Thermal Misalignment of Scalar Dark Matter

Generating scalar misalignment through Planck suppressed interactions

Akshay Ghalsasi, Brian Batell, arxiv:2109.04476

Roller Coaster Dark Matter

Generating scalar misalignment through Planck suppressed interactions

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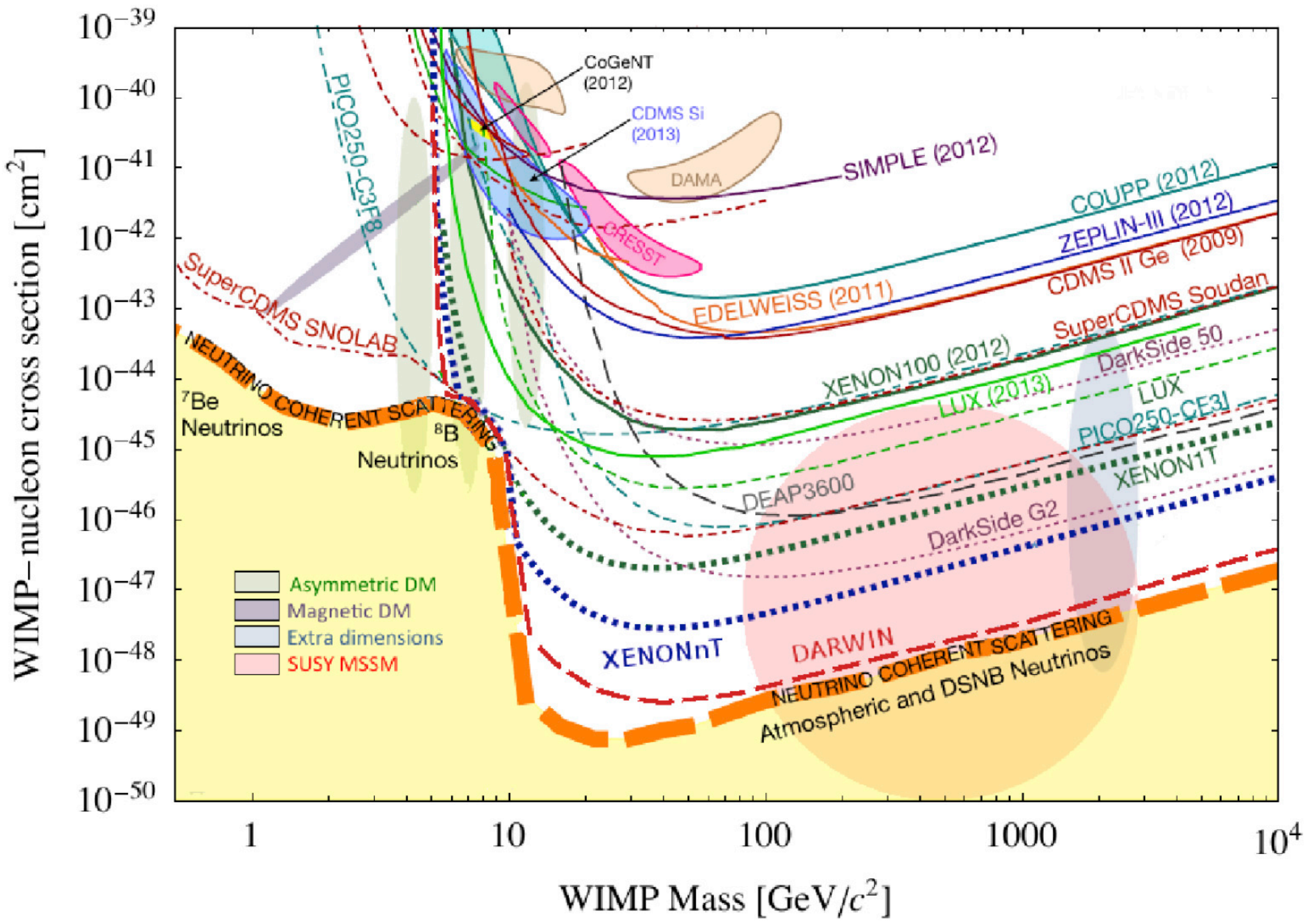
Overview

- Introduction to the model
- Visualizing Potential and Analytical Understanding
- Parameter space exploration
- Constraints
- Conclusions and Future Work

Motivation

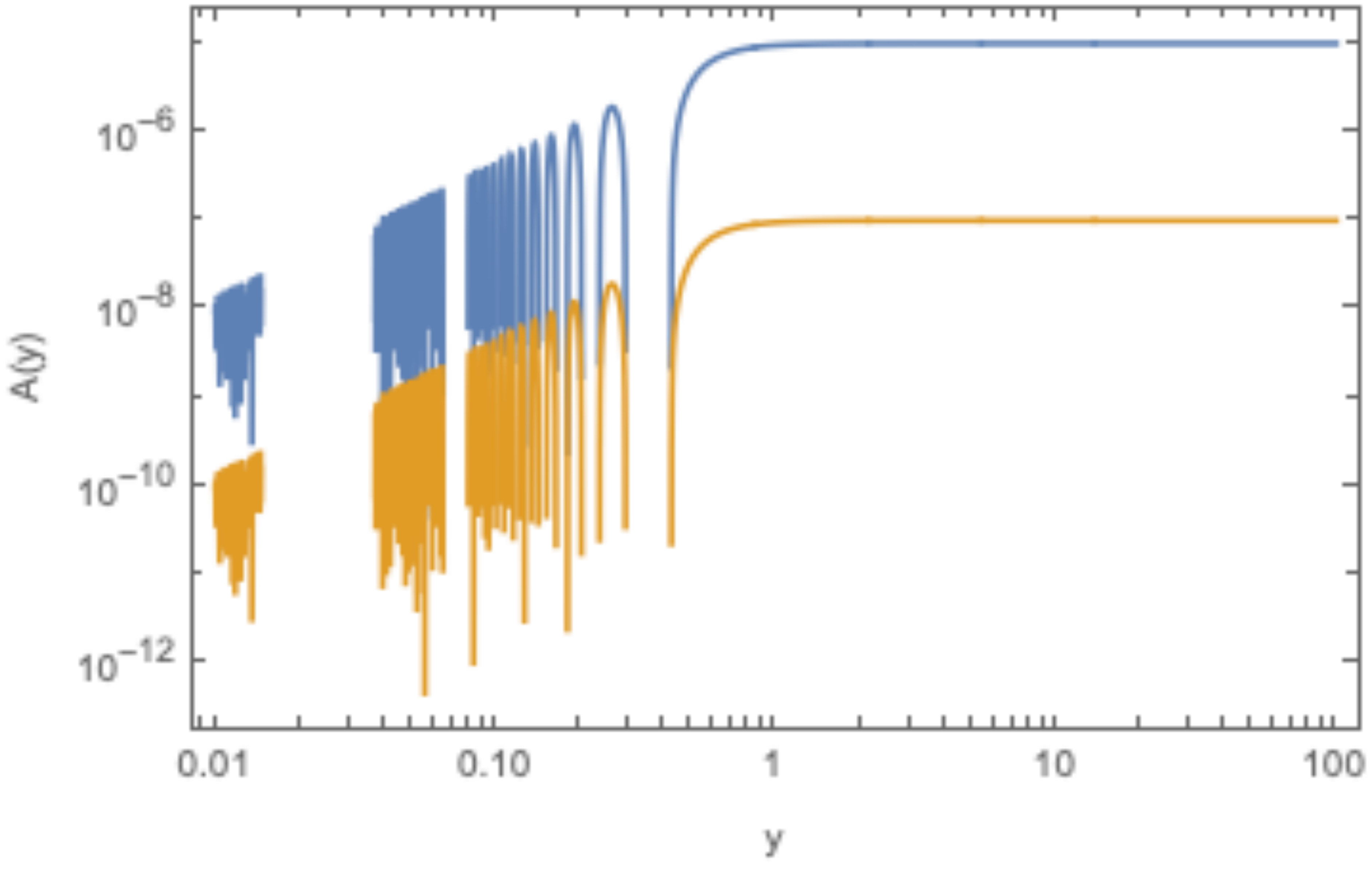
WIMPs under pressure



Motivation

Standard misalignment

- Coherent oscillations of a scalar field can constitute dark matter
- In standard scenario
  - Inflation generates misalignment
  - Scalar oscillates when Hubble equals mass
- Final yield sensitive to initial conditions



- Worst case scenario - no coupling to SM, impossible to detect

Introduction to the Model

The Lagrangian

- Scalar couples to fermions through Planck suppressed 5-dim operator

$$\mathscr{L} \supset -\left[m_f\left(1-\frac{\beta\phi}{M_{\rm pl}}\right)f_L f_R - \mathrm{h.c.}\right] + \frac{1}{2}m_\phi^2\phi^2$$

- Large β corresponds to a UV scale smaller than $M_{\rm pl}$ (through a Higgs portal)
- Same Lagrangian explored in Weiner and Zurek (2006) for other purposes

Introduction to the Model

The Potential

- Free energy of fermions gives rise to effective potential on the scalar

$$\delta V(\phi) = \frac{-g}{2\pi^2} T^4 \int_0^\infty dx\, x^2 \log\left[1 + e^{-\sqrt{x^2 + \frac{1}{y^2}\left(1 - \frac{\beta\phi}{M_{\rm pl}}\right)^2}}\right]$$

- Standard equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \xrightarrow{\;y = \frac{T}{m_f}\;} \frac{d^2\phi}{dy^2} + \frac{M_{\rm pl}^2}{m_f^4 \gamma^2 y^6}\frac{\partial V}{\partial \phi} = 0$$

$$\kappa = \frac{m_\phi M_{\rm pl}}{m_f^2}$$

$$\frac{d^2\phi}{dy^2} + \frac{\kappa^2}{\gamma^2 y^6}\left(\phi - \frac{2}{\pi^2}\frac{y^2 M_{\rm pl}}{\kappa^2}\beta\left(1 - \frac{\beta\phi}{M_{\rm pl}}\right)\int_0^\infty dx \frac{x^2}{\left(1 + e^{\xi}\right)\xi}\right) = 0$$

$$\xi = \sqrt{x^2 + \frac{1}{y^2}\left(1 - \frac{\beta\phi}{M_{\rm pl}}\right)^2}$$

Analytical Understanding

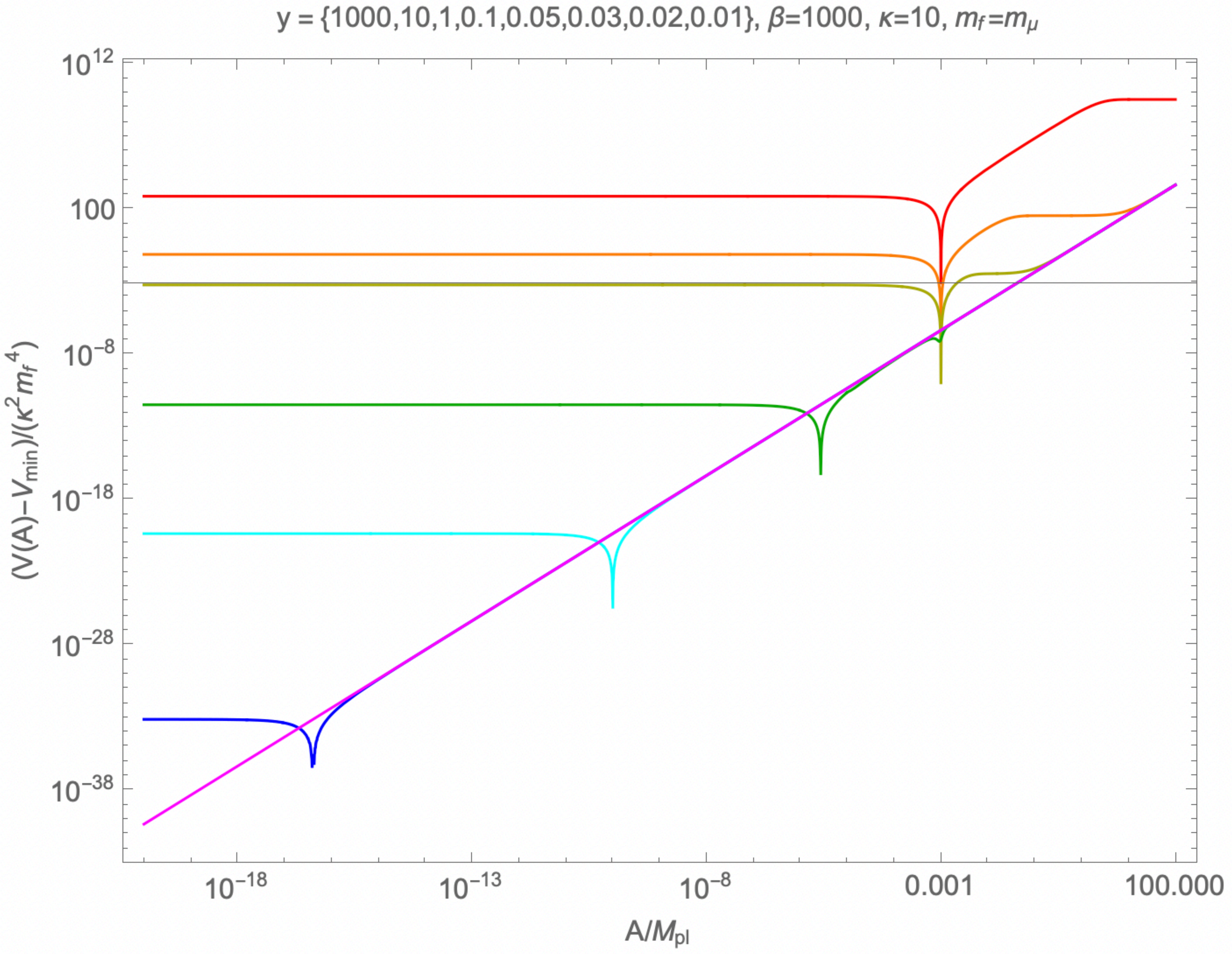
- High Temperature regime $(T \gg m_\psi, y \gg 1)$

$$\delta V_\phi = \frac{-g}{2\pi^2} T^4 \int_0^\infty dx\, x^2 \log\left[1 + e^{-\sqrt{x^2 + \frac{1}{y^2}\left(1 - \frac{\beta\phi}{M_{\rm pl}}\right)^2}}\right] = m_f^4 \left(\frac{y^2}{12}\left(1 - \beta\phi\right)^2 + \frac{1}{2}\kappa^2\phi^2\right) \Rightarrow \phi_{min} = \frac{y^2\beta}{y^2\beta^2 + 6\kappa^2}$$

