Ultralight Scalars and Vectors

Dark Interactions 2024, Vancouver

Akshay Ghalsasi

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Dark Interactions 2024, Vancouver

The B Team

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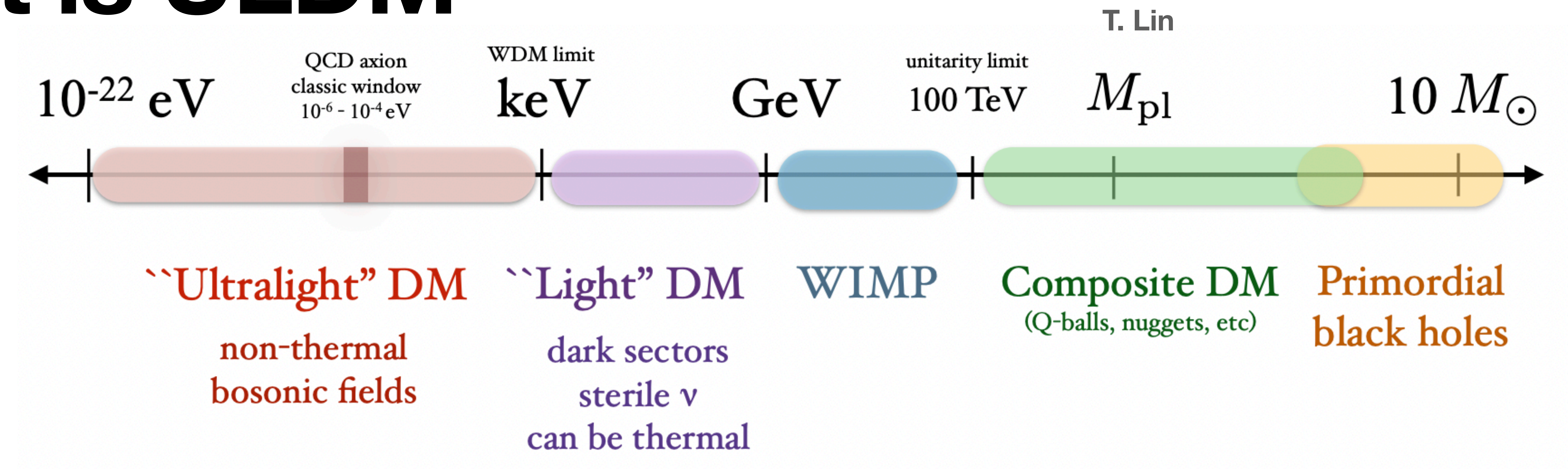
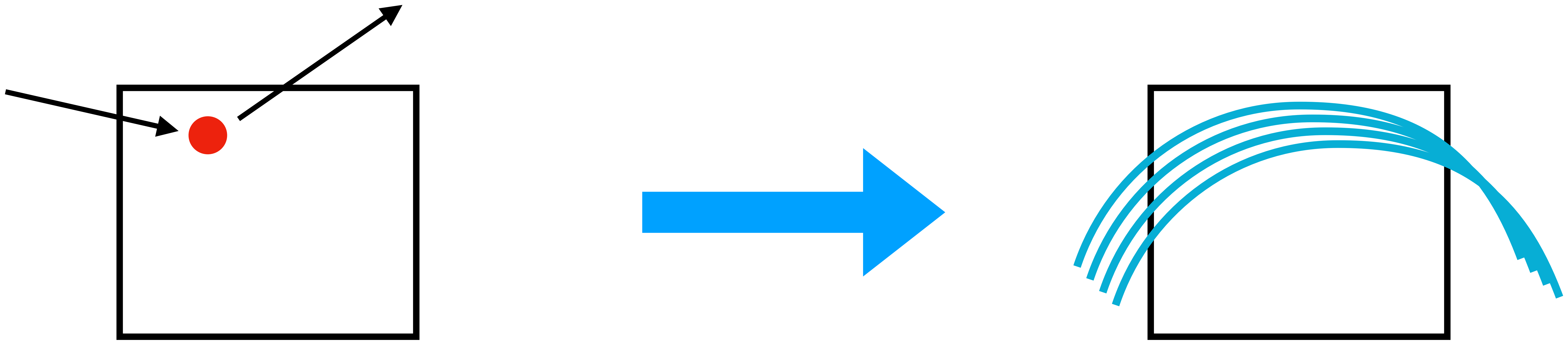
What is ULDM



