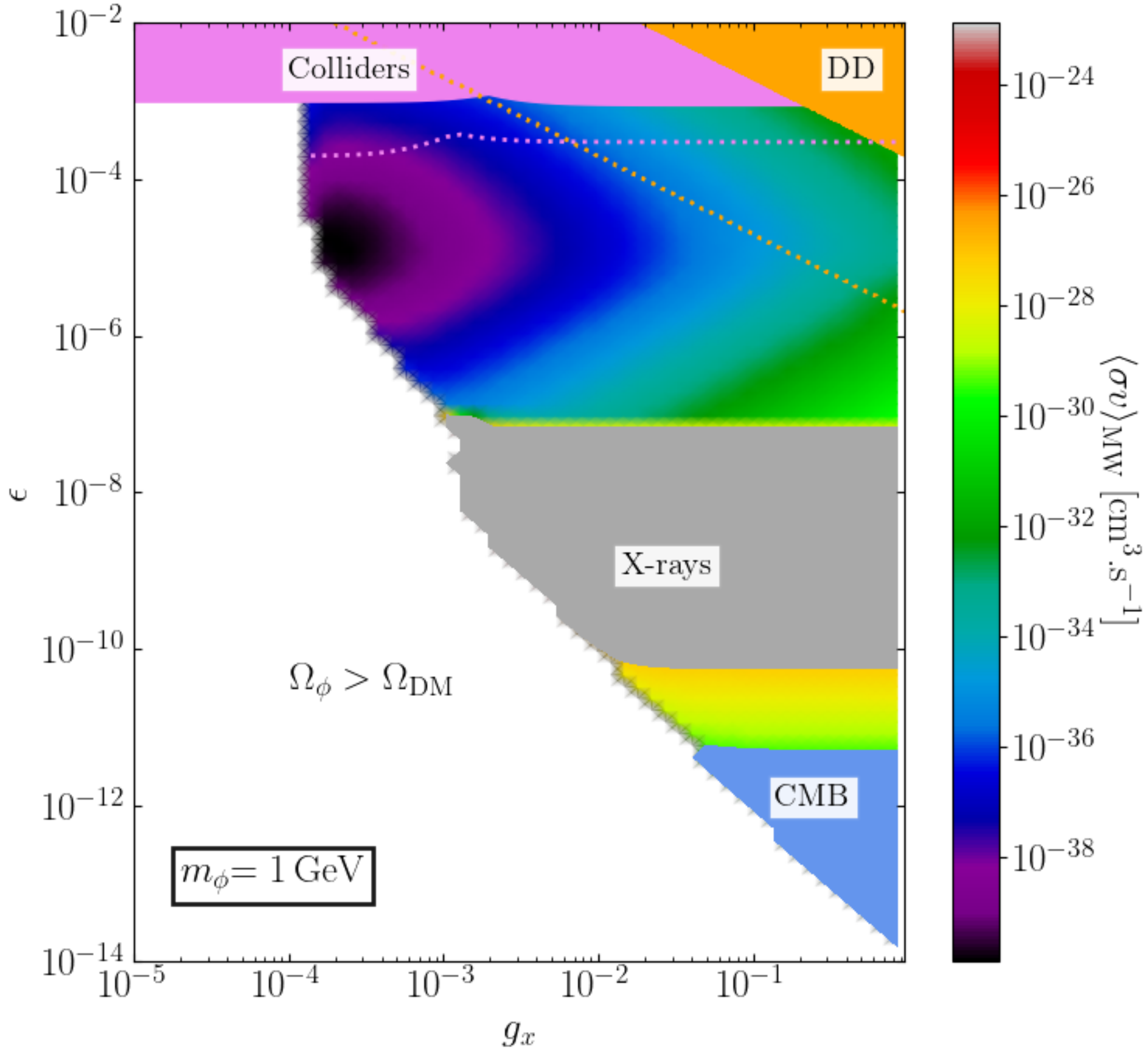

- X-ray limits - XMM-Newton
- CMB $\mu$-distortion limits - FIRAS (COBE)
- Direct detection - PandaX-4T (S2 only+Migdal)
- Accelerator limits - *visible decay* : LHCb (upper band), $\nu$-CAL, CHARM (lower band)