- Low Temperature regime $(T \ll m_\psi, y \ll 1)$

$$\delta V_\phi = m_f^4 \left(y^{5/2} e^{-1/y} + \frac{1}{2}\kappa^2\phi^2\right)$$

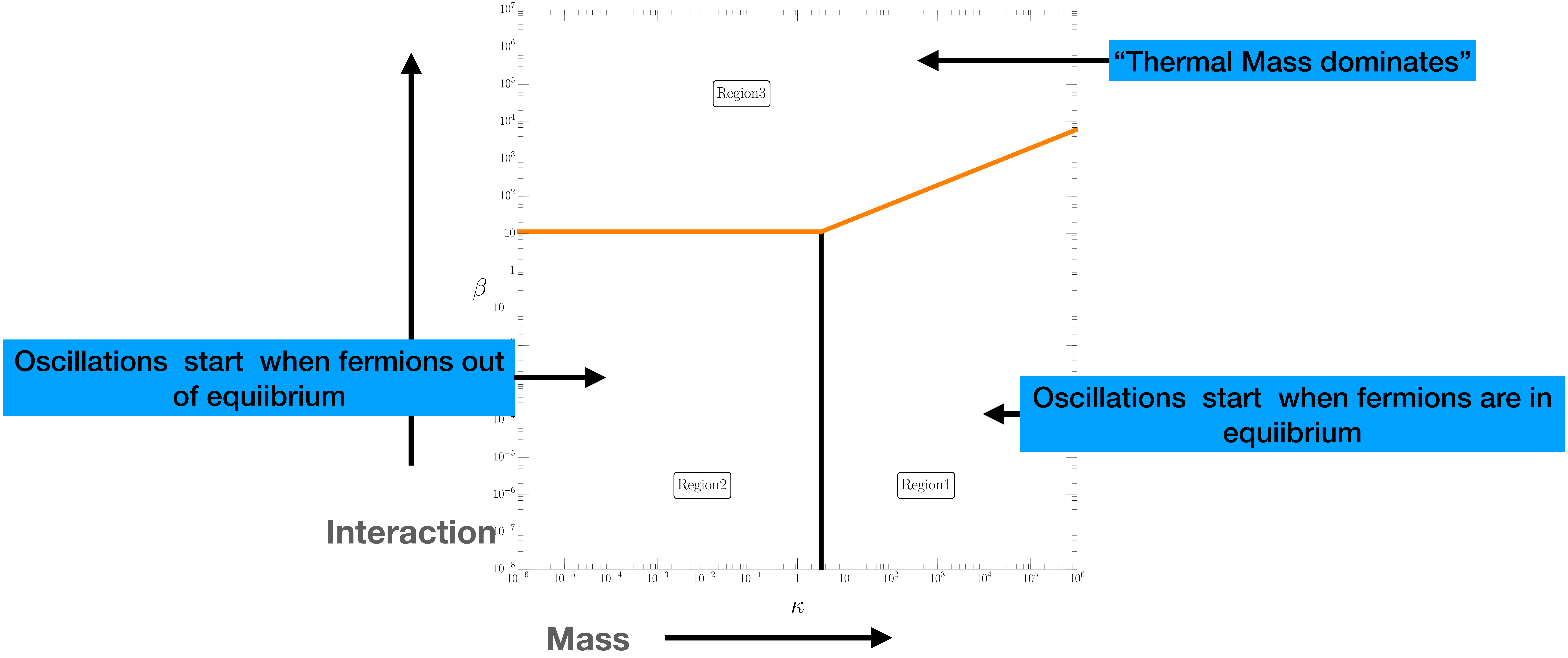
Visualizing the Potential



Parameter space exploration

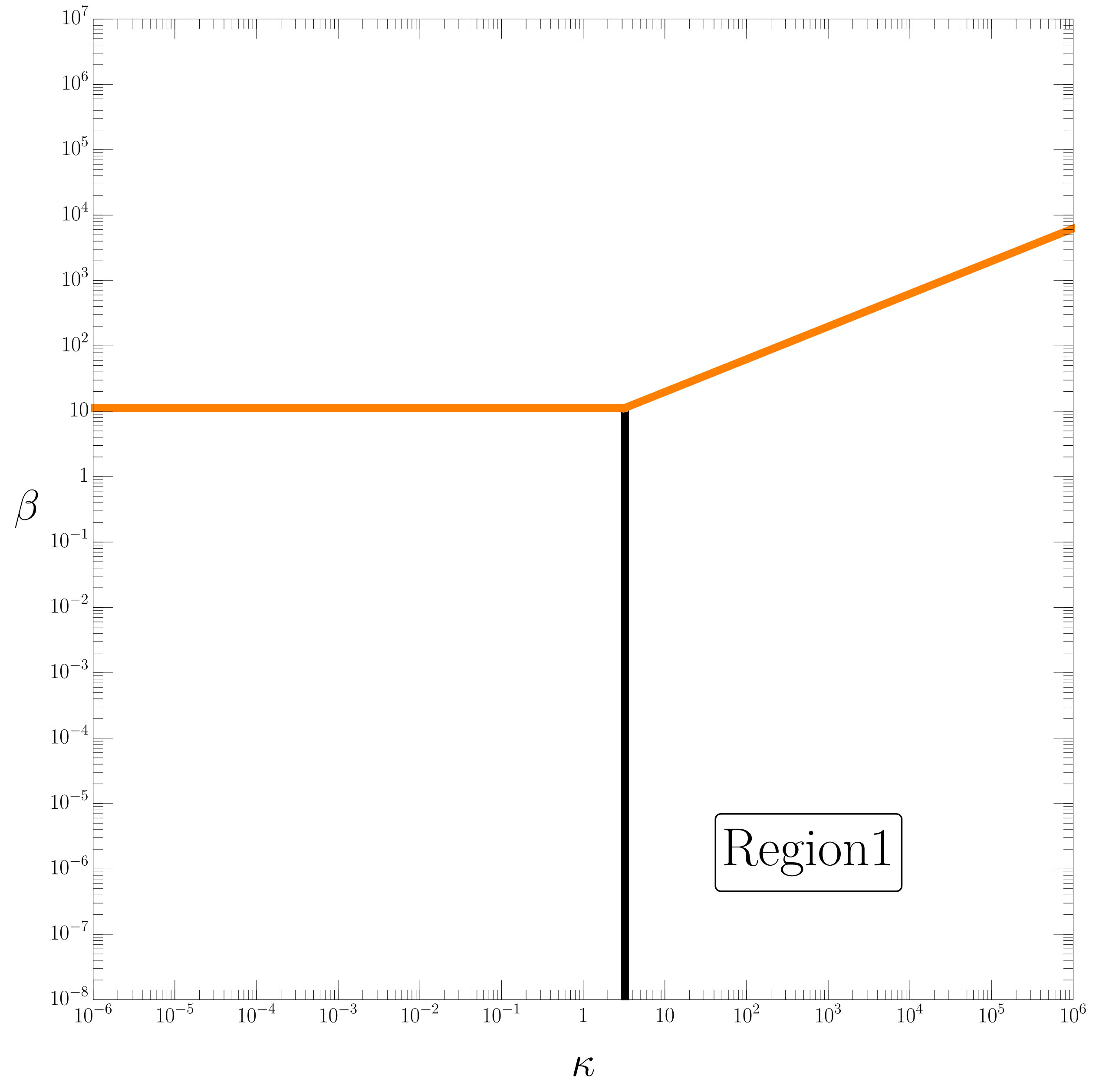
Overview

- For large y, $m_\phi^2(T) = m_\phi^2\left(1 + \frac{y^2\beta^2}{6\kappa^2}\right)$ $\rightarrow$ $y_{osc} = \frac{\beta}{6\sqrt{3}\gamma}\sqrt{\left(1+\sqrt{1+\frac{1296\gamma^2\kappa^2}{\beta^4}}\right)}$



Parameter space exploration

Large κ and small β, Region 1

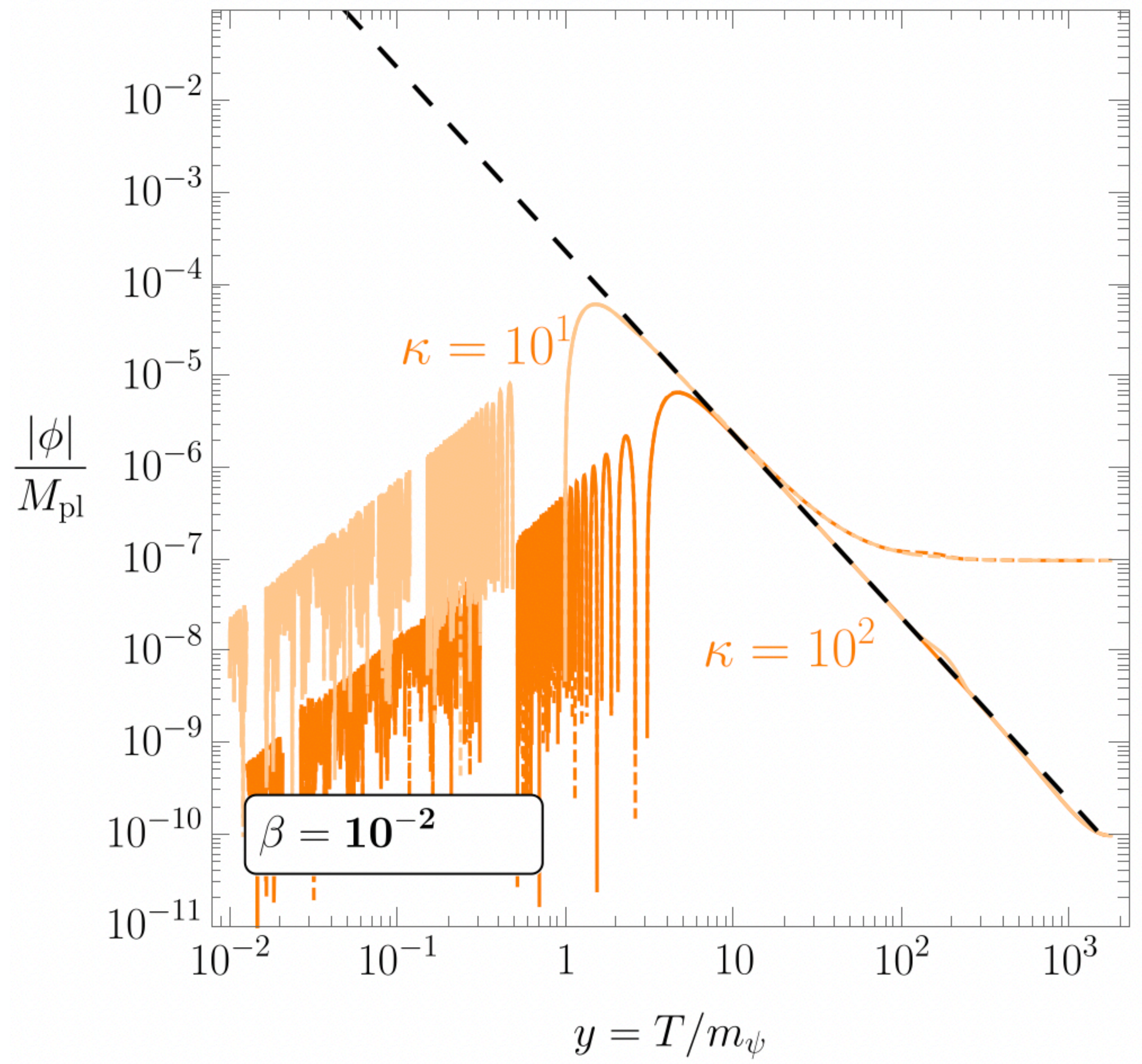


- Large κ, small β, mass of scalar initiates the oscillation

$$y_{osc} \simeq \sqrt{\frac{\kappa}{3\gamma}}$$

- However minima still controlled by β, since $T \gg m$ potential applies

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \quad \Rightarrow \quad \dot{\phi} = \frac{\beta m_\psi^2}{18\gamma} = const\,.$$