- Local DM density is known $\sim 0.4 \text{ GeV cm}^{-3}$
- The de Broglie wavelength of a particle is given by $\lambda_{\rm db} = \dfrac{2\pi}{mv}$
- For local DM density we get $N \simeq \left(\dfrac{30\text{eV}}{m}\right)^3$ within one dB wavelength

What is ULDM

- In this limit we can approximate DM as classical wave
- Presence of ULDM can be modeled by solving the classical EOM



- Production of boson DM can typically be modeled by classical EOM for $m \gg 30\text{eV}$

ULDM Snowmass Whitepaper

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

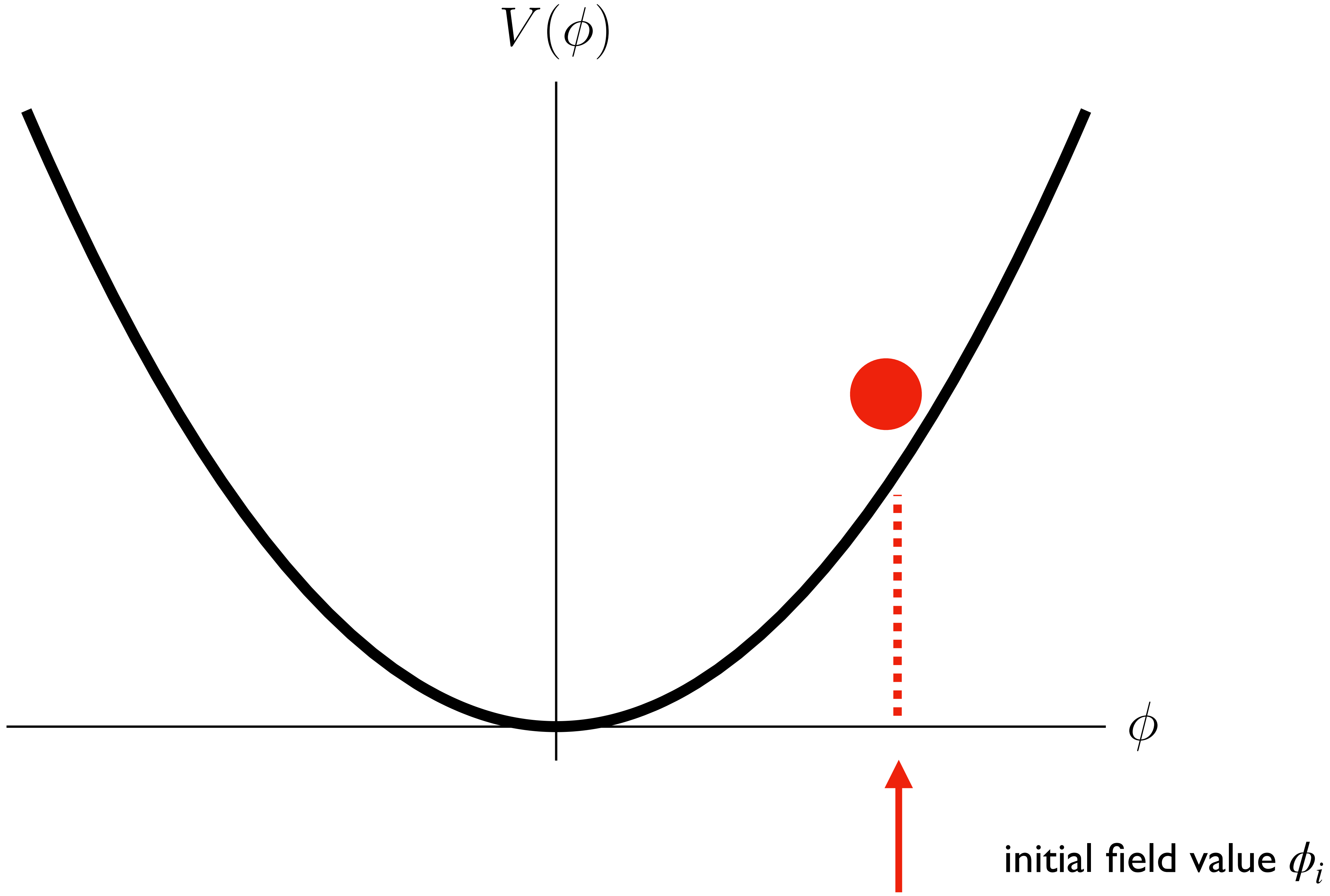
Snowmass 2021 White Paper
New Horizons: Scalar and Vector Ultralight Dark Matter