*invisible decay* : BaBar (upper band)

# Summary Plots

**1 GeV**



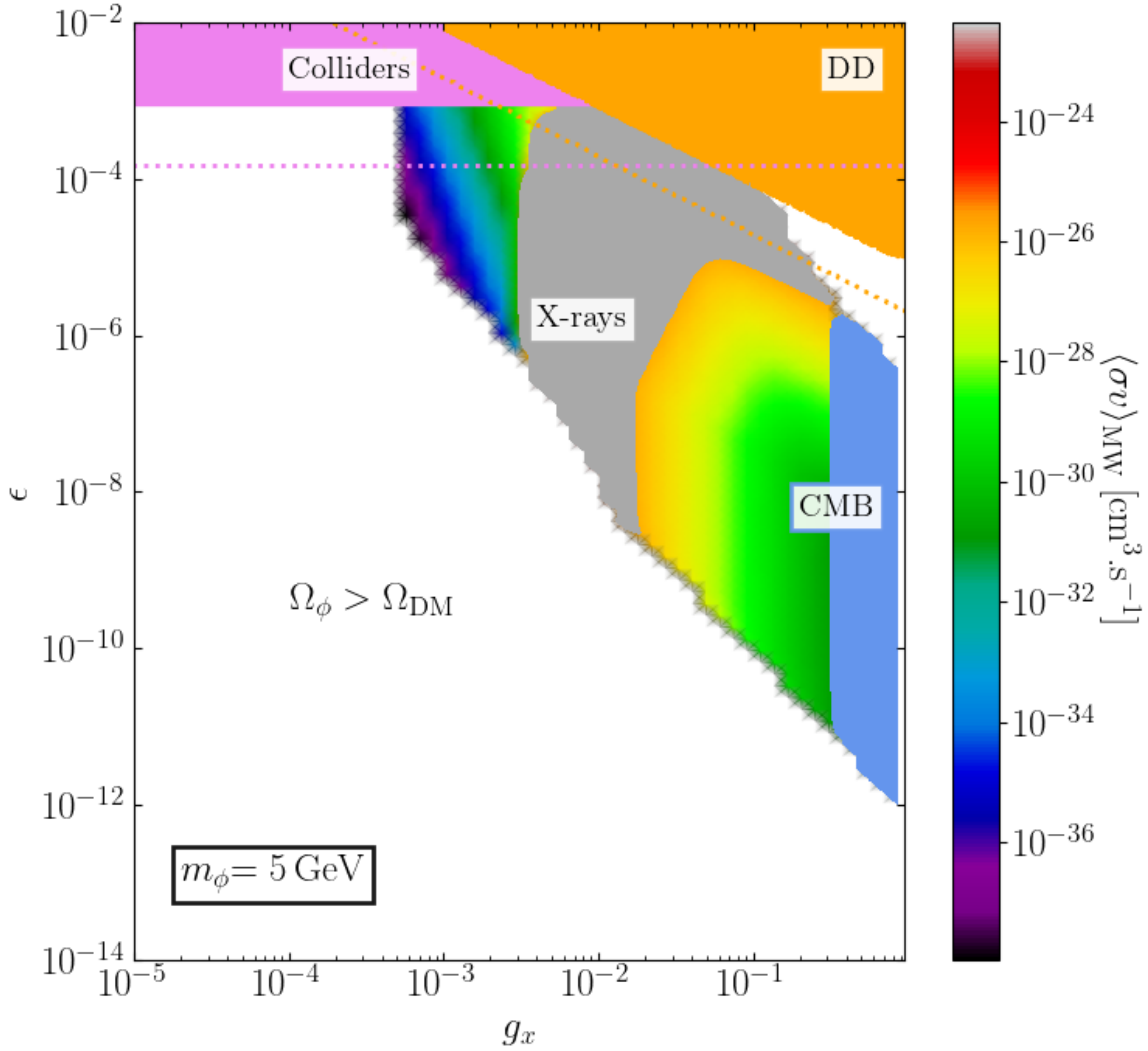



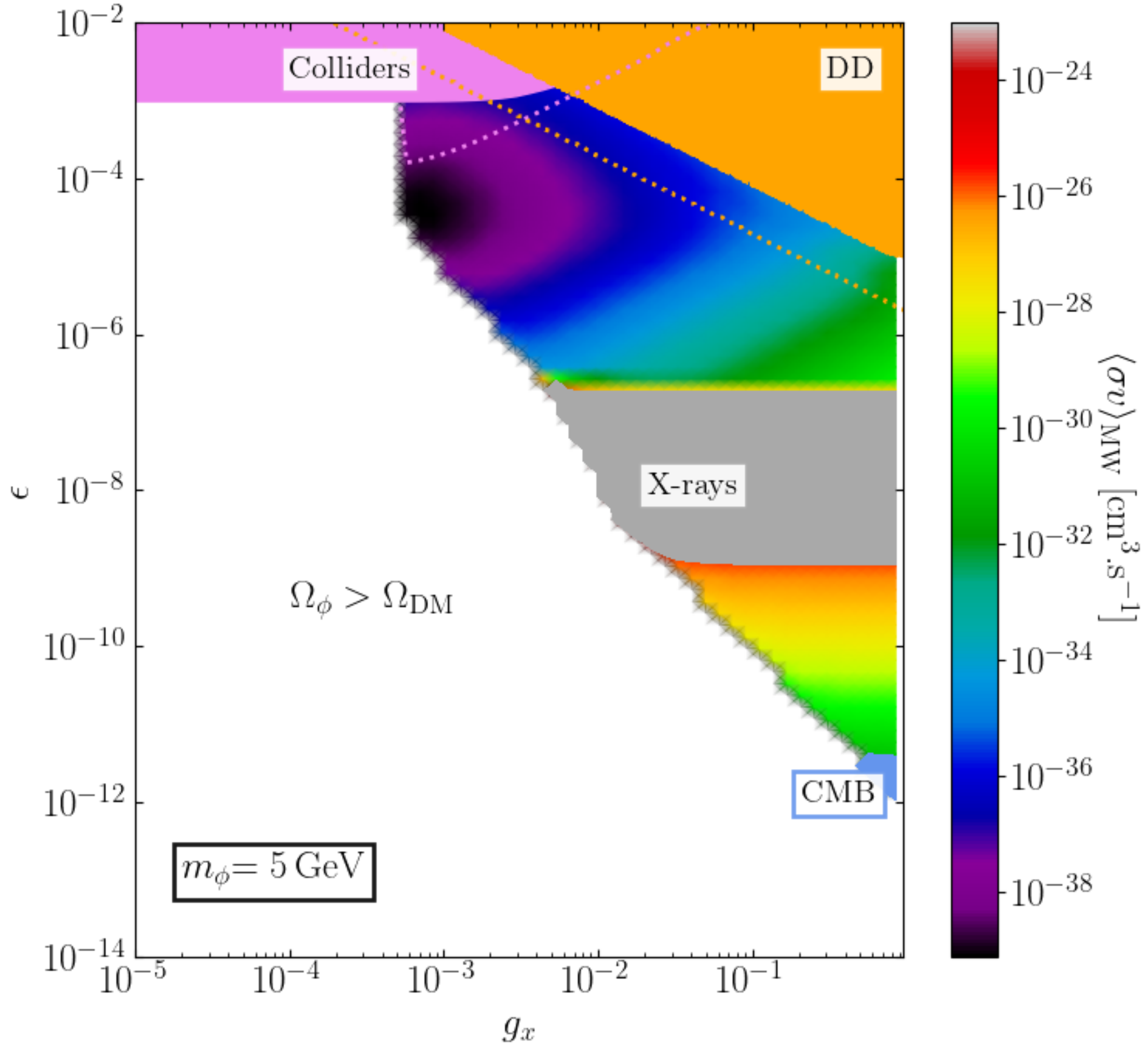

- X-ray limits - XMM-Newton
- CMB $\mu$-distortion limits - FIRAS (COBE)
- Direct detection - PandaX-4T (S2 only+Migdal)
- Accelerator limits - *visible decay* : LHCb

  *invisible decay* : BaBar

# Summary Plots

**5 GeV**




- X-ray limits - XMM-Newton
- CMB $\mu$-distortion limits - FIRAS (COBE)
- Direct detection - PandaX-4T (S1+S2)
- Accelerator limits - *visible decay* : BaBar