- Thus it can be shown

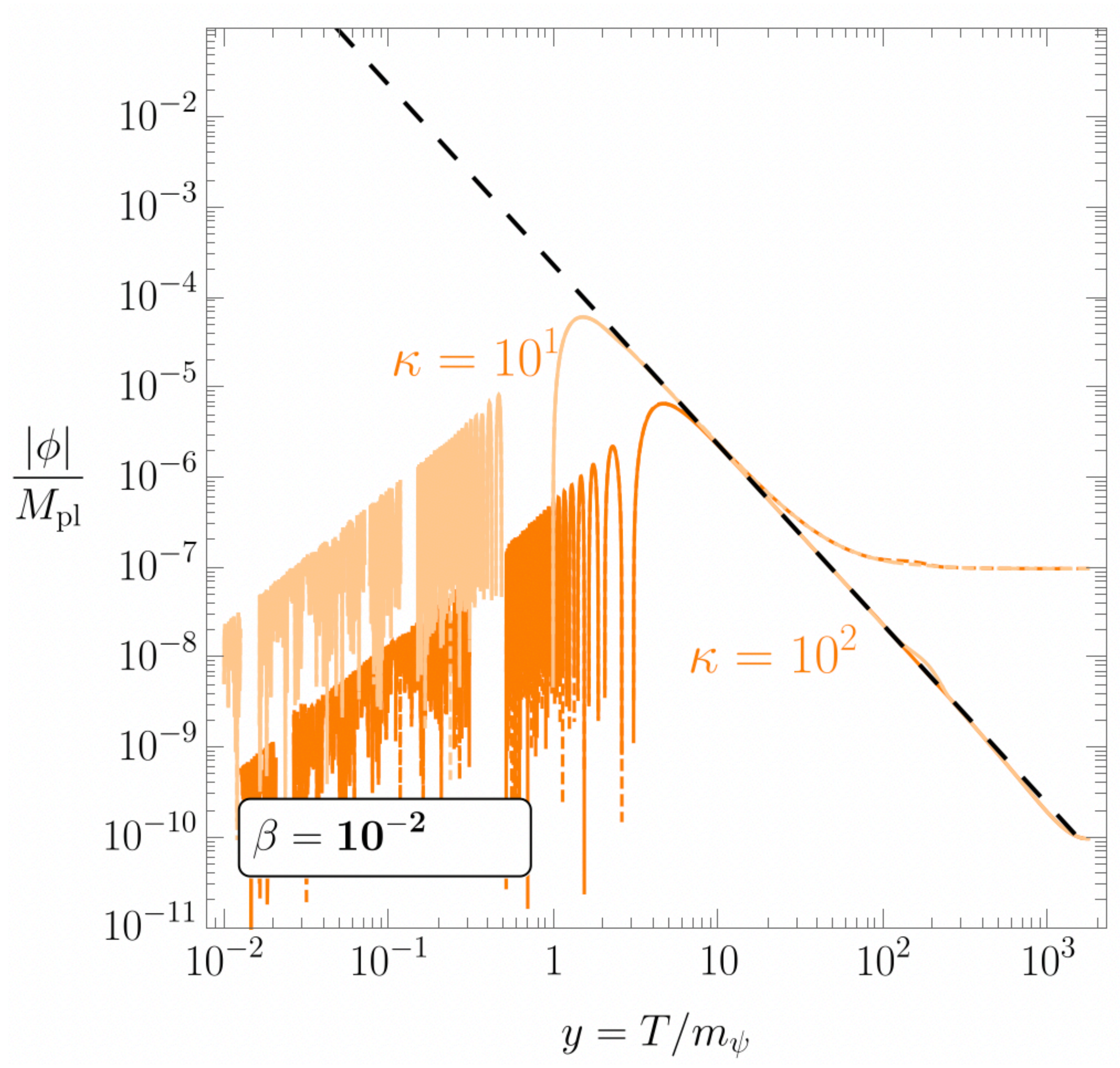
$$\phi(y) \simeq \frac{\beta M_{\rm pl}}{36\gamma^2 y^2} \quad \Rightarrow \quad \phi(y_{osc}) \simeq \frac{\beta}{12\gamma\kappa}$$

Parameter space exploration

Region 1, DM density

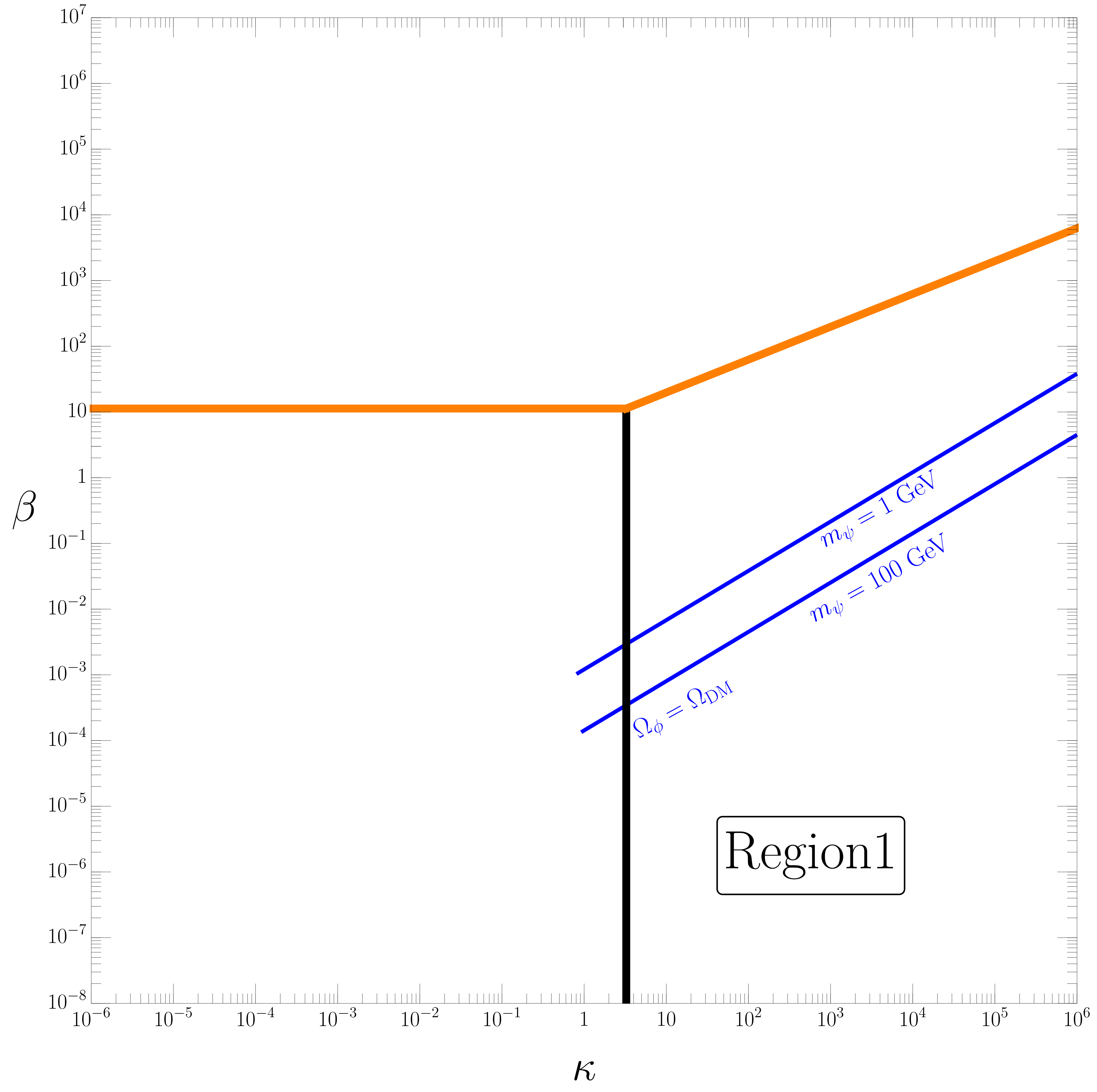
- Initial condition irrelevant as long as $\phi(y_i) < \phi(y_{osc})$
- DM density can then be written as

$$\Omega_\phi \simeq \Omega_{\rm DM} \left(\frac{m_\psi}{0.1\,\mathrm{GeV}}\right)\left(\frac{\beta}{0.1}\right)^2\left(\frac{400}{\kappa}\right)^{3/2}\left(\frac{10.75}{g_{*S}^{\rm osc}}\right)^{5/4}$$



Parameter space exploration

Region 1, Plot



Parameter space exploration

Small κ and small β, Region 2

- For $y \gg 1$ scalar follows similar path as Region 1

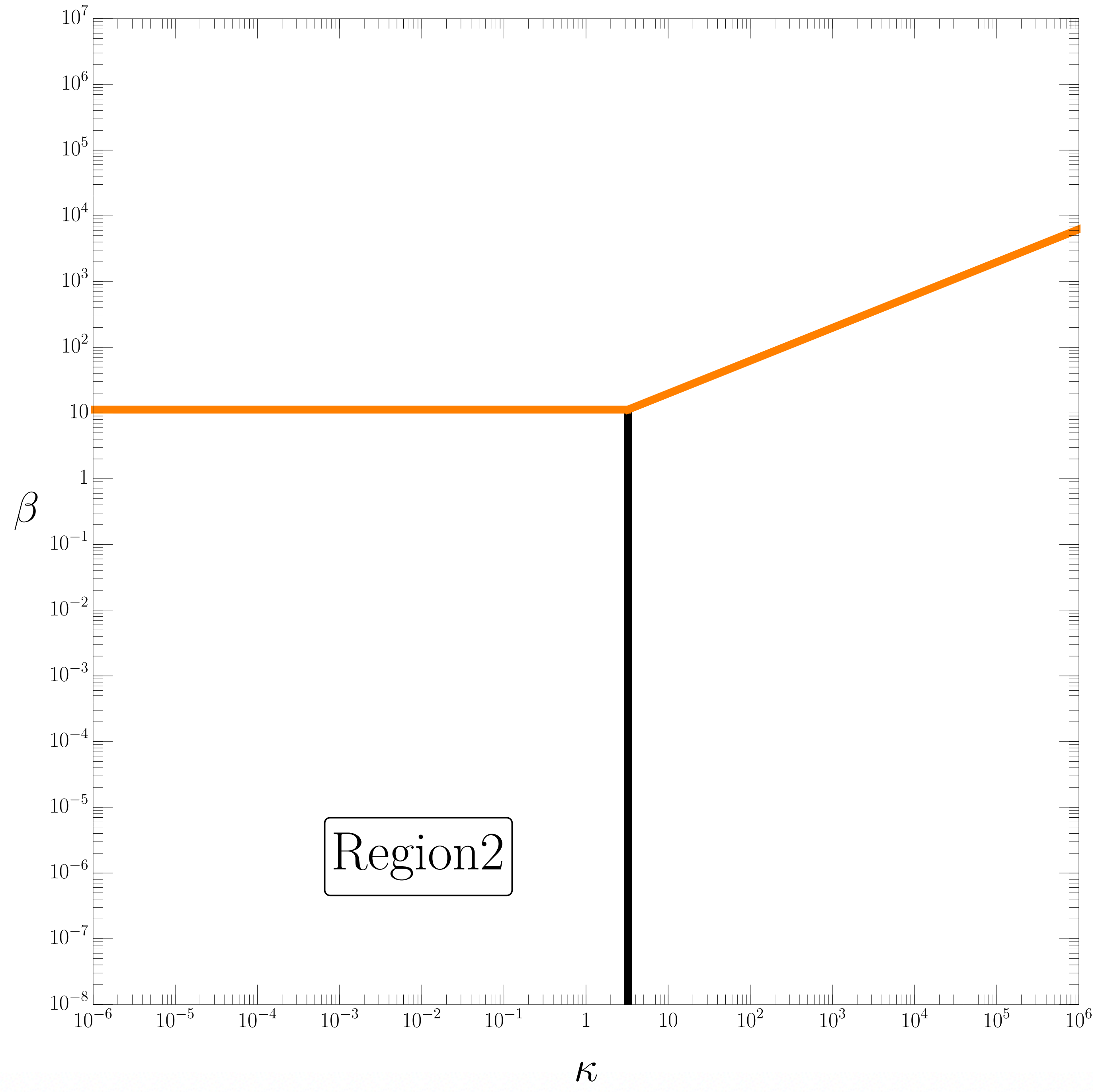
$$\phi(y) \simeq \frac{\beta M_{\rm pl}}{36\gamma^2 y^2}$$

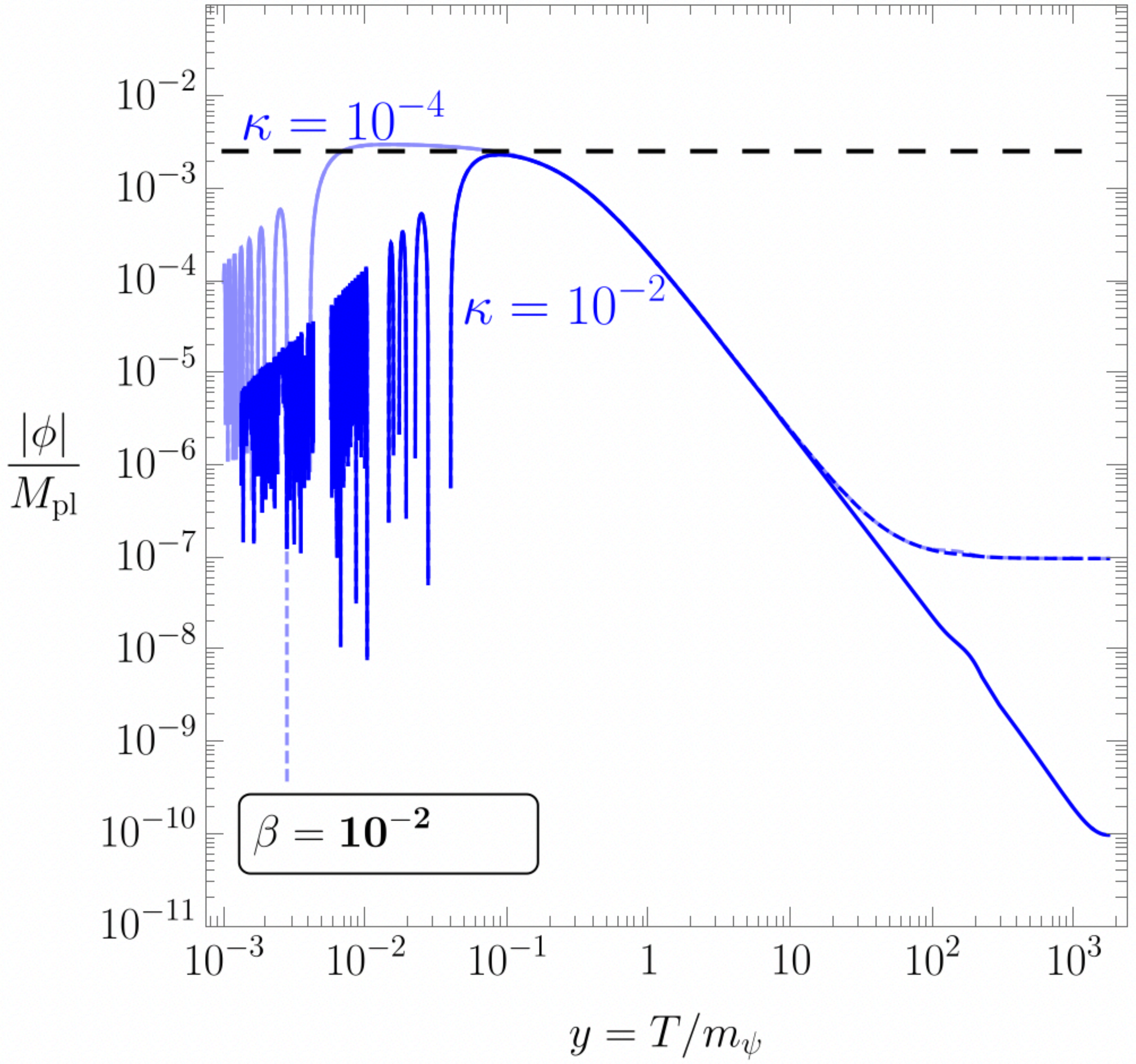
- For small κ oscillations start for y < 1

