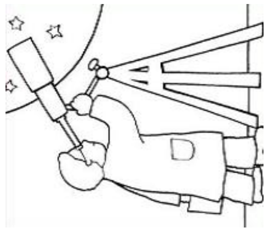
# RELAXED RELAXION!



Abhishek Banerjee

Weizmann Institute of Science

## Based On:

AB, H Kim, G. Perez, O. Matsedonskyi, M Safronova (2004.02899)

NYUAD-WIS Conference, Rehovot, 2020

# RELAXION

- Proposed to solve the hierarchy problem

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- Dynamical relaxation in the early universe makes

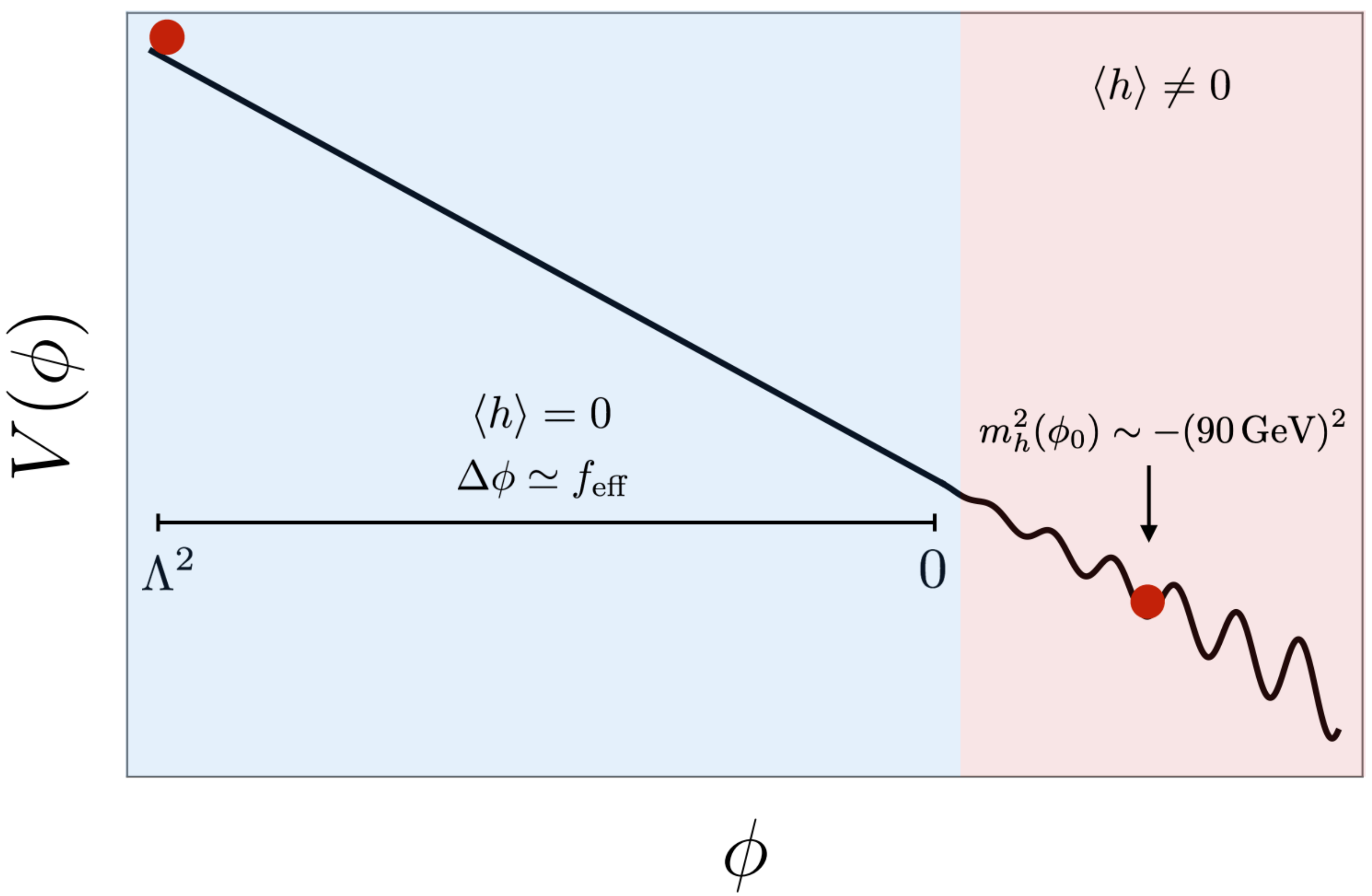
$$v_{\mathrm{EW}}^2 \ll \Lambda^2$$

# RELAXION

➤ Proposed to solve the hierarchy problem

**Dynamical selection of EW scale**

$$V(\phi) = \left(\Lambda^2 - \frac{\Lambda^2}{f_{\rm eff}}\phi\right)|h|^2 - c\frac{\Lambda^4}{f_{\rm eff}}\phi \; + \mu_b^2|h|^2\cos(\phi/f)$$




Slide by Hyungjin Kim

[Graham, Kaplan, Rajendran 15]

# RELAXION MASS AND MIXING ANGLE

To a low energy observer, relevant informations are the mass and the mixing angle with the Higgs

$$\mathcal{L}_{\text{eff}} \supset -\sin\theta_{h\phi}\frac{\phi}{v}\left(\sum_f m_f \bar{f} f - c_{\gamma\phi}\frac{\alpha}{4\pi}F_{\mu\nu}F^{\mu\nu} - c_{g\phi}\frac{\alpha_s}{4\pi}G_{a\mu\nu}G^{a\mu\nu}\right)$$

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$$(\sin\theta_{h\phi})_{\rm max} \sim \frac{m_\phi}{v_{\rm EW}}\,,\ (\sin\theta_{h\phi})_{\rm min} \sim \frac{m_\phi^2}{v_{\rm EW}^2}$$

# NAIVE NATURALNESS

For any natural theory $\quad (\sin\theta_{h\phi})_{\max} \sim \dfrac{m_\phi}{v_{\mathrm{EW}}}$