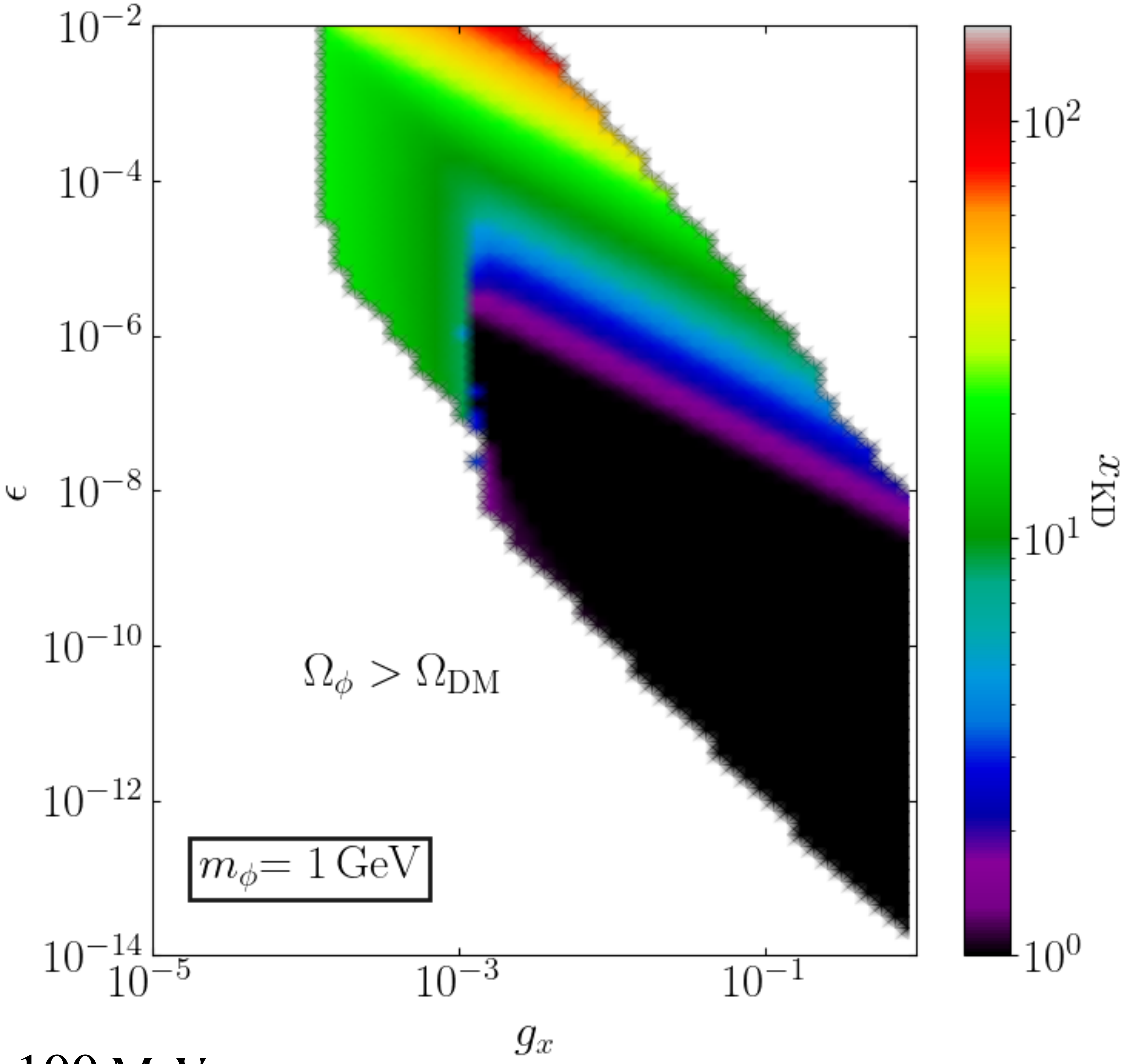
  *invisible decay* : LEP

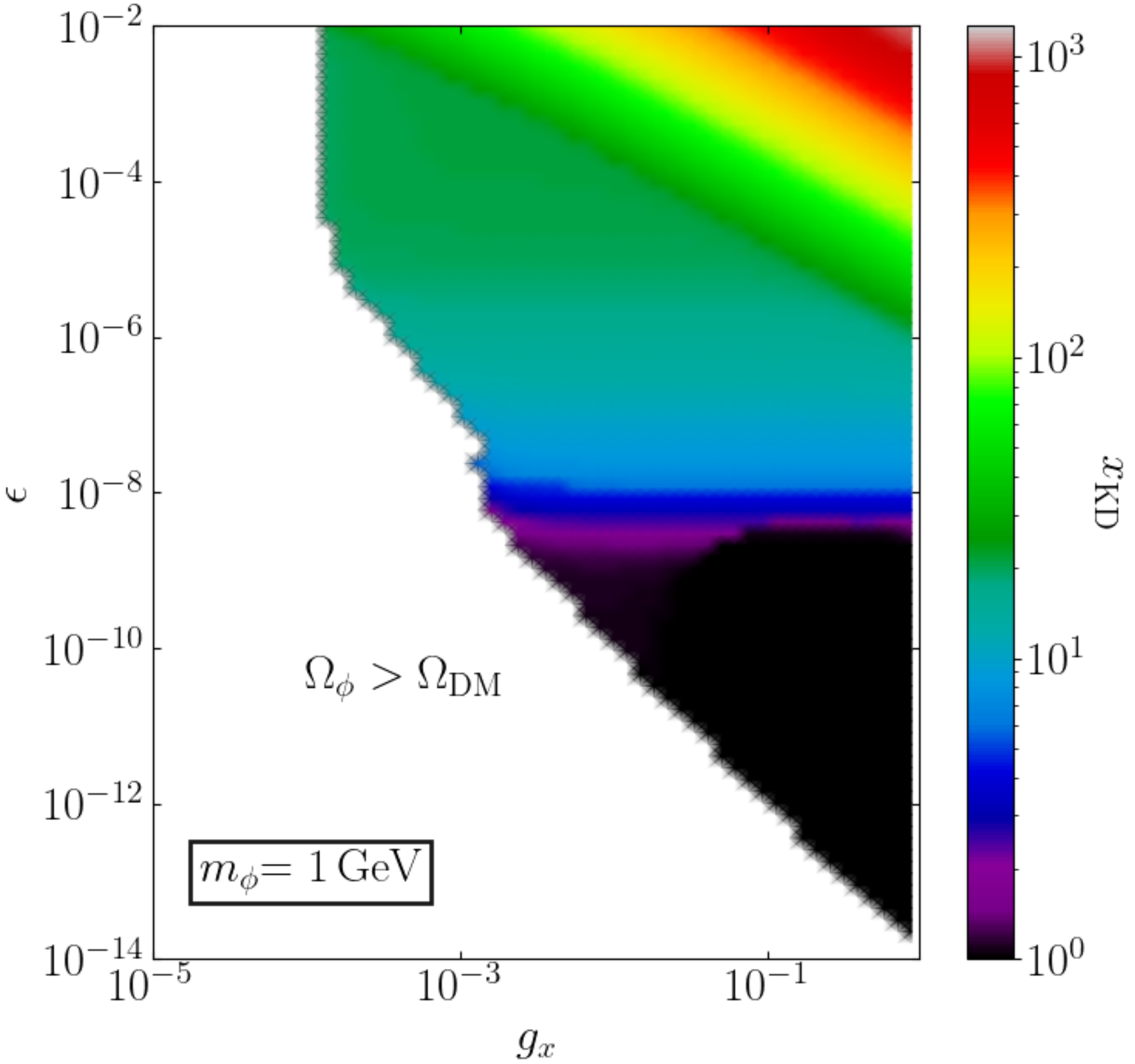
# Take home

- ✓ We have considered a GeV-scale dark matter model where annihilation is essentially *p*-wave
- ✓ Focussing on the BW resonance region makes way for interesting probes through indirect searches
- ✓ Strong CMB-constraints are evaded by tuning the resonance parameters
- ✓ Low-energy direct detection and accelerator searches (proton and electron beam-dumps, searches through rare meson decays etc) give complementary probes