$$y_{osc} \simeq \sqrt{\frac{\kappa}{3\gamma}}$$

- Fermion feedback switches off scalar asymptotes to

$$\phi(y_{osc}) \simeq \frac{0.27\beta}{\gamma^2}$$



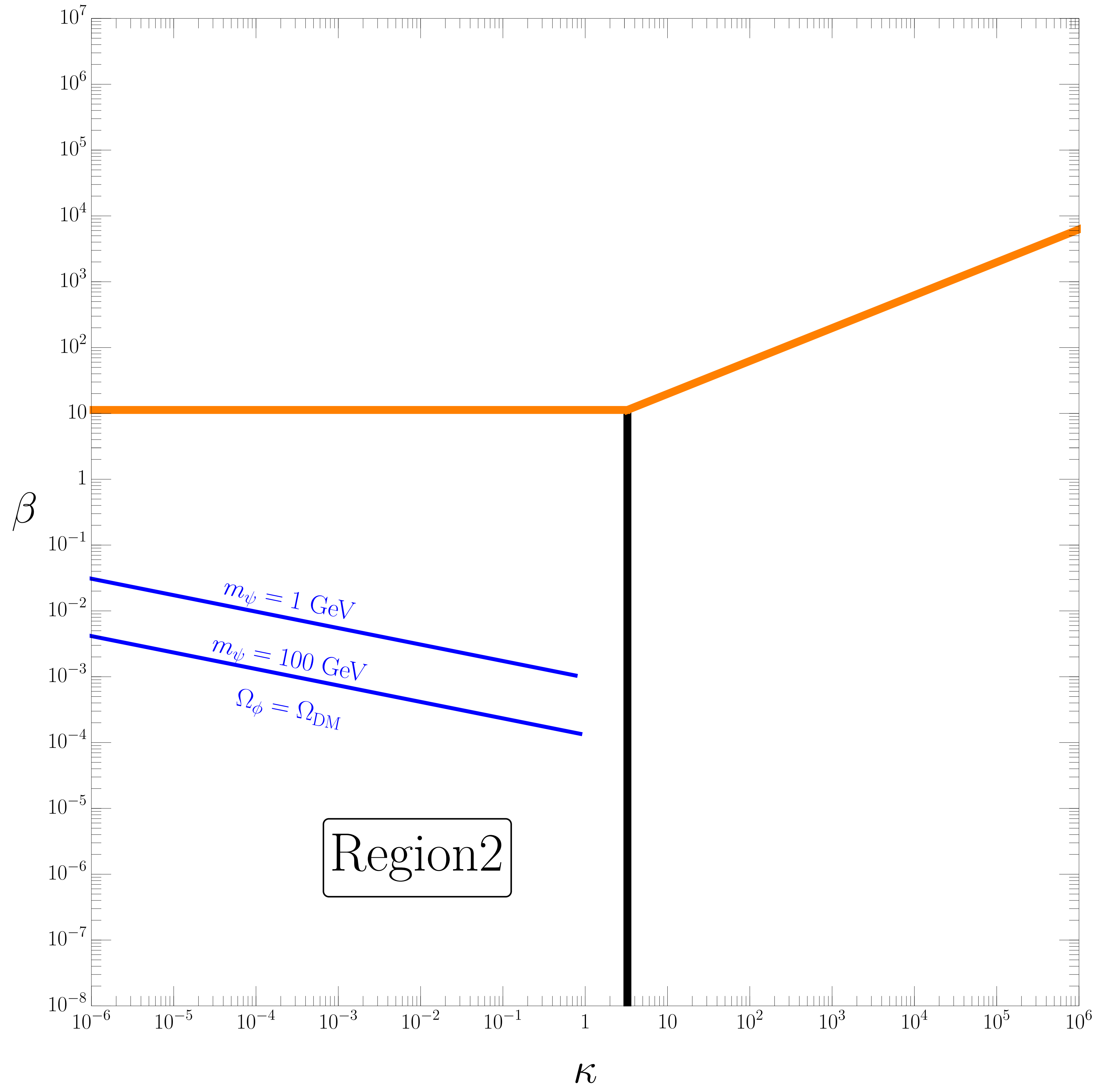


Parameter space exploration

Small κ and small β, DM density, Plots

- Thus the energy density at matter radiation equality is given by

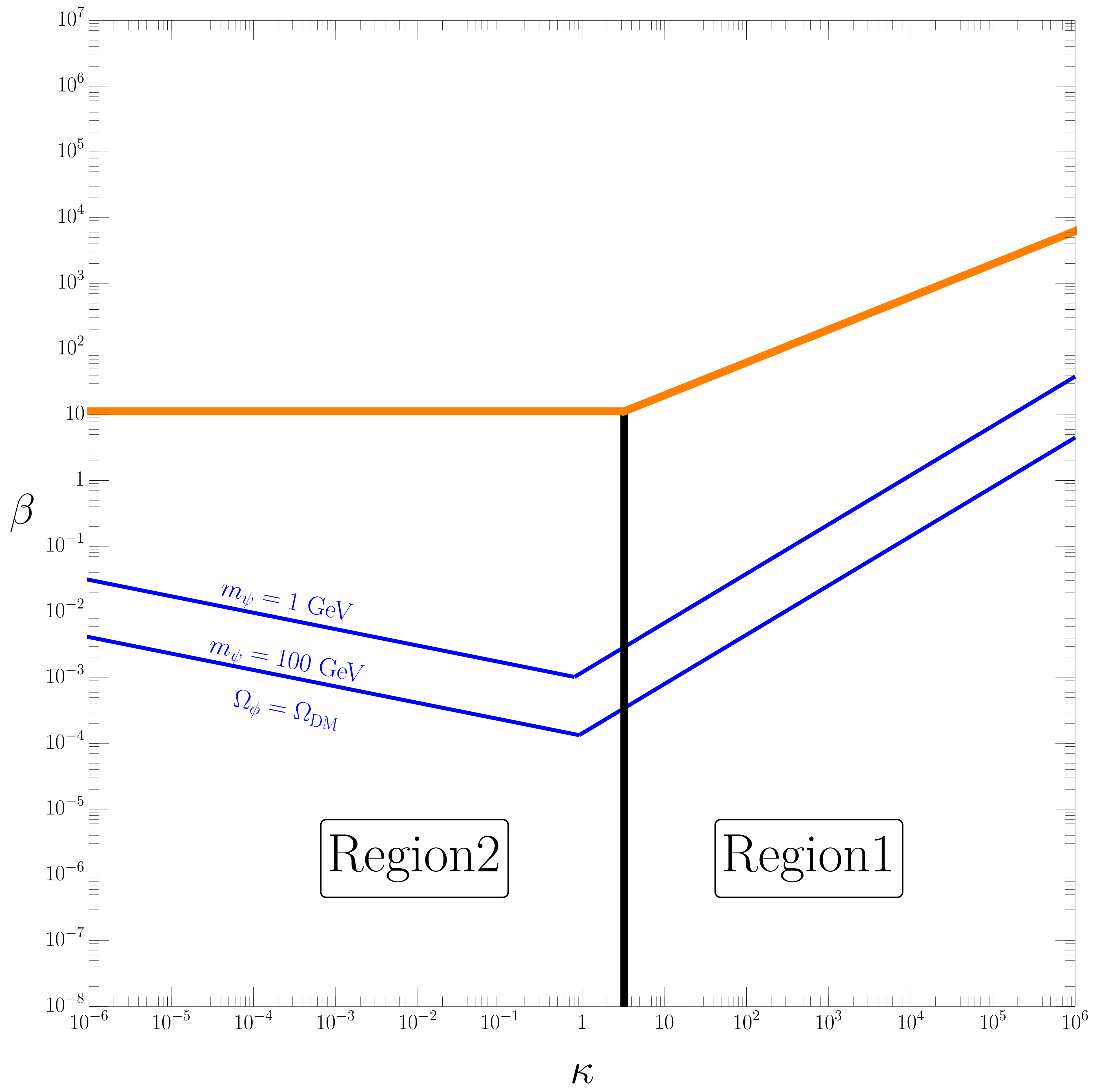
$$\Omega_\phi \simeq \Omega_{\rm DM} \left(\frac{m_\psi}{0.1\,\mathrm{GeV}}\right)\left(\frac{\beta}{10^{-3}}\right)^2\left(\frac{\kappa}{0.01}\right)^{1/2}\left(\frac{10.75}{g_{*S}^{\rm osc}}\right)^{9/4}$$