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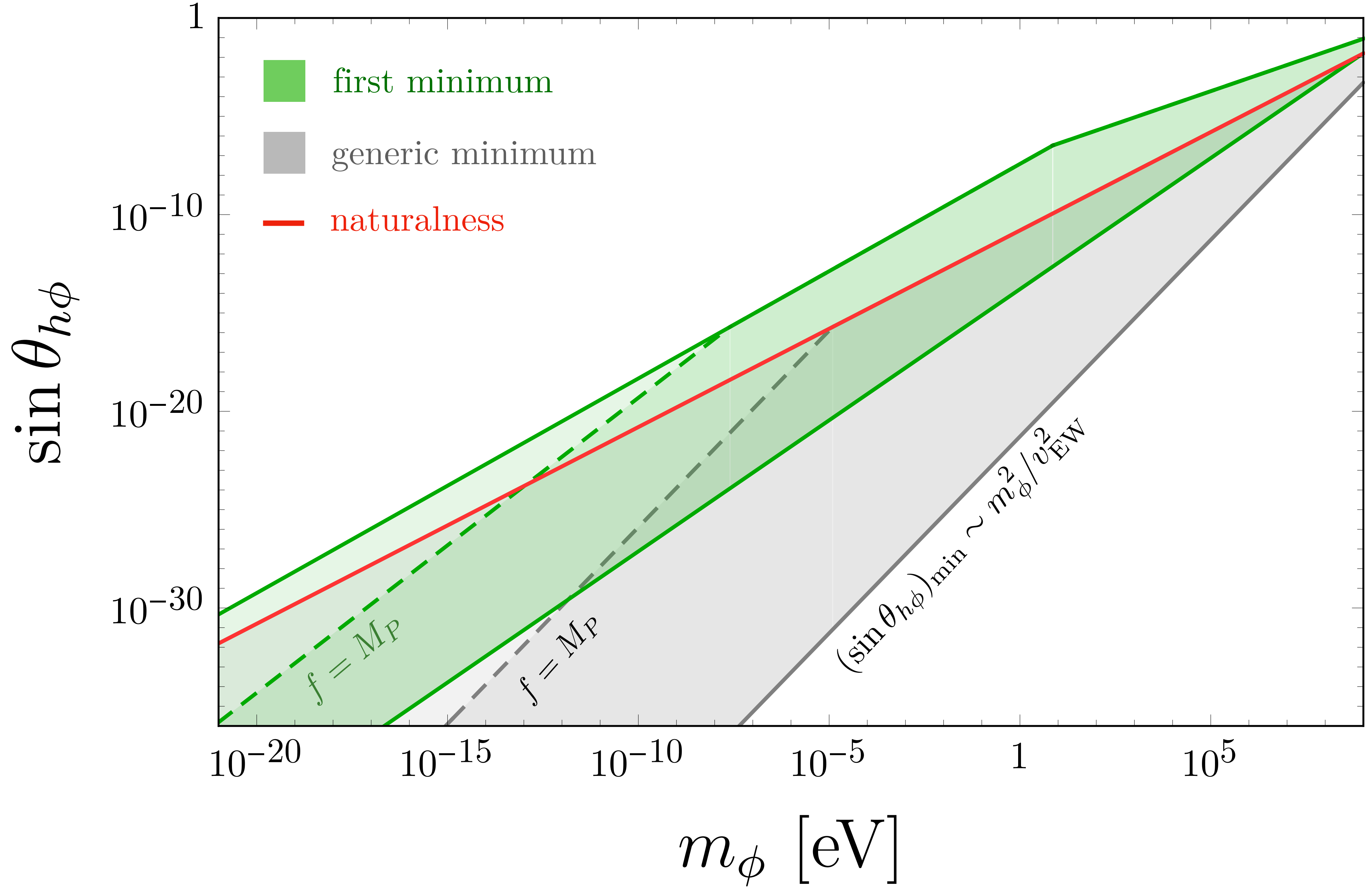
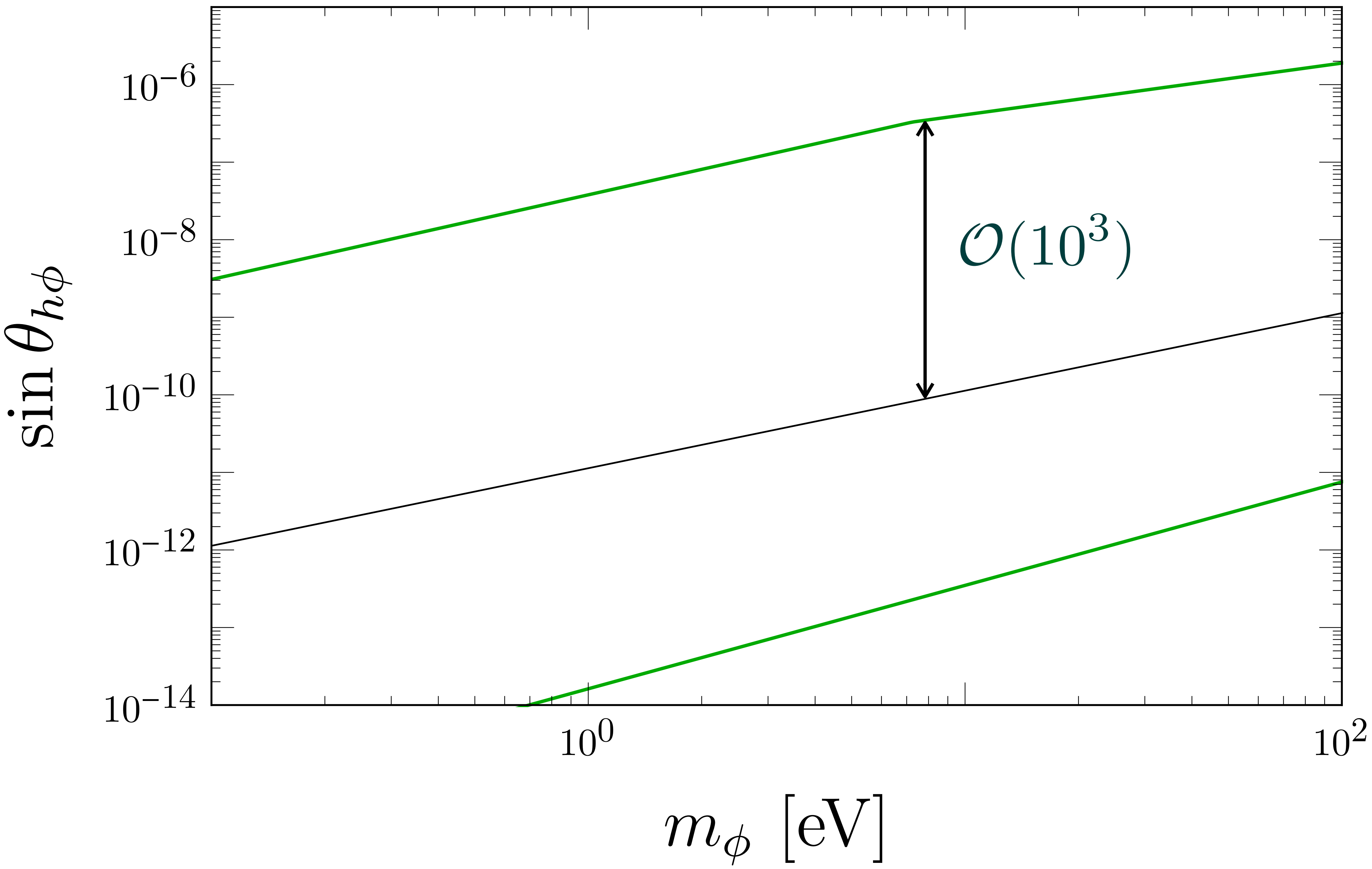
Can we go beyond the “naturalness bound” ? Relaxion!