D. Antypas,[1,2] A. Banerjee,[3] C. Bartram,[4] M. Baryakhtar,[4] J. Betz,[5] J. J. Bollinger,[6] C. Boutan,[7] D. Bowring,[8] D. Budker,[2,1,9] D. Carney,[10] G. Carosi,[11,4] S. Chaudhuri,[12] S. Cheong,[13,14] A. Chou,[8] M. D. Chowdhury,[15] R. T. Co,[16] J. R. Crespo López-Urrutia,[17] M. Demarteau,[18] N. DePorzio,[19] A. V. Derbin,[20] T. Deshpande,[21] M. D. Chowdhury,[15] L. Di Luzio,[22,23] A. Diaz-Morcillo,[24] J. M. Doyle,[19,25] A. Drlica-Wagner,[8,26,27] A. Droster,[9] N. Du,[11] B. Döbrich,[28] J. Eby,[29] R. Essig,[30] G. S. Farren,[31] N. L. Figueroa,[1,2] J. T. Fry,[32] S. Gardner,[33] A. A. Geraci,[21] A. Ghalsasi,[34] S. Ghosh,[35,36] M. Giannotti,[37] B. Gimeno,[38] S. M. Griffin,[39,40] D. Grin,[41] D. Grin,[41] H. Grote,[42] J. H. Gundlach,[4] M. Guzzetti,[4] D. Hanneke,[43] R. Harnik,[8] R. Henning,[44,45] V. Irsic,[46,47] H. Jackson,[9] D. F. Jackson Kimball,[48] J. Jaeckel,[49] M. Kagan,[13] D. Kedar,[50,51] R. Khatiwada,[8,52] S. Knirck,[8] S. Kolkowitz,[53] T. Kovachy,[21] S. E. Kuenstner,[14] Z. Lasner,[19,25] A. F. Leder,[9,10] R. Lehnert,[54] D. R. Leibrandt,[6,51] E. Lentz,[7] S. M. Lewis,[8] Z. Liu,[55] J. Manley,[56] R. H. Maruyama,[35] A. J. Millar,[57,58] V. N. Muratova,[20] N. Musoke,[59] S. Nagaitsev,[8,27] O. Noroozian,[60] C. A. J. O'Hare,[61] J. L. Ouellet,[32] K. M. W. Pappas,[32] E. Peik,[62] G. Perez,[3] A. Phipps,[48] N. M. Rapidis,[14] J. M. Robinson,[50,51] V. H. Robles,[63] K. K. Rogers,[64] J. Rudolph,[14] G. Rybka,[4] M. Safdari,[13,14] M. Safdari,[14,13] M. S. Safronova,[5] C. P. Salemi,[32] P. O. Schmidt,[62,65] T. Schumm,[66] A. Schwartzman,[13] J. Shu,[67] M. Simanovskaia,[14] J. Singh,[14] S. Singh,[56,5] M. S. Smith,[18] W. M. Snow,[54] Y. V. Stadnik,[6] C. Sun,[68] A. O. Sushkov,[69] T. M. P. Tait,[70] V. Takhistov,[29] D. B. Tanner,[71] D. J. Temples,[8] P. G. Thirolf,[72] J. H. Thomas,[52] M. E. Tobar,[73] O. Tretiak,[1,2] Y.-D. Tsai,[70,8] J. A. Tyson,[74] M. Vandegar,[13] S. Vermeulen,[42] L. Visinelli,[75,76] E. Vitagliano,[77] Z. Wang,[78] D. J. Wilson,[15] L. Winslow,[32] S. Withington,[47] M. Wooten,[9] J. Yang,[7] J. Ye,[50,51] B. A. Young,[79] F. Yu,[80] M. H. Zaheer,[5] T. Zelevinsky,[81] Y. Zhao,[82] and K. Zhou[13]