# Backup

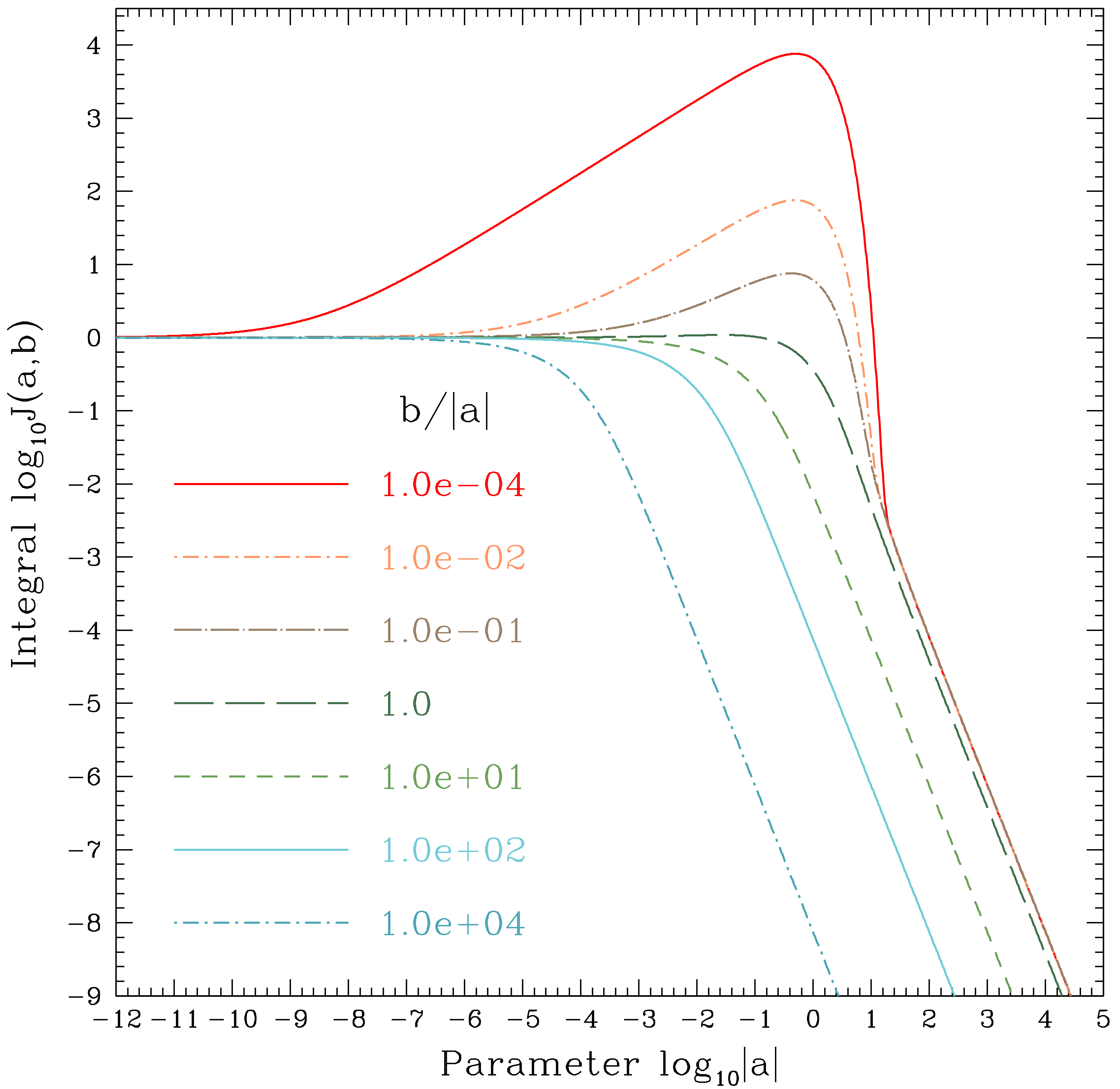
# More on early kinetic decoupling



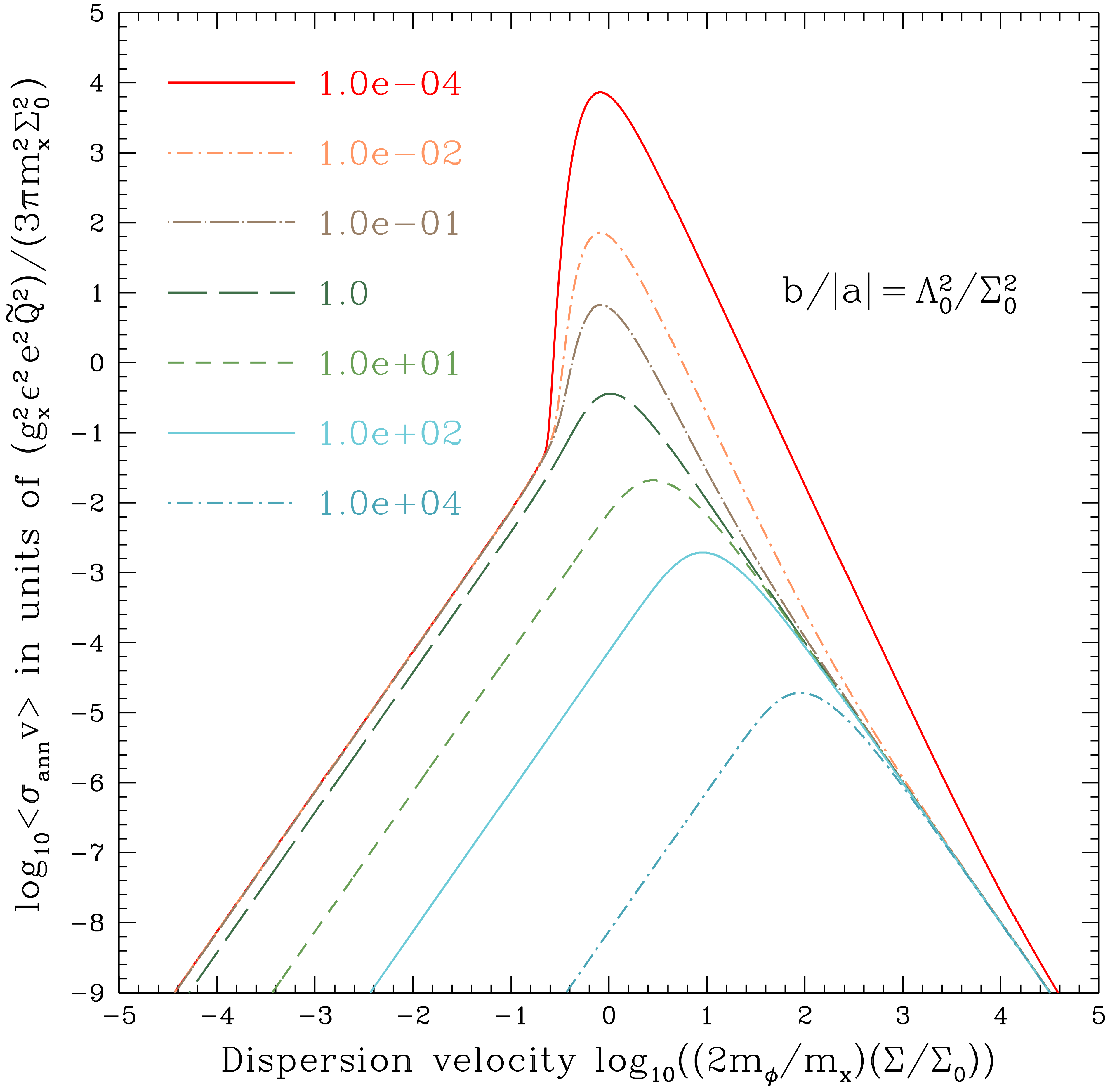




✓ $T_{KD} \sim 100$ MeV

✓ When kinetic decoupling occurs close to freeze out, it can lead to ~ one order of magnitude difference in relic density