# RELAXION PARAMETER SPACE



# ENHANCEMENT FACTOR



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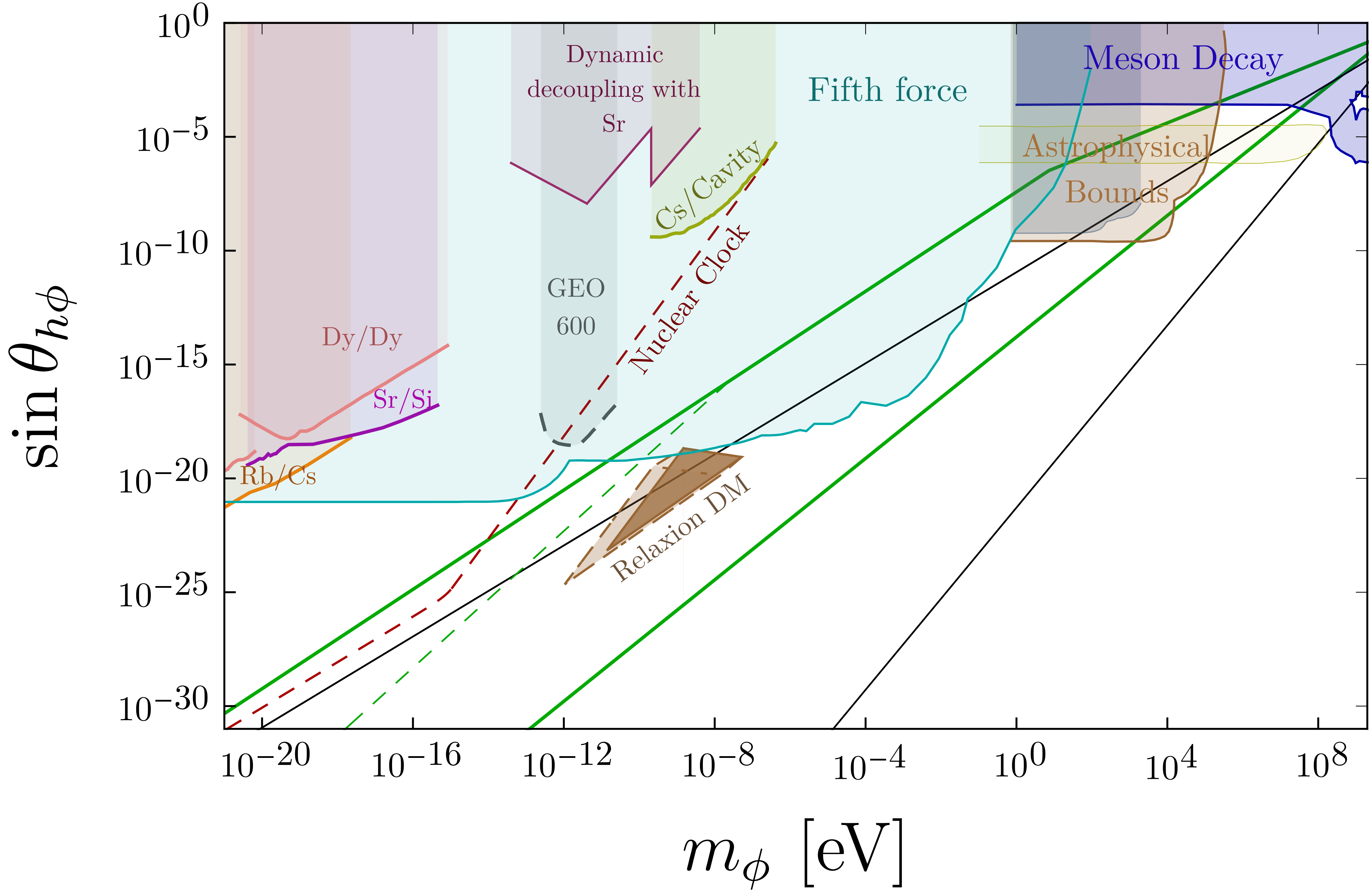

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$$m_\phi^2 \sim \partial_\phi^2 V_{br}(\phi,h) \sim \frac{\mu_b^2 v_{\text{EW}}^2}{f^2}\cos\frac{\phi_0}{f} \sim 1$$

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Naive estimation

How well we understand the stopping point?