Standard Misalignment

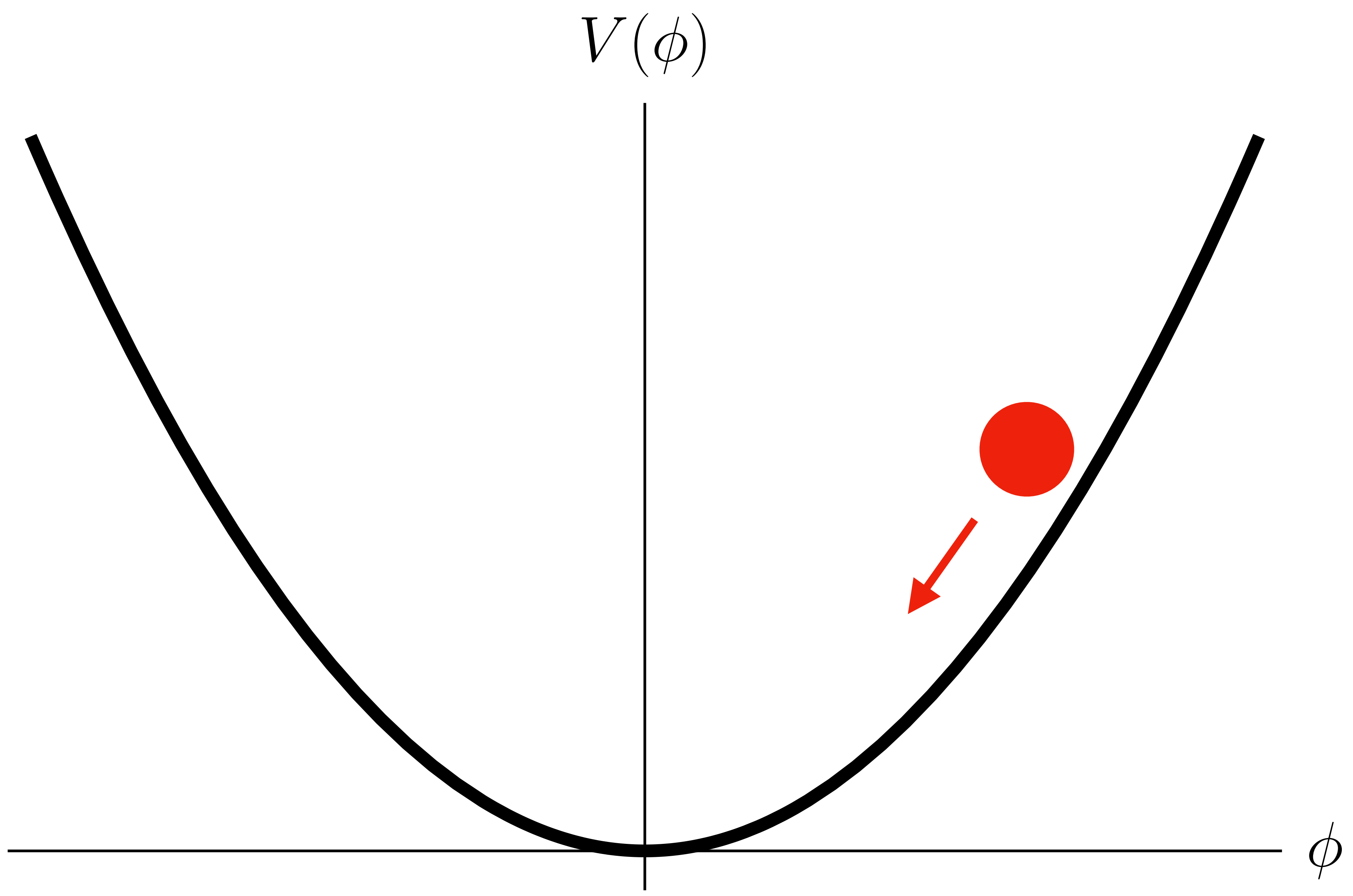
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