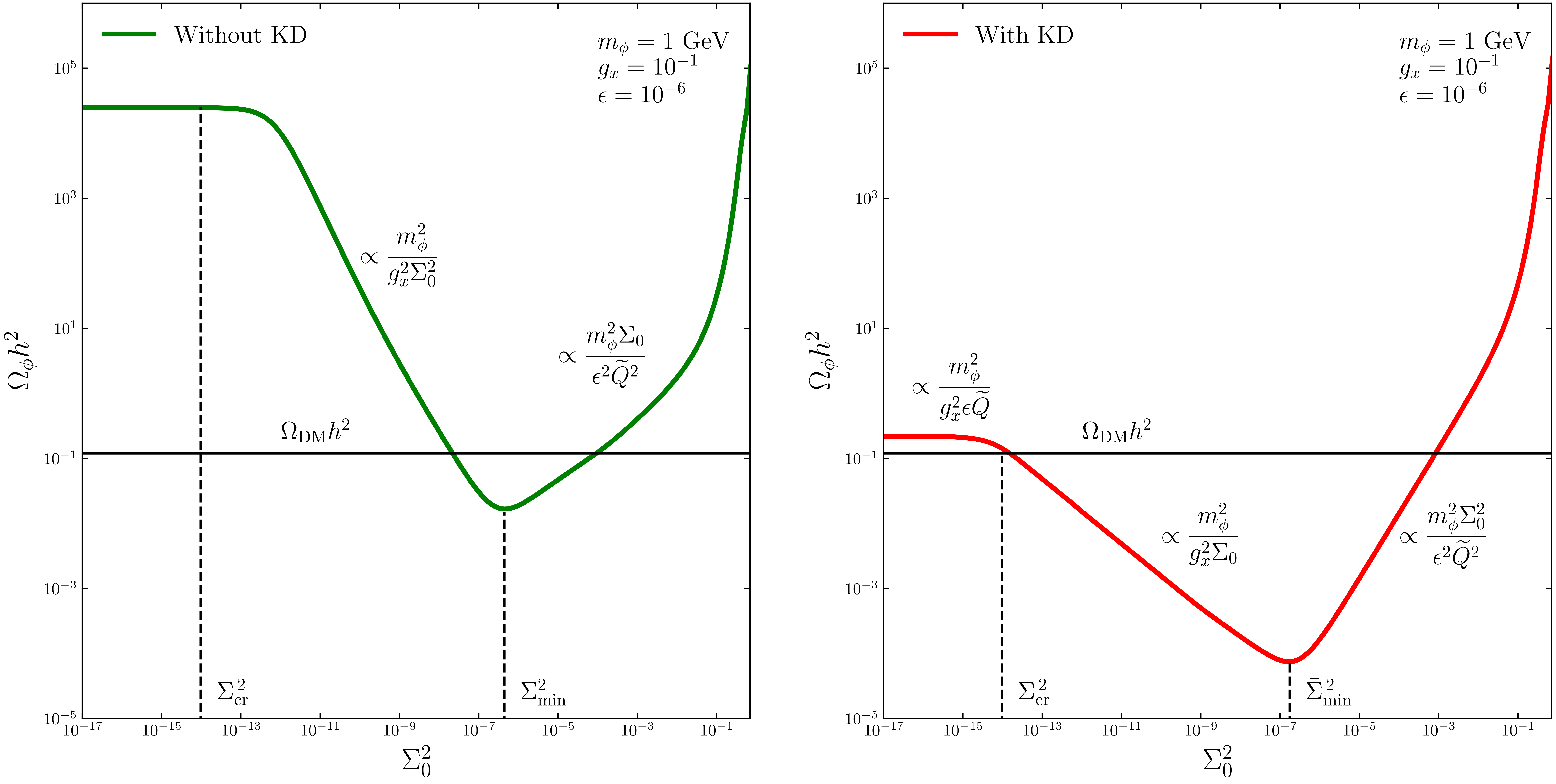

$$a = -\left\{ \frac{m_x^2}{4m_\phi^2} \right\} \left\{ \frac{\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2}{\Sigma^2} \right\}$$




$$a = -\left\{ \frac{m_x^2}{4m_\phi^2} \right\} \left\{ \frac{\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2}{\Sigma^2} \right\}$$

$$\boxed{\langle \sigma_{\rm ann} v \rangle = \frac{g_x^2 \epsilon^2 e^2 \tilde{Q}^2}{3\pi m_x^2 \Sigma_0^2} \times \{ |a| J(a,b) \}}$$

$$1/\sqrt{|a|} \equiv (2m_\phi/m_x)(\Sigma/\Sigma_0)$$




$$\bar{\Sigma}_{\rm min}^2 = \left\{ \frac{2\epsilon^2 e^2 Q'^2}{g_x^2} \right\}^{2/3}$$