# RELAXION DYNAMICS

Relaxion stops at a special point

$$m_\phi^2 = V^{''}(\phi_{\rm min}) = |V^{'}_{\rm roll}|\frac{1}{f}\left(\frac{\phi_{\rm min}}{f} - \frac{\phi_*}{f}\right) = \frac{\mu_b^2 v_{\rm EW}^2}{f^2}\sqrt{\frac{\Delta v^2}{v_{\rm EW}^2}} = \frac{\mu_b^2 v_{\rm EW}^2}{f^2}\frac{\mu_b}{\Lambda}$$

Mixing Angle $\quad \sin\theta_{h\phi} = \dfrac{\mu_b^2}{f v_{\rm EW}}$

# RELAXION DYNAMICS

$$V(\phi, h) = (\Lambda^2 - \Lambda^2 \frac{\phi}{f_{\rm eff}})|h|^2 - \frac{\Lambda^4}{f_{\rm eff}}\phi - \mu_{\rm b}^2 |h|^2 \cos\frac{\phi}{f} \qquad v^2(\phi) = \begin{cases} 0 \ \text{ when } \phi < \mathrm{f_{eff}} \\ > 0 \ \text{ when } \phi > \mathrm{f_{eff}} \end{cases}$$

Relaxion stopping point determines the EW scale

$$V^{'} = 0 = V^{'}_{\rm br} + V^{'}_{\rm roll} = \frac{\mu_{\rm b}^2 |h|^2}{f}\sin(\phi/f) - \Lambda^4/f_{\rm eff} \longrightarrow \boxed{\frac{\Lambda^4}{f_{\rm eff}} \sim \frac{\mu_{\rm b}^2 v_{\rm EW}^2}{f}}$$

Higgs mass change for $\Delta\phi = 2\pi f$, $\quad \dfrac{\delta v^2}{v^2} \sim \dfrac{\Lambda^2}{f_{\rm eff}}\dfrac{f}{v^2} \sim \dfrac{\mu_b^2}{\Lambda^2} \ll 1$

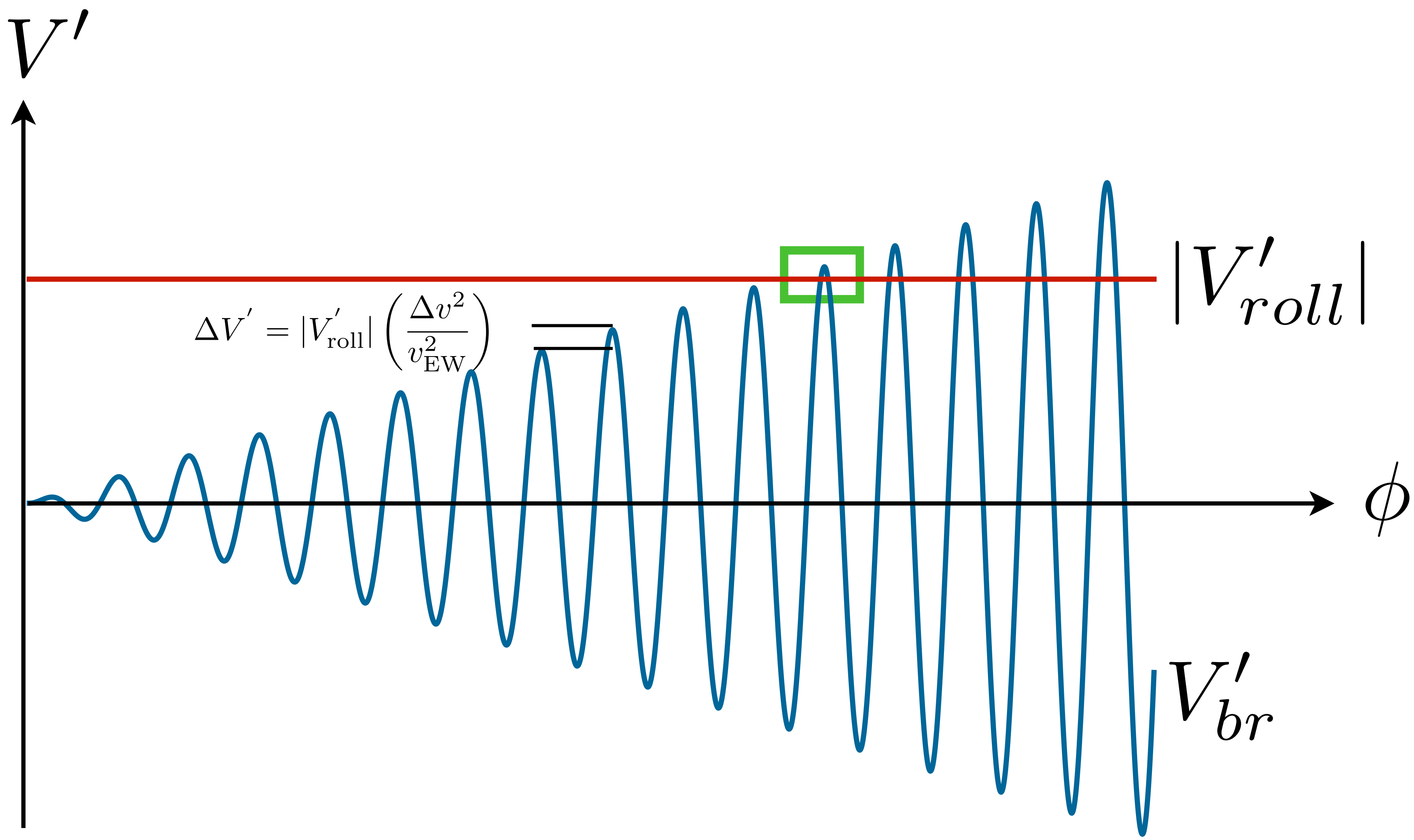
Potential height increases incrementally and relaxion stops at the shallow part of the potential

# THE STOPPING POINT

$$V'_\phi = 0 \Rightarrow \sin\theta = \frac{v_{\rm EW}^2}{v^2(\phi)} + \frac{v_{\rm EW}^2}{\Lambda^2}$$