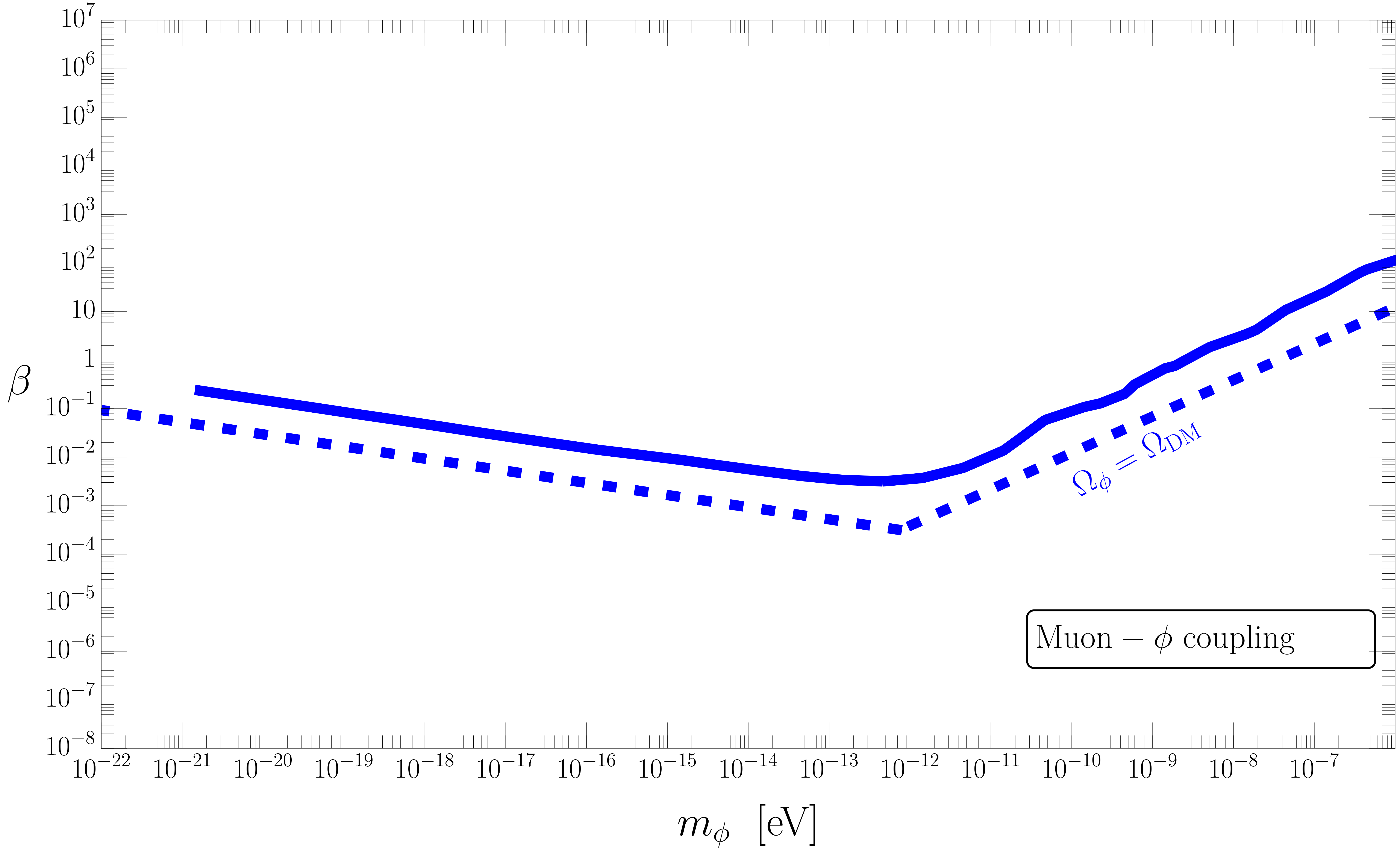
Parameter space exploration

Small κ and small β, Plots

- Combined Plot



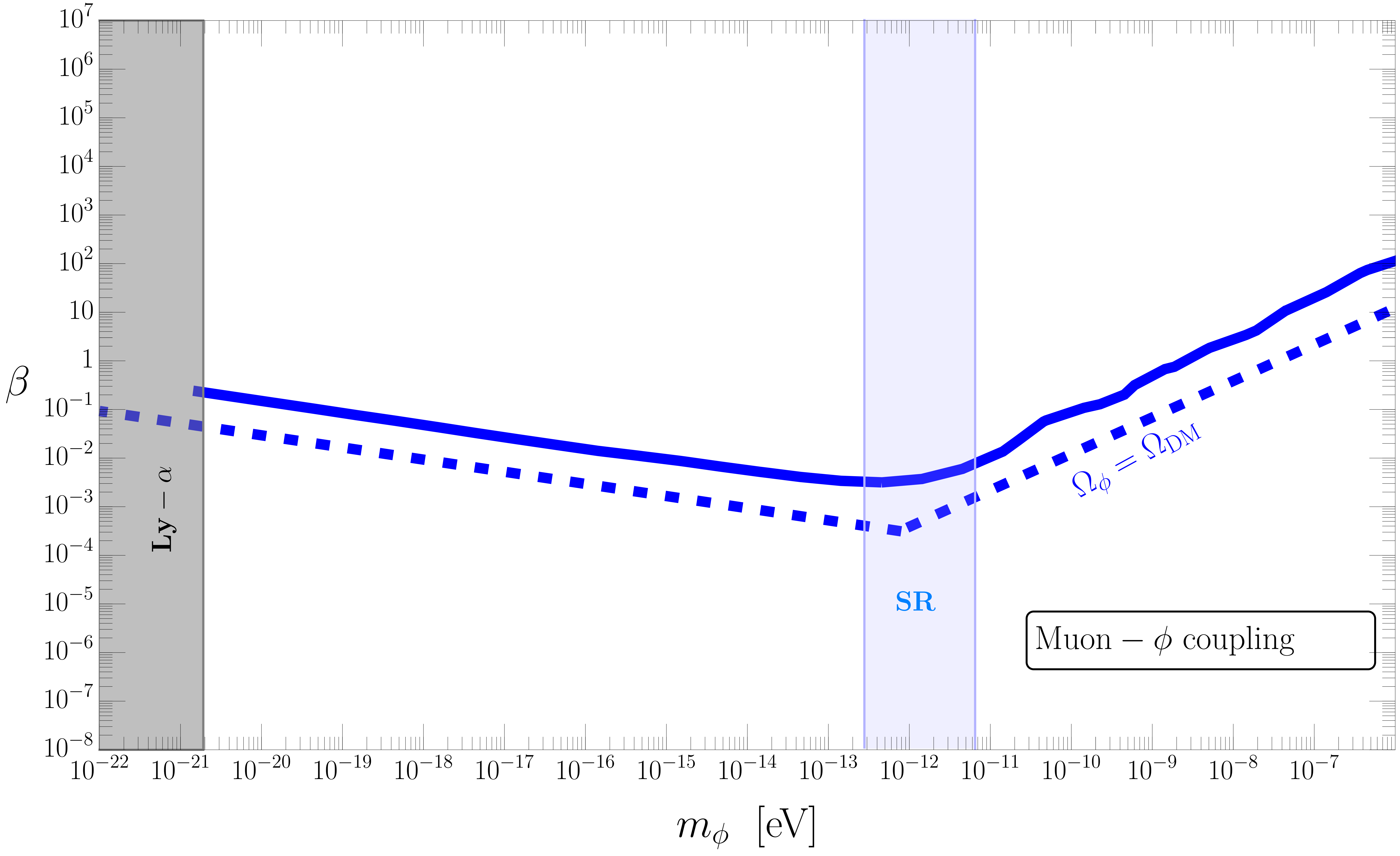
Muon Case



10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
β
10^{-22} 10^{-21} 10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7}
m_ϕ [eV]
$\Omega_\phi = \Omega_{\mathrm{DM}}$
Muon $- \phi$ coupling