⇒

$$\frac{\phi_0}{f} \sim \frac{\pi}{2} \text{ upto resolution factors}$$



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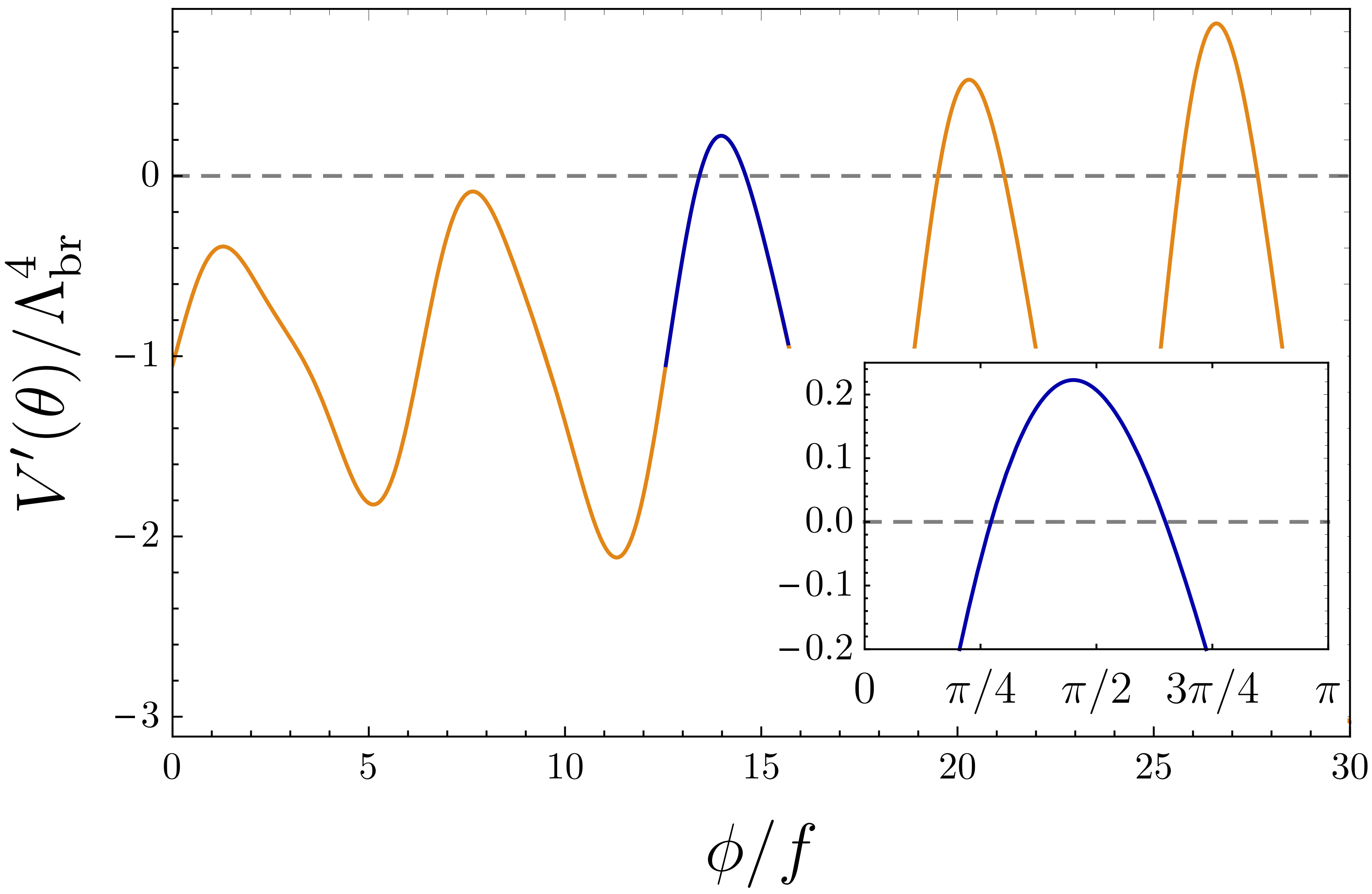

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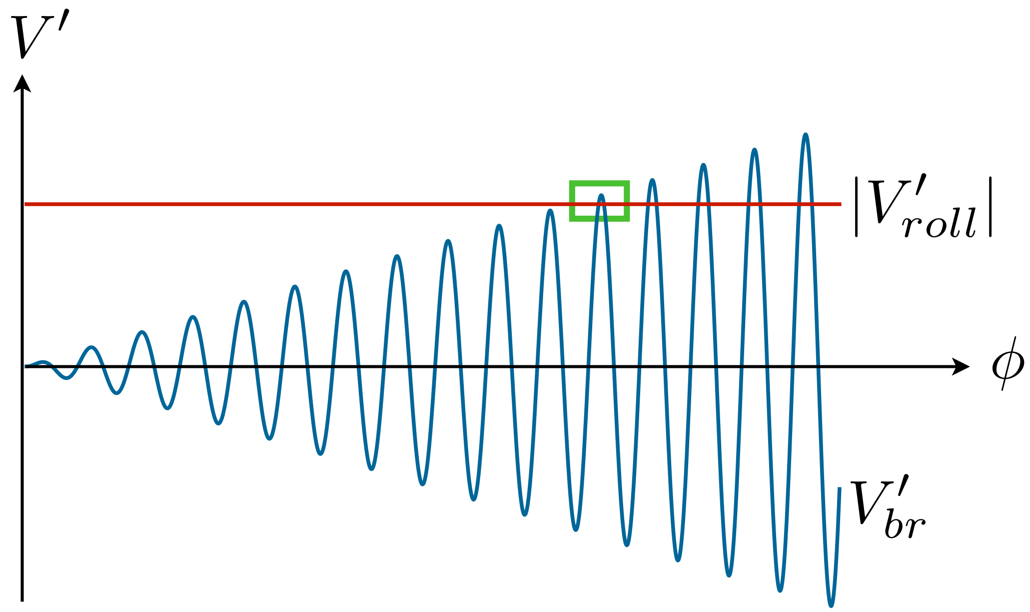


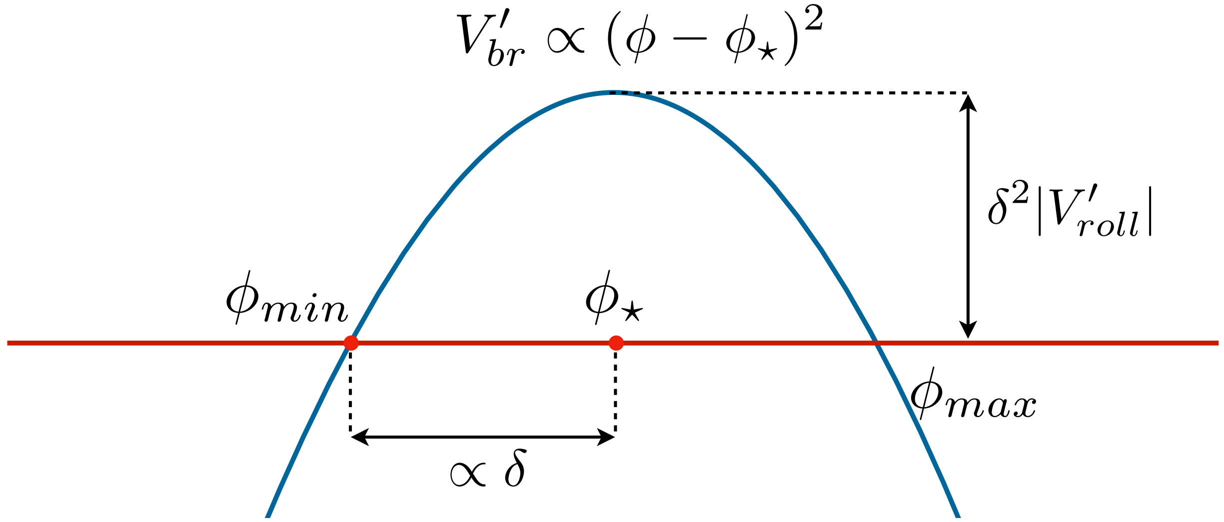


$$\frac{V'(\phi)}{|V'_{\rm roll}|} = \left(\frac{\Delta v^2}{v_{\rm EW}^2}\right) + \frac{1}{2}\left(\frac{\phi}{f} - \frac{\phi_*}{f}\right)^2 + \cdots$$

$$V'_{\rm roll} = \frac{\Lambda^4}{f_{\rm eff}} \sim \frac{\mu_{\rm b}^2 v_{\rm EW}^2}{f}$$

$$V'(\phi_{\rm min}) = 0 \Rightarrow \left(\frac{\phi_{\rm min}}{f} - \frac{\phi_*}{f}\right) \sim \sqrt{\frac{\Delta v^2}{v_{\rm EW}^2}}$$

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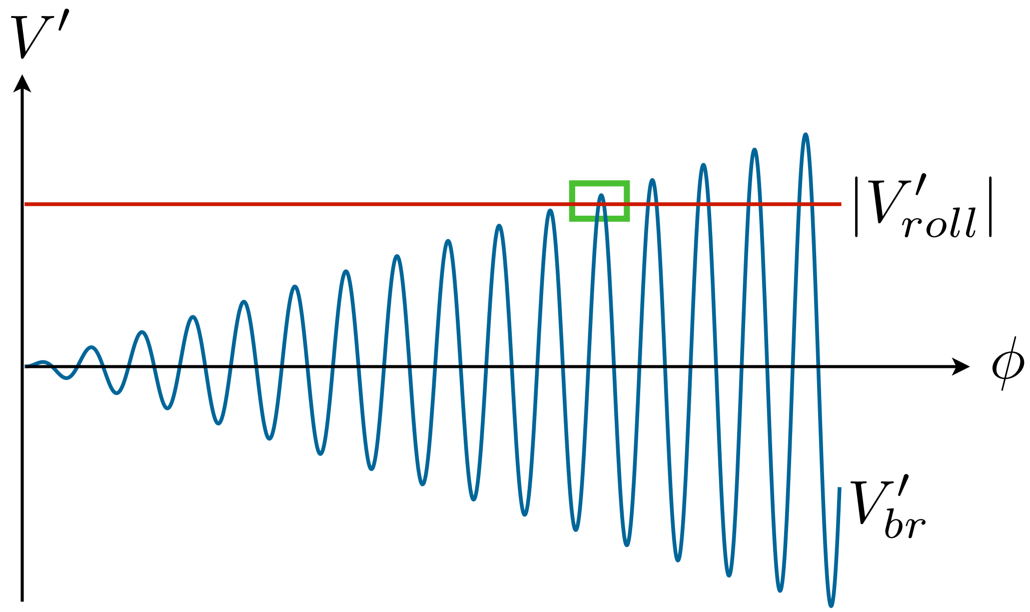