Constraints

Ly-α and Superradiace



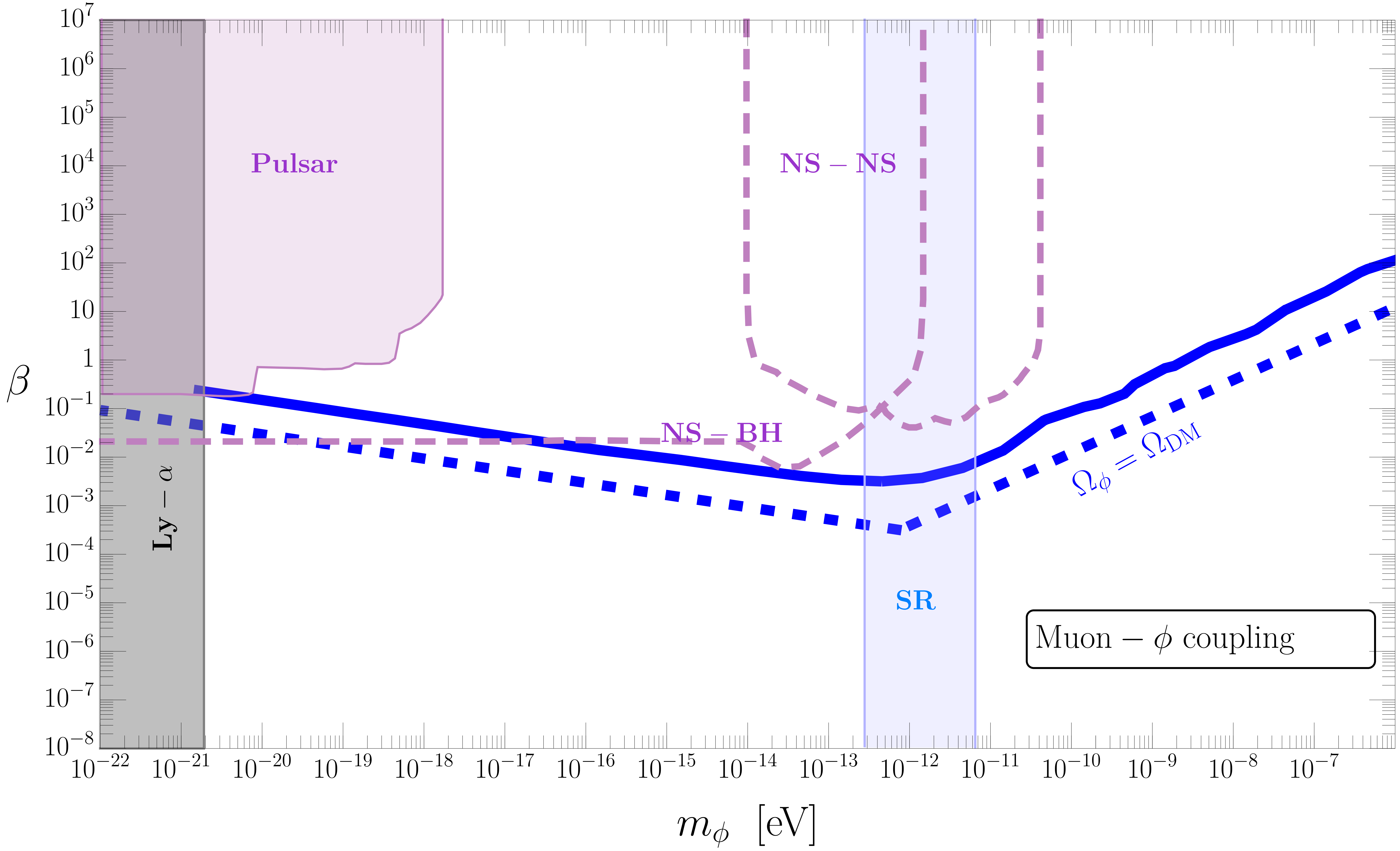
Irsic et. al. : 1703.04683

Baryakhtar et. al. : 2011.11646

Constraints

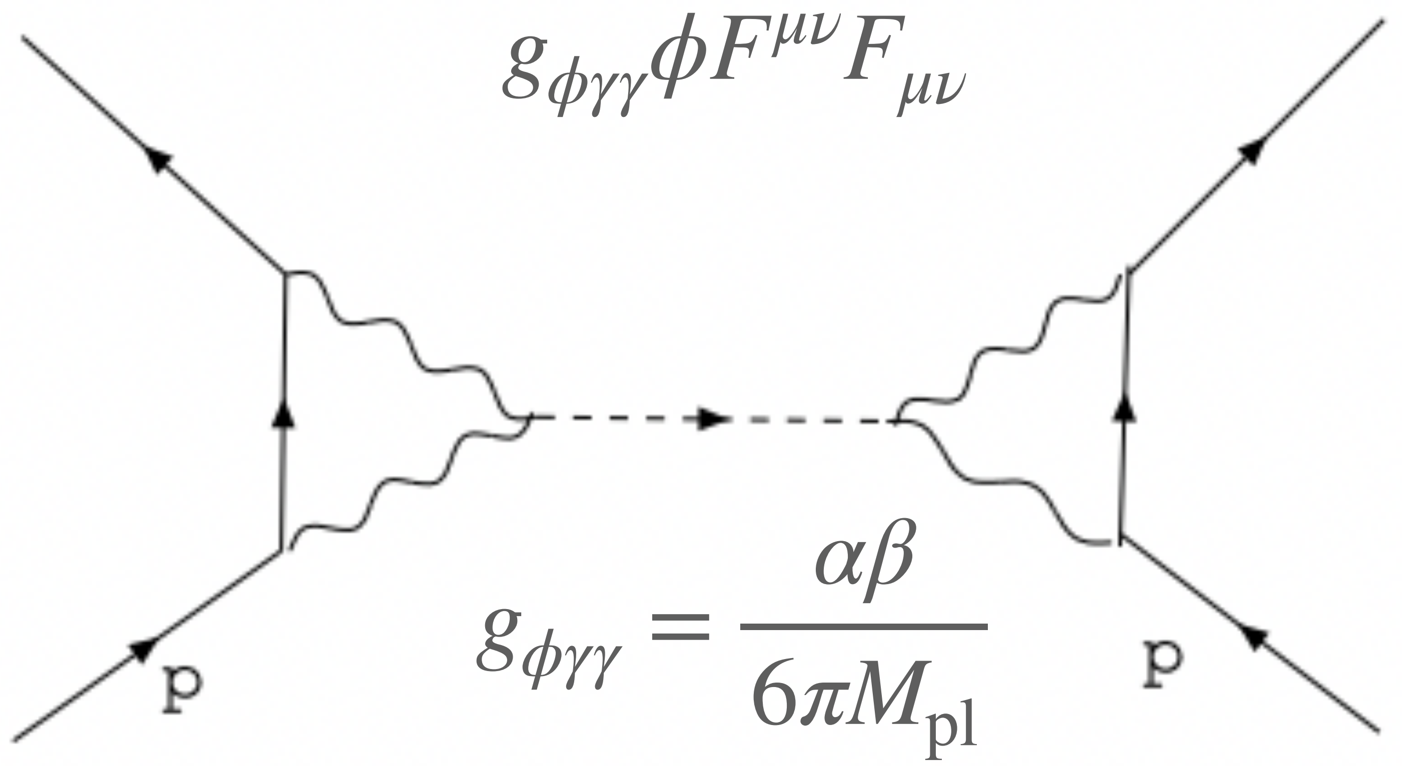
Astrophysical

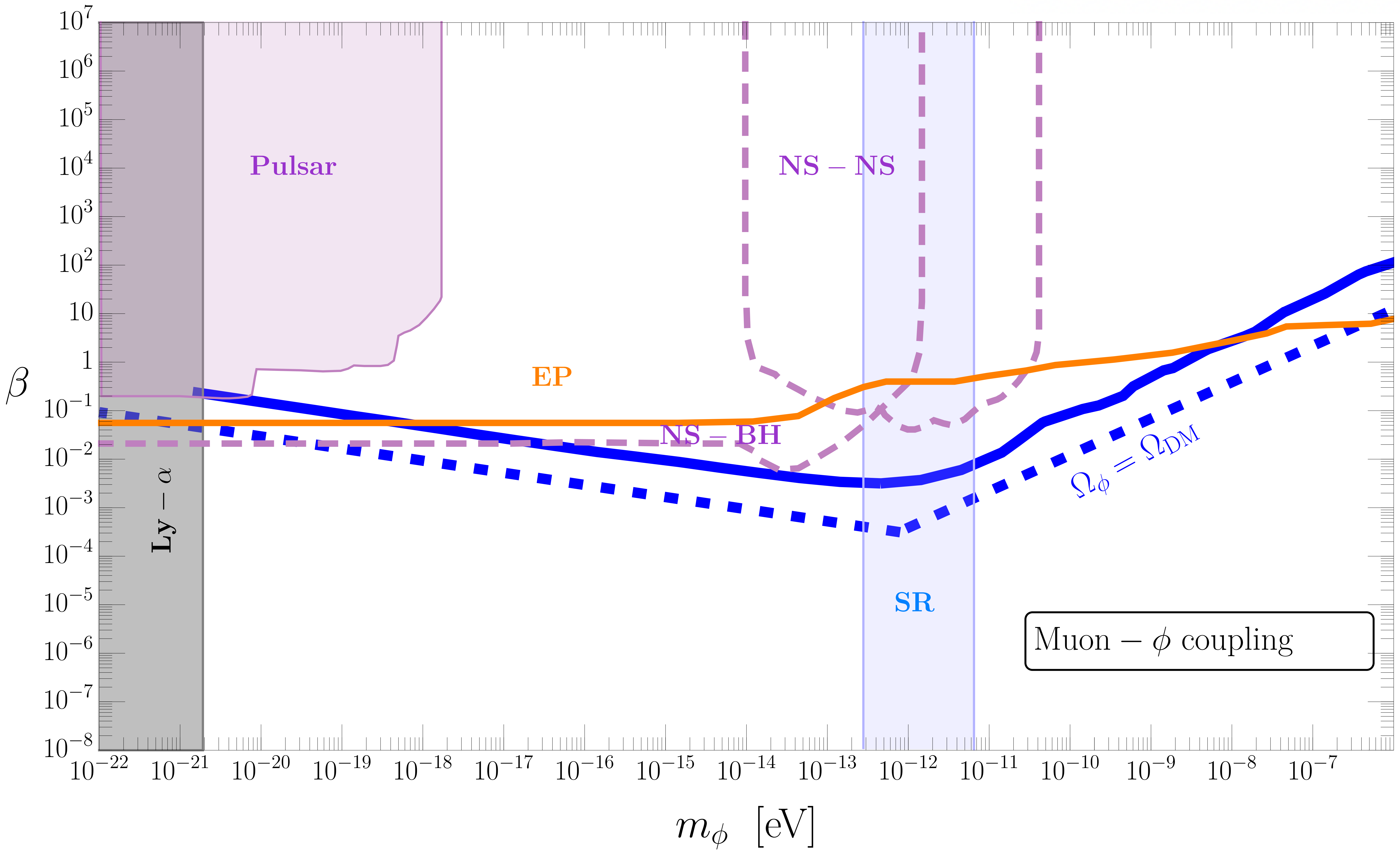
Dror et. al. : 1909.12845



Constraints

From coupling to photon, EP

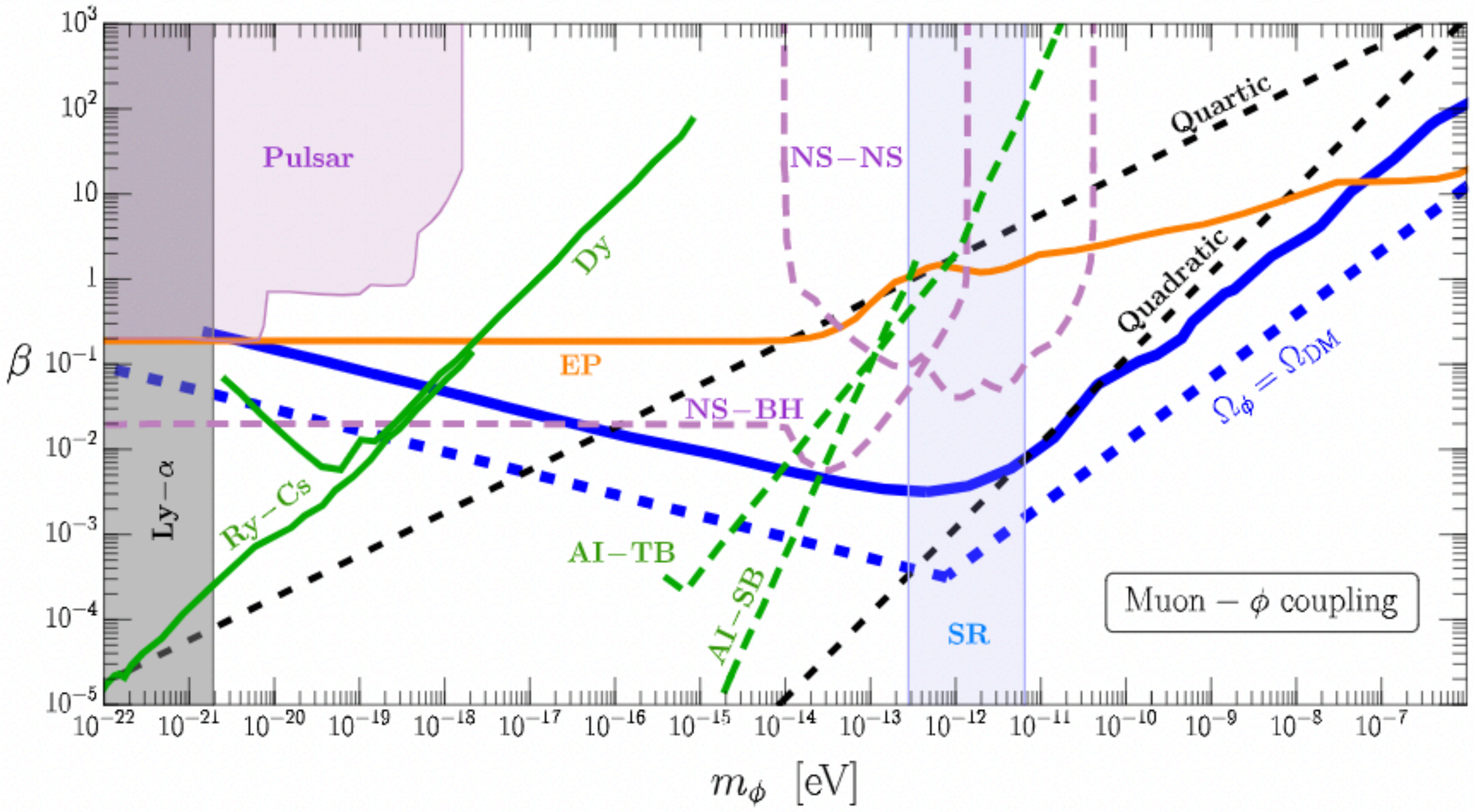




Schlamminger et.al : 0712.0607
Hees et. al. : 1807.04512
Berge et. al. : 1712.00483

Constraints

Atomic Clocks, Interferometers



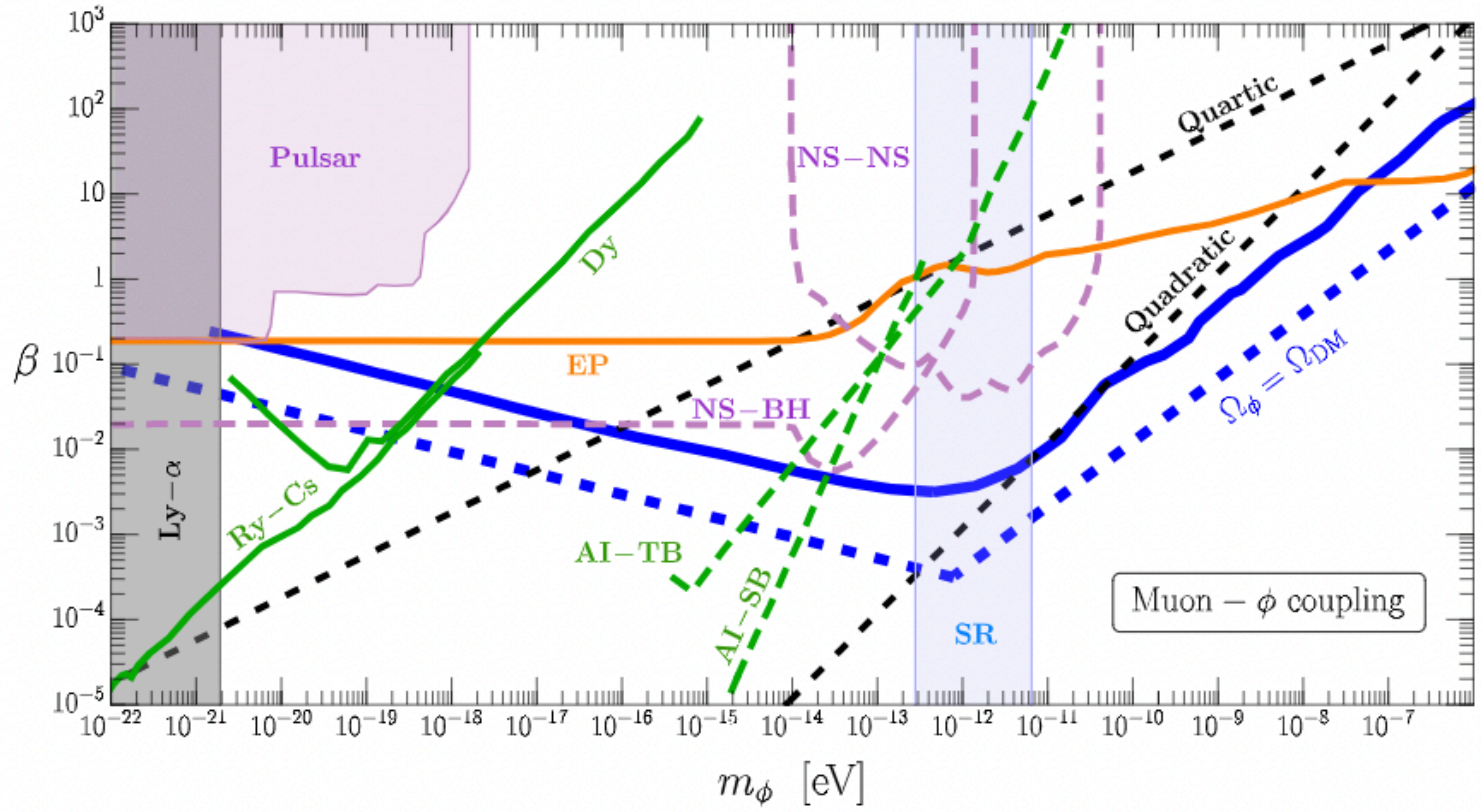
Tillburg et.al : 1503.06886
Hees et. al. : 1604.08514
Arvanitaki et. al. : 1606.04541

Constraints

Naturalness

Quartic $\lambda A_{max}^4 > m_A^2 A_{max}^2$

Quadrartic $\delta m_A^2 = \frac{1}{16\pi^2}\left(\frac{\beta m_f}{M_{\rm pl}}\right)^2 \Lambda_{EW}^2 < m_A^2$



Constraints

Other constraints that can be avoided

- Fine-tuning of initial conditions
- Isocurvature constraints
- Decay, Freeze-in and thermalization

Conclusion

Things learned so far

- Generic couplings to fermions can generate a misalignment for scalar fairly independently of initial conditions
- Allows us to relate scalar mass and couplings to get required DM density
- Mechanism within reach of being confirmed/ruled out for muons
- Assuming standard cosmology provides strongest constraints on scalar muon coupling in much of the parameter space

Ongoing Work

Things to investigate

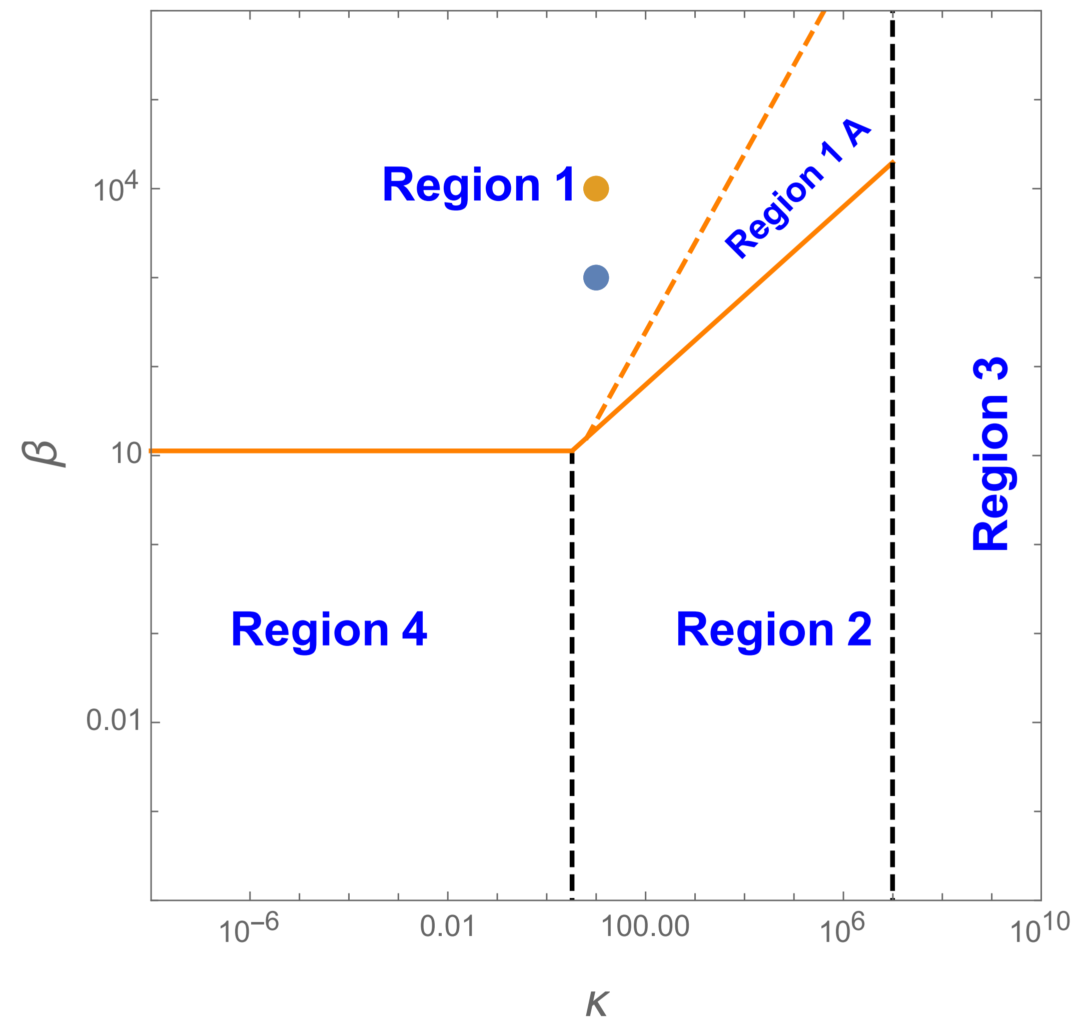
- Explore Region 3 in depth
- Explore thermal feedback from coupling to photons
- Explore electron and tau lepton parameter space.
- Higgs portal
- Neutrino portal
- UV completion of model
- Others …

Questions?