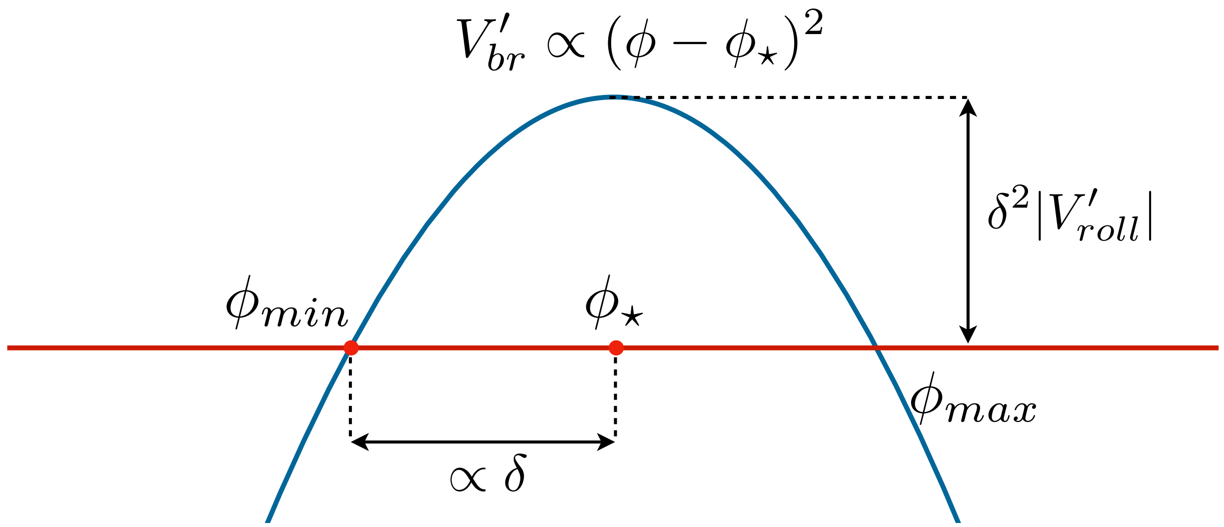


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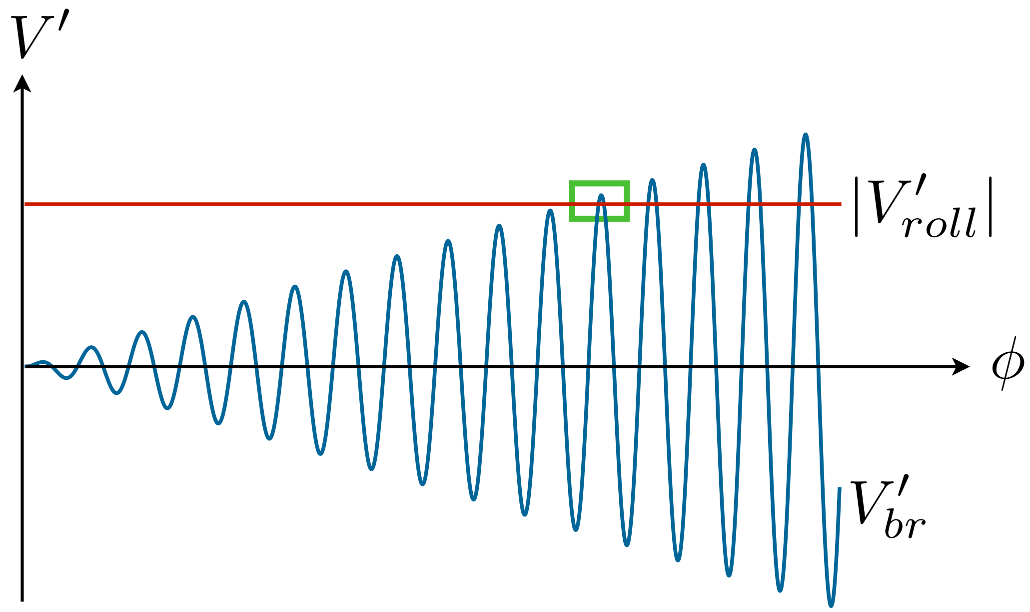


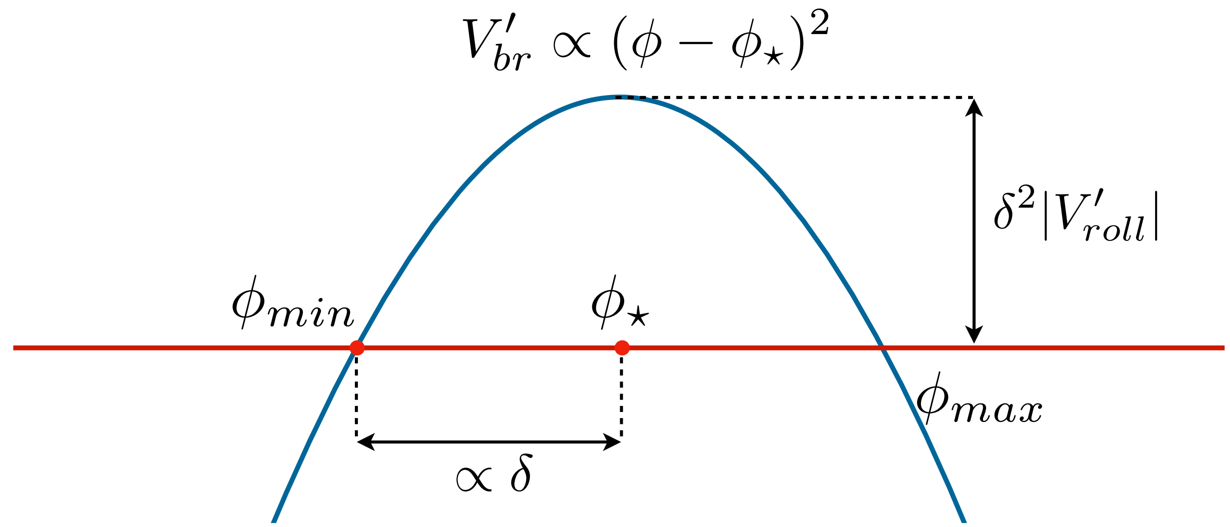


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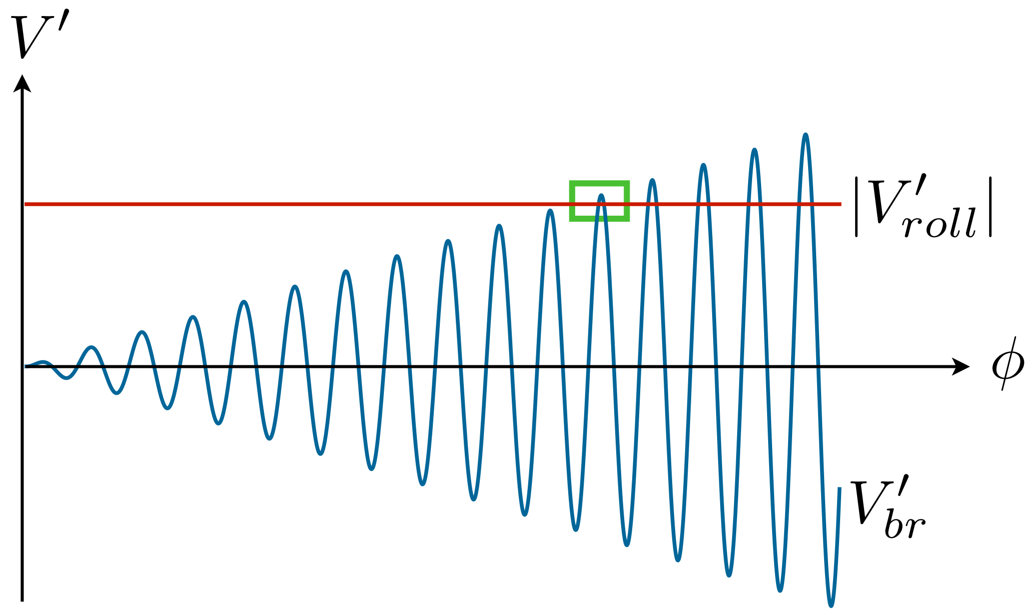


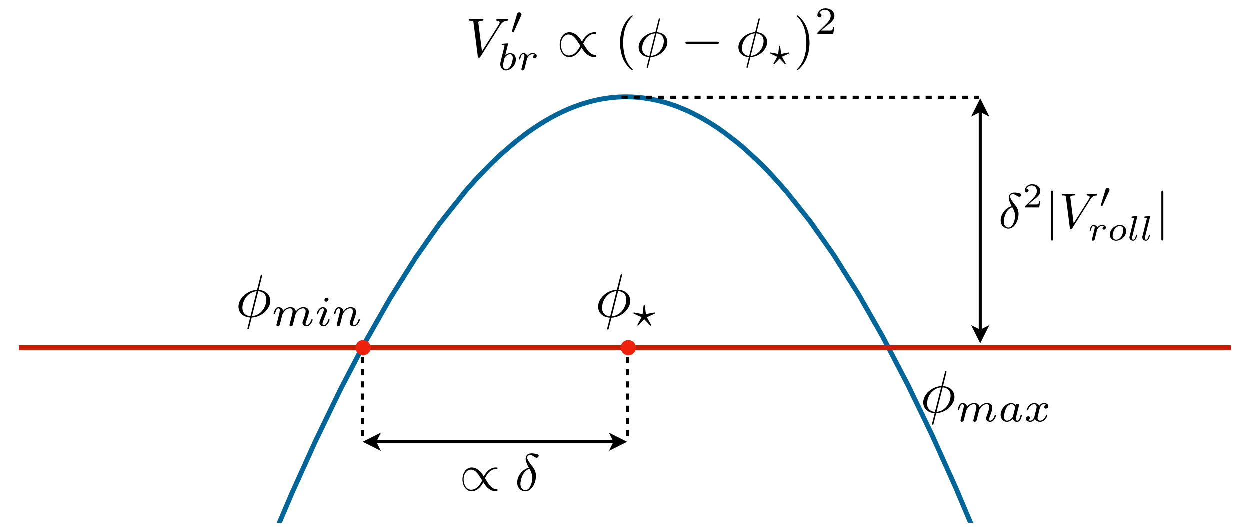


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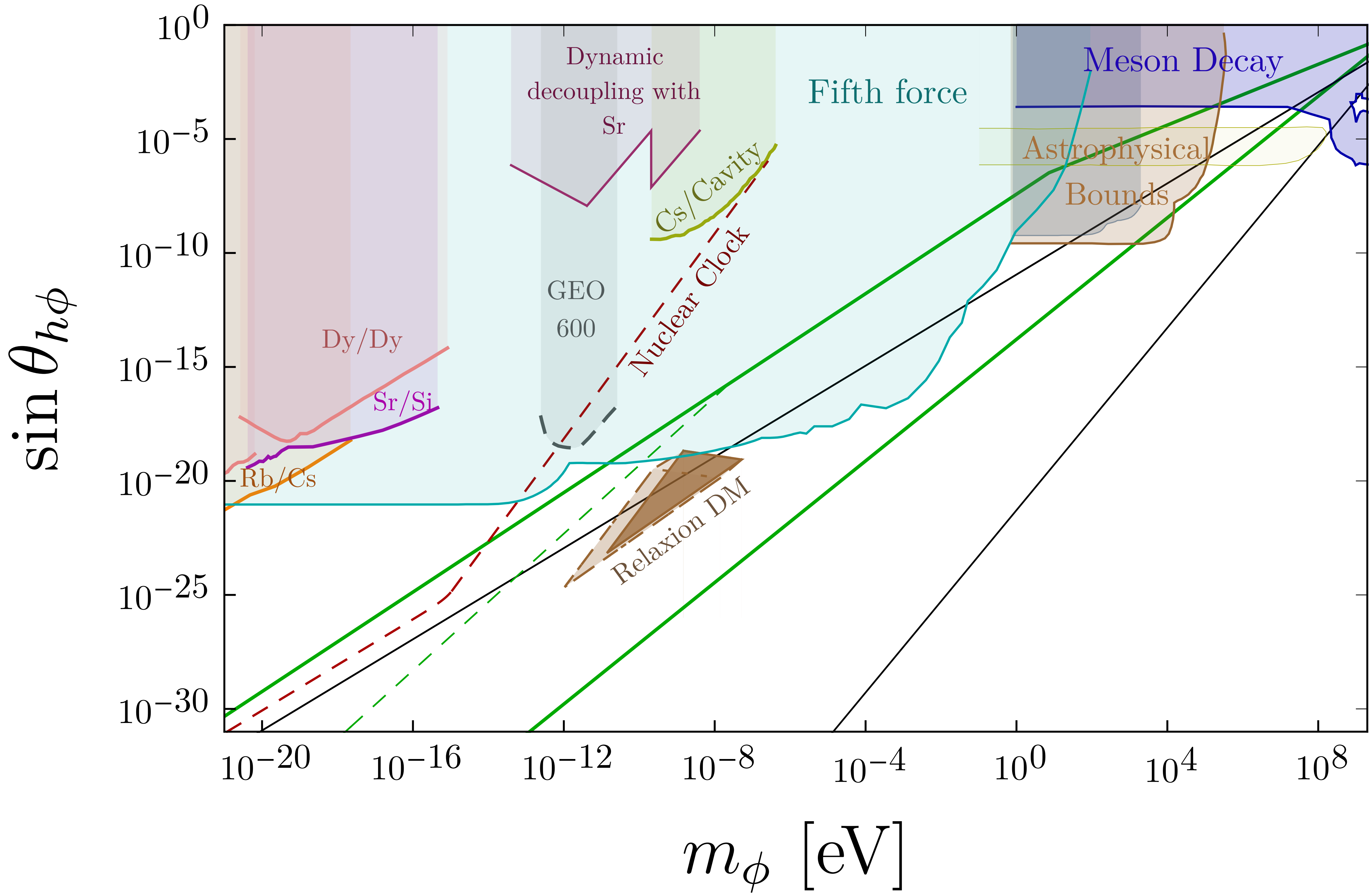

# CONCLUSIONS

- Enhancement in mixing angle! Go beyond the naturalness line in a technically natural model!
- Relaxion stops at a shallow part of the potential.
- Relaxion mass is not natural - it is relaxed!

UNCUT

IT !


damn anti-gravity cat
always disproving ma theorem
ICANHASCHEEZBURGER.COM

# MASS AND MIXING ANGLE

1. The hierarchy problem
2. Dark matter
3. Matter-Antimatter asymmetry
4. Neutrino masses
5. The strong CP problem.


1. R.S. Gupta, J.Y. Reiness, M. Spannowsky,Phys. Rev. D 100, 055003 (2019)
2.
3.
4.
5.


From a low energy observable point of view, how would we know whether it is natural or not?