Backup Slides

Parameter space exploration

Large β and κ , Region 3



- Oscillations start controlled by β, scalar oscillates around

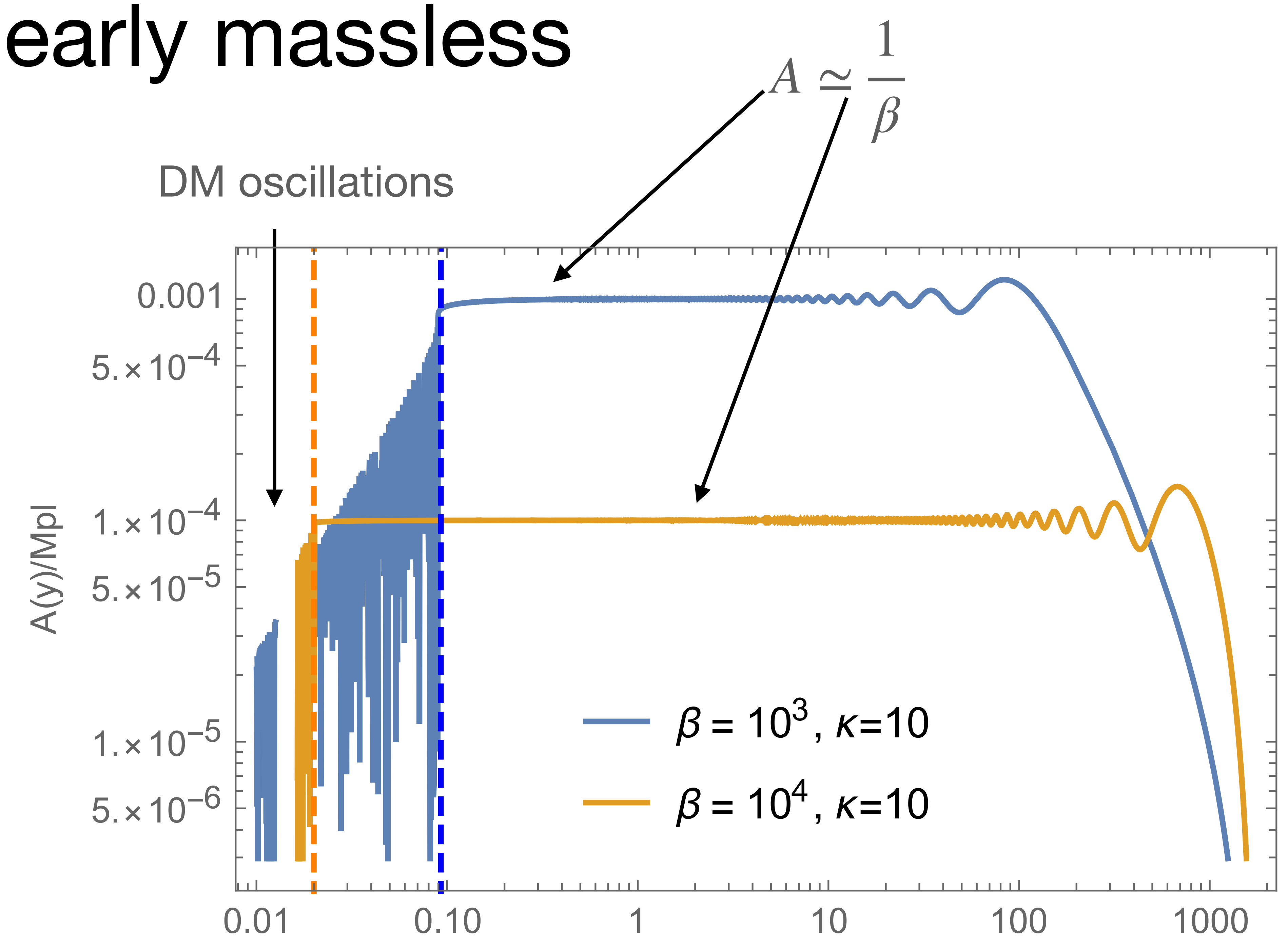
$$A_{min}(y) = \frac{y^2\beta}{y^2\beta^2 + 6\kappa^2}\Big|_{y\gg 1} \simeq \frac{1}{\beta}$$

- Scalar oscillates around 1/β, making fermions nearly massless

$$y_{eff} = \frac{T}{m\left(1 - \frac{\beta A}{M_{\rm pl}}\right)} \simeq \frac{y(y^2\beta^2 + 6\kappa^2)}{6\kappa^2}$$

- Once $y_{\rm eff} < 1$, the feedback shuts off at

$$y_d \simeq 2 \times \left(\frac{\kappa}{\beta}\right)^{2/3} + \mathcal{O}\left(\frac{\kappa}{\beta}\right)^{4/3}$$

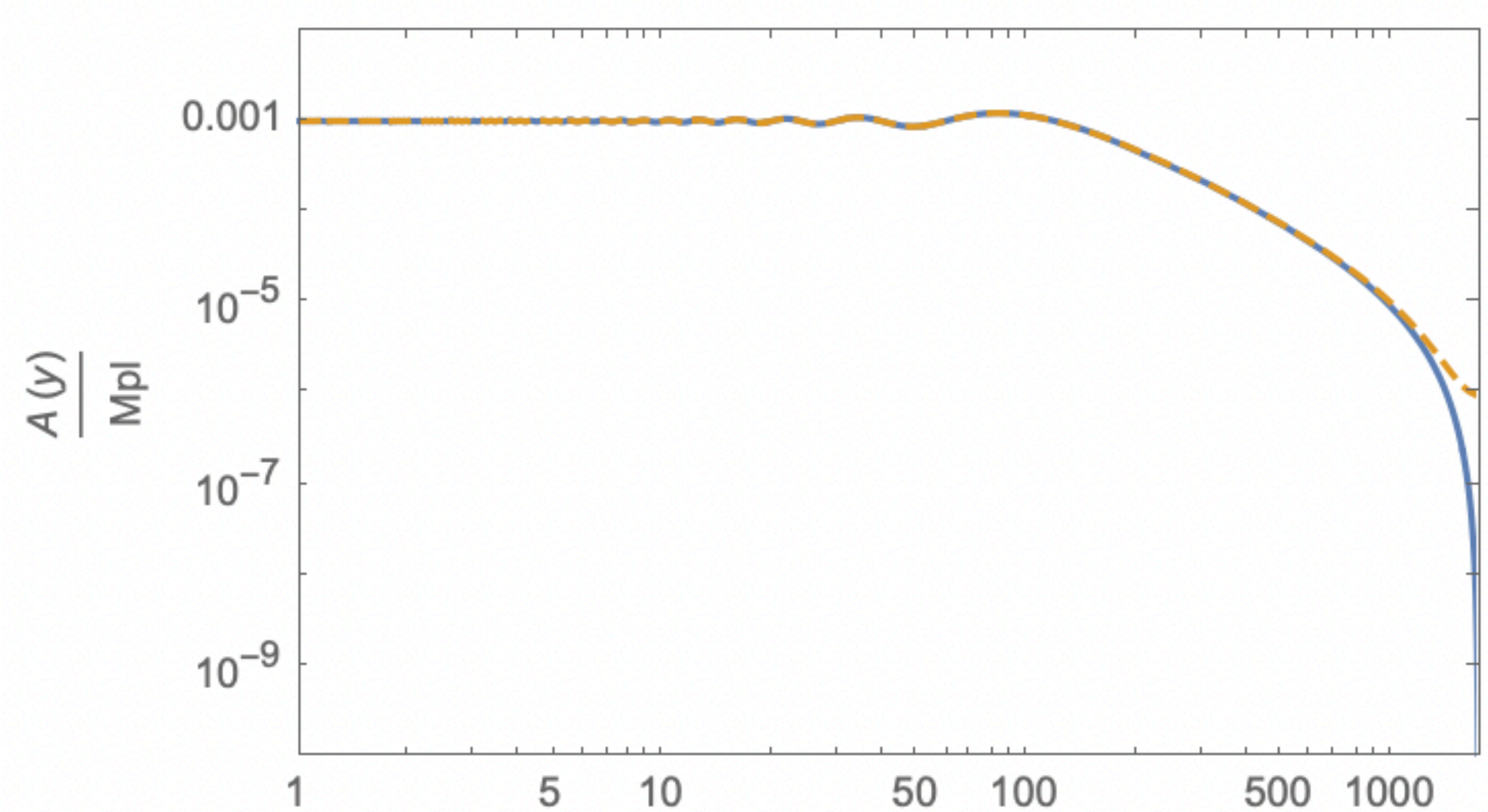


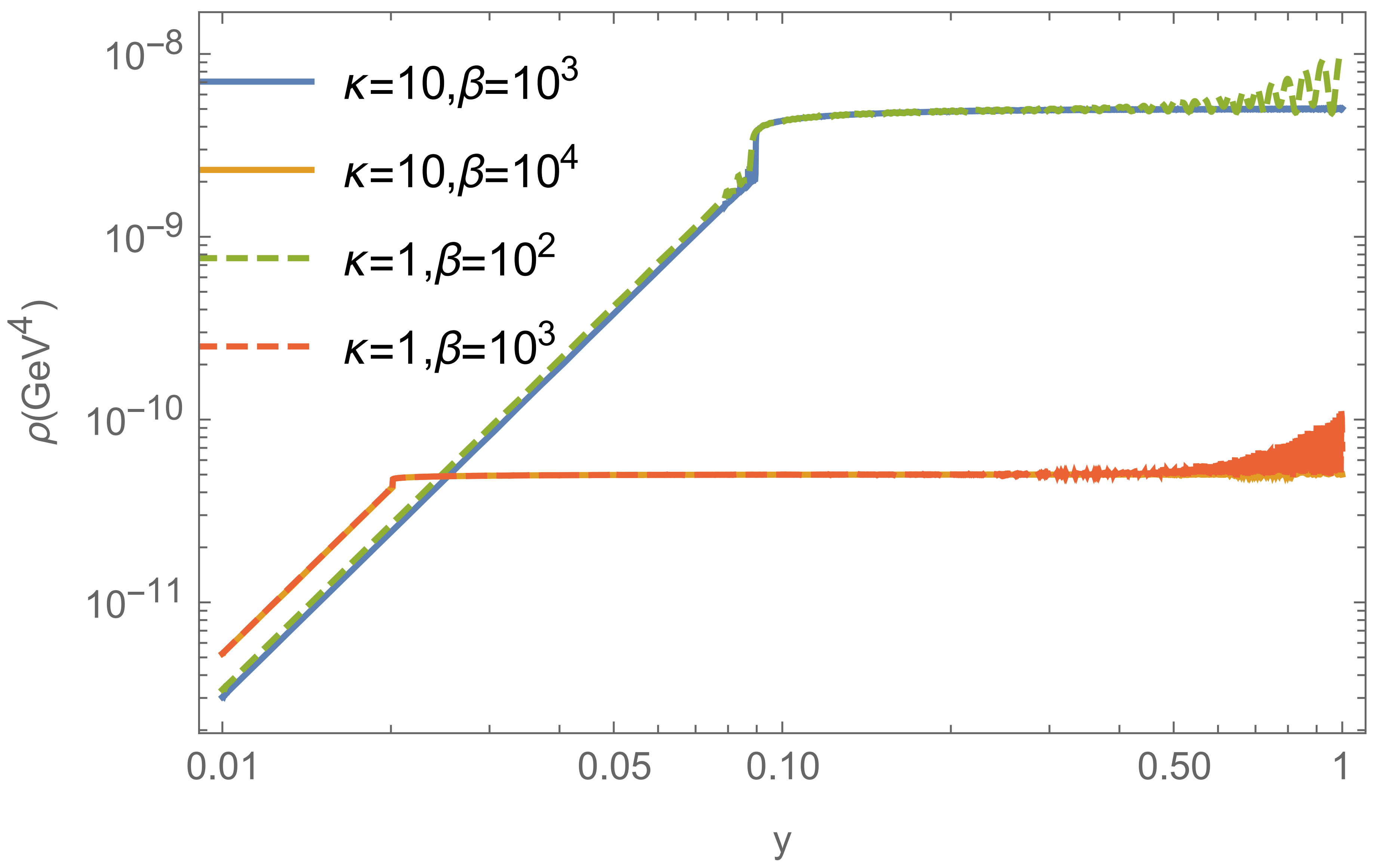
Parameter space exploration

Large β and κ , DM density, Plots

- Expected energy density is independent of κ, β. Too large even for electron mass

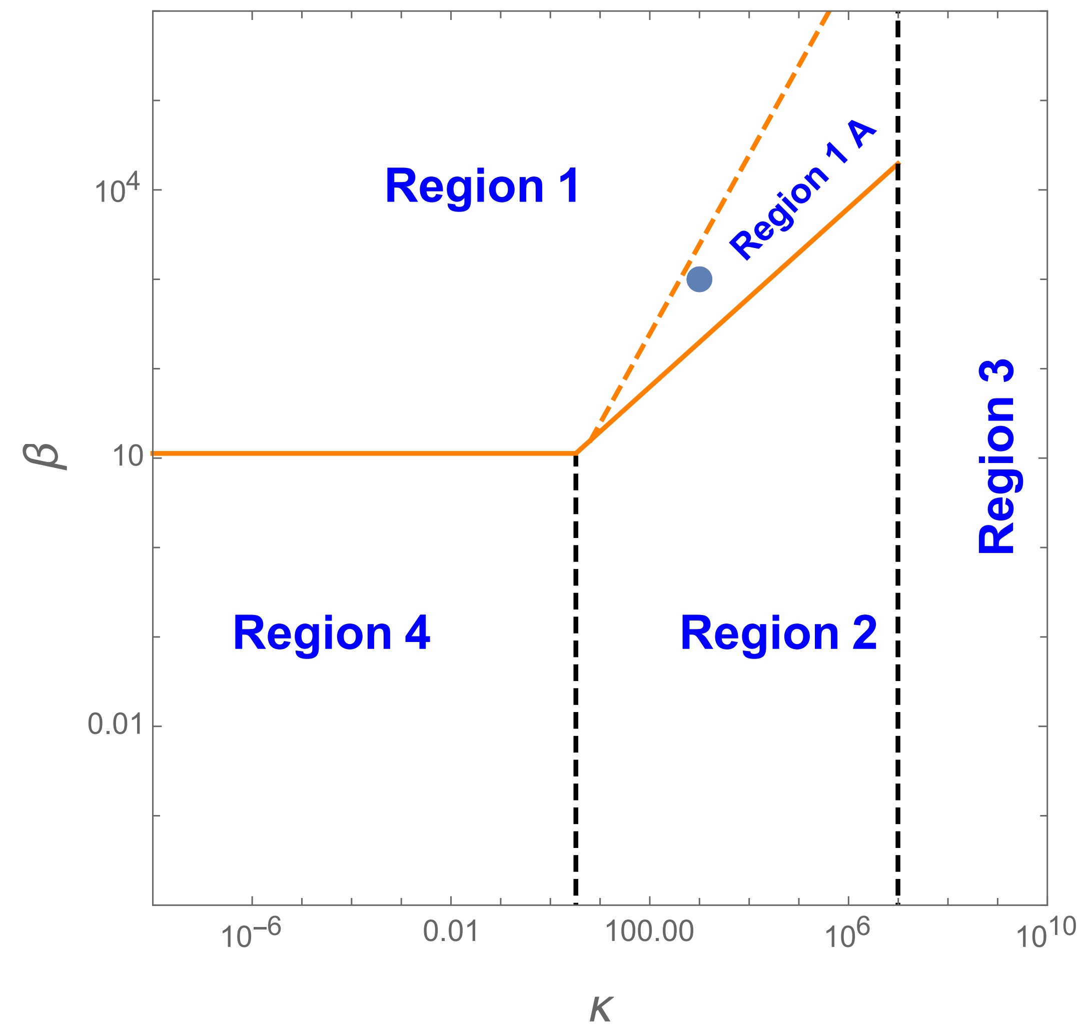
$$\Omega_{eq} = \xi \frac{\frac{1}{2} m_A^2 \overbrace{A_{min}^2}^{\frac{1}{\beta^2}}(y_d)}{\frac{\pi^2 g(y_d)}{30} y_d^4 m_f^4} \frac{y_d}{y_{eq}} = 2.8 \times 10^5 \left(\frac{10.75}{g(y_d)}\right) \left(\frac{\xi}{0.1}\right) \left(\frac{m}{0.1\mathrm{GeV}}\right)$$





Parameter Space exploration

Large β and κ , Region 1 A

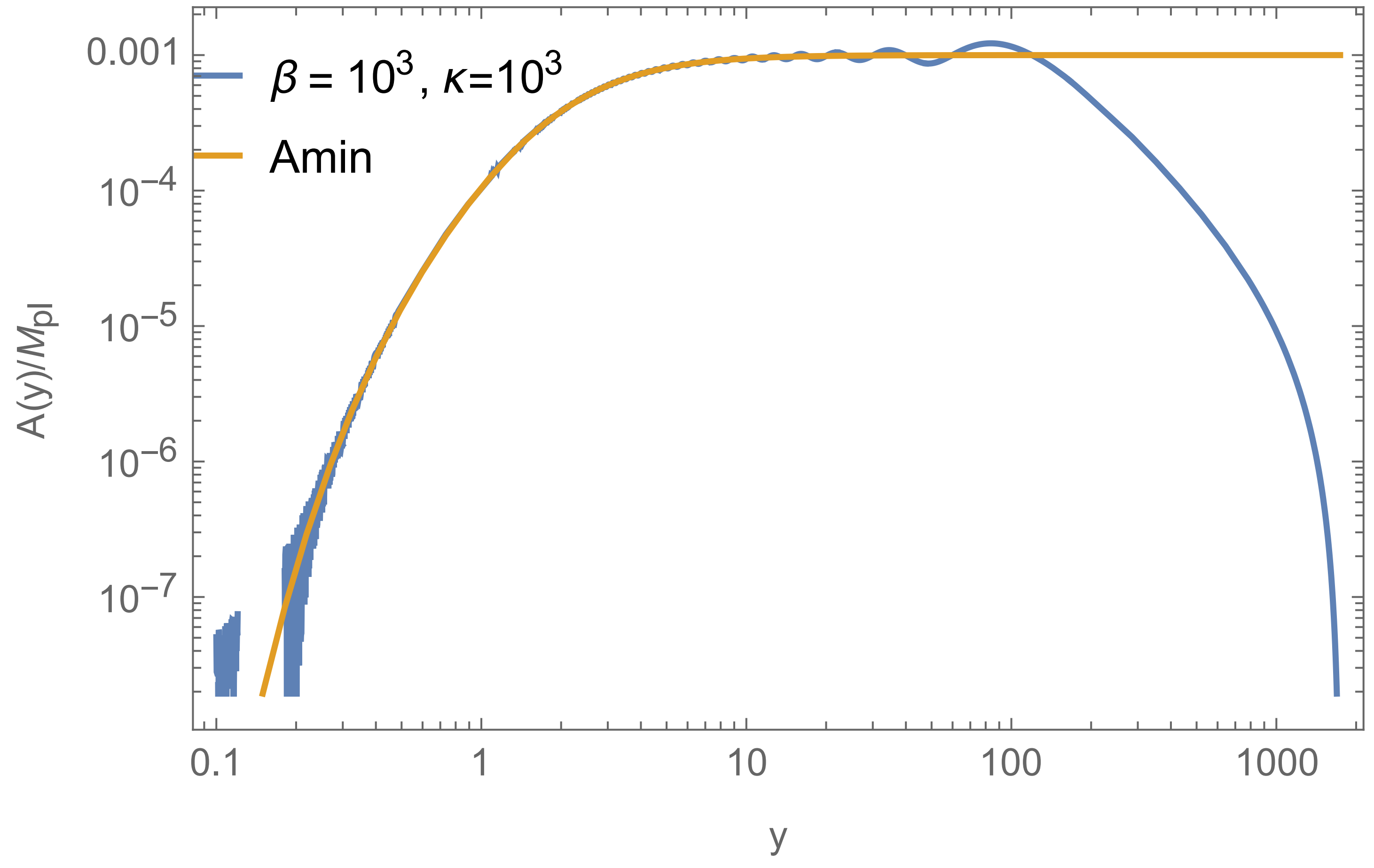


- Oscillations start controlled by β, scalar oscillates around

$$A_{min}(y) = \frac{y^2\beta}{y^2\beta^2 + 6\kappa^2}\Big|_{y\gg1} \simeq \frac{1}{\beta}$$

- However since κ ~ β in this region $y_d \simeq 2 \times \left(\frac{\kappa}{\beta}\right)^{2/3}$ does not hold
- Instead scalar starts to oscillate like matter at $y_{osc,DM} \simeq \sqrt{6}\frac{\kappa}{\beta}$
- DM density is given by

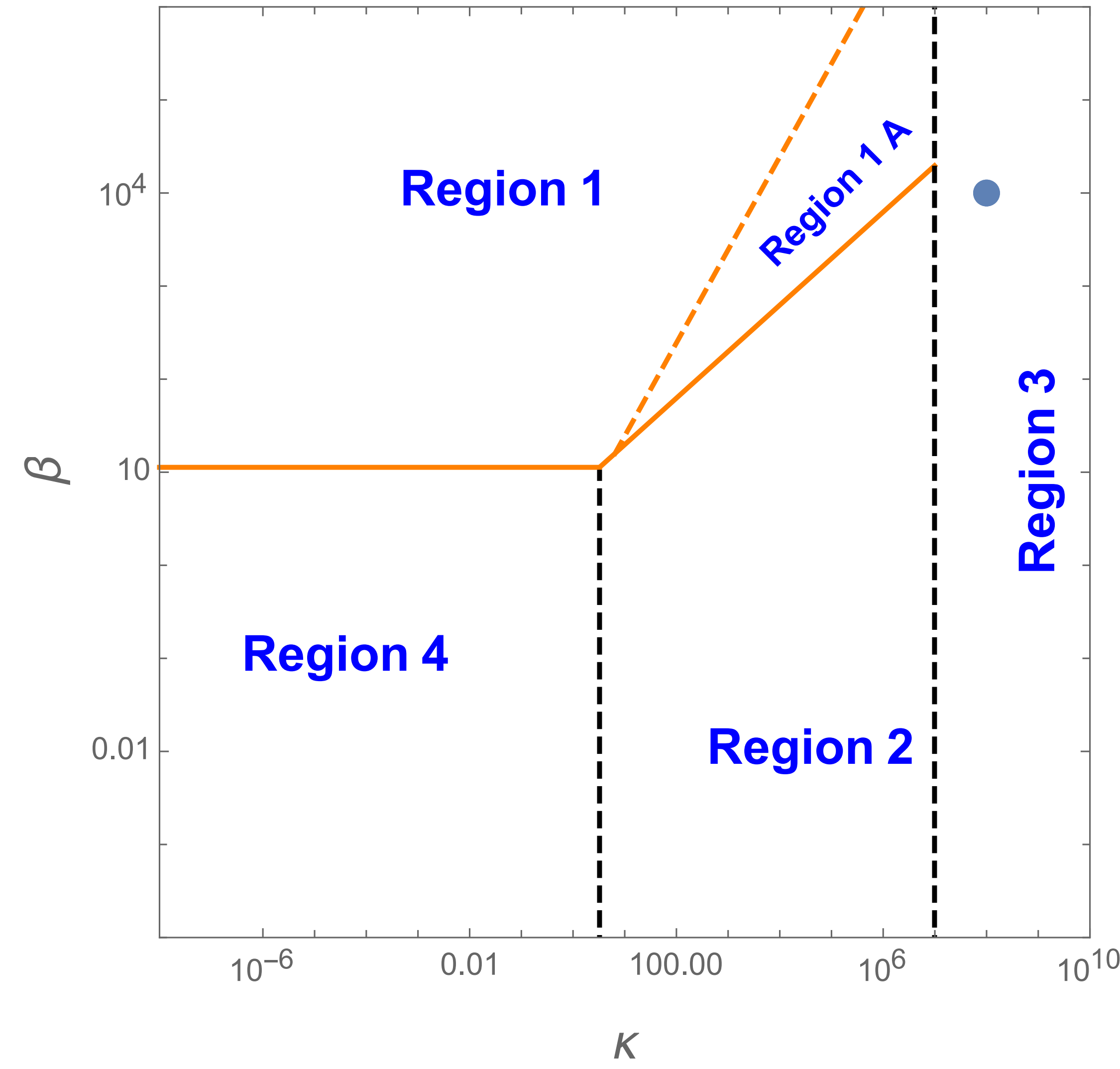
$$\Omega_{eq} = \frac{\frac{1}{2}m_A^2\left(A(y_{osc,DM}) - Amin(y_{osc,DM})\right)^2}{\frac{\pi^2 g_*}{30}y_{osc,DM}^4 m_f^4}\frac{y_{osc,DM}}{y_{eq}} \simeq 8.6\times10^8\left(\frac{\kappa}{\beta^3}\right)\left(\frac{m}{0.1\mathrm{GeV}}\right)$$



- Correct relic density not obtained for muons

Parameter space exploration

Large (Huge) κ and small β, Analytical understanding



- Our fermion feedback starts at $y = y_i = \frac{T_{EW}}{m_f}$
- For huge κ oscillations start before EW transition, hence before feedback

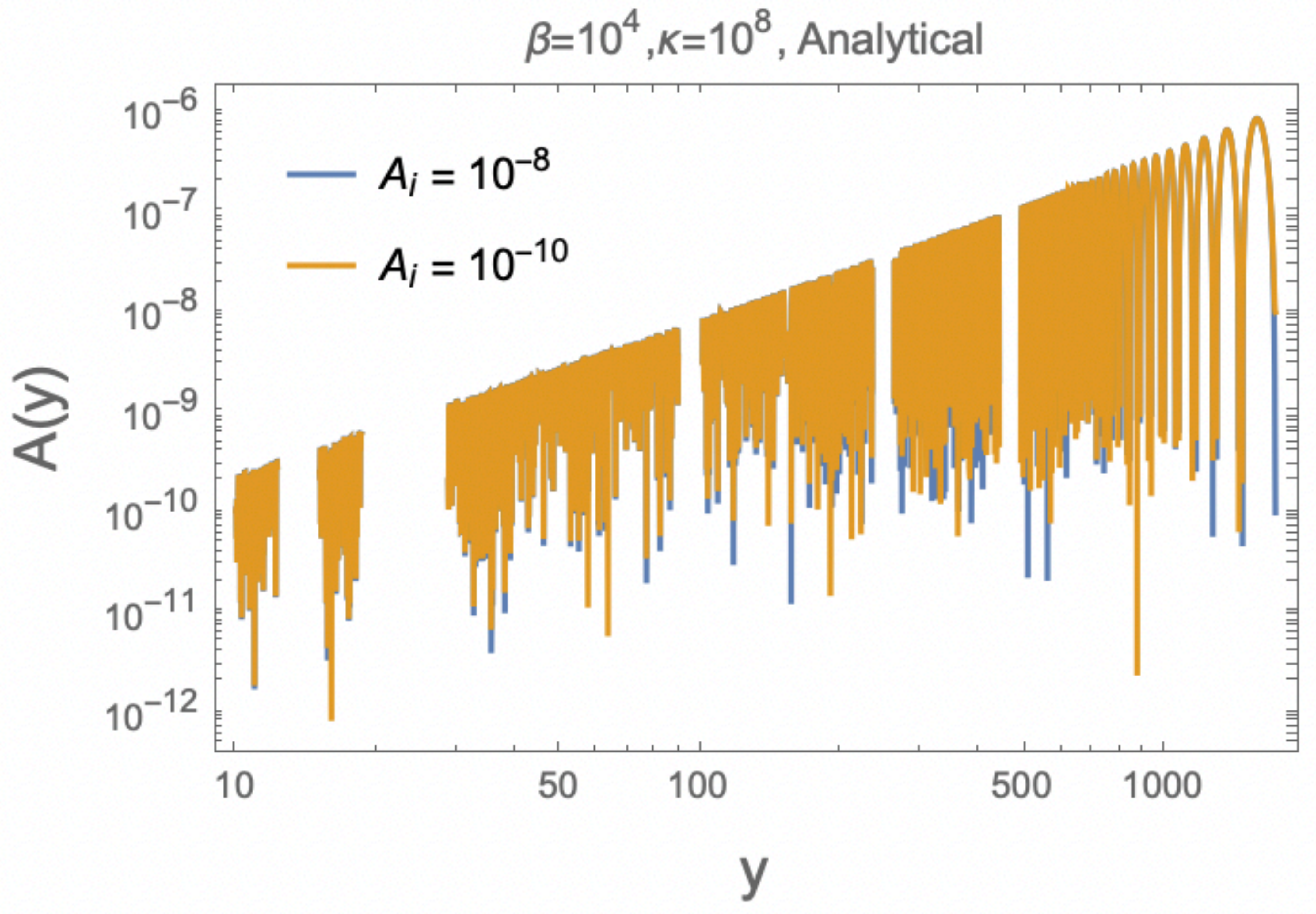
$$y_{osc} > y_i \Rightarrow \kappa > 3\gamma y_i^2$$

- Can analytically solve in this regime

$$A(y < y_i) = \frac{y^2\beta}{6\kappa^2} + \left(\frac{y}{y_i}\right)^{3/2} \frac{\left(-\beta y_i^2 + 6\kappa^2 A_i\right)}{6\kappa^2} \cos\left(\zeta\right)$$

Minima

Amplitude of oscillation



Parameter space exploration

Large (Huge) κ and small β, DM density, Plots

- Initial condition needs to be small enough, i.e. $A_i \ll \frac{\beta y_i^2}{6\kappa^2}$

- DM density given by

$$\Omega_{eq} = \frac{\frac{1}{2}m_A^2 A^2(y_i)}{\frac{\pi^2 g(y_i)}{30} y_i^4 m_f^4} \frac{y_i}{y_{eq}} = \frac{5 y_i \beta^2}{12\pi^2 g_* y_{eq} \kappa^2} = \frac{8.6 \times 10^7 \beta^2}{\kappa^2} \left(\frac{100}{g(y_i)} \right)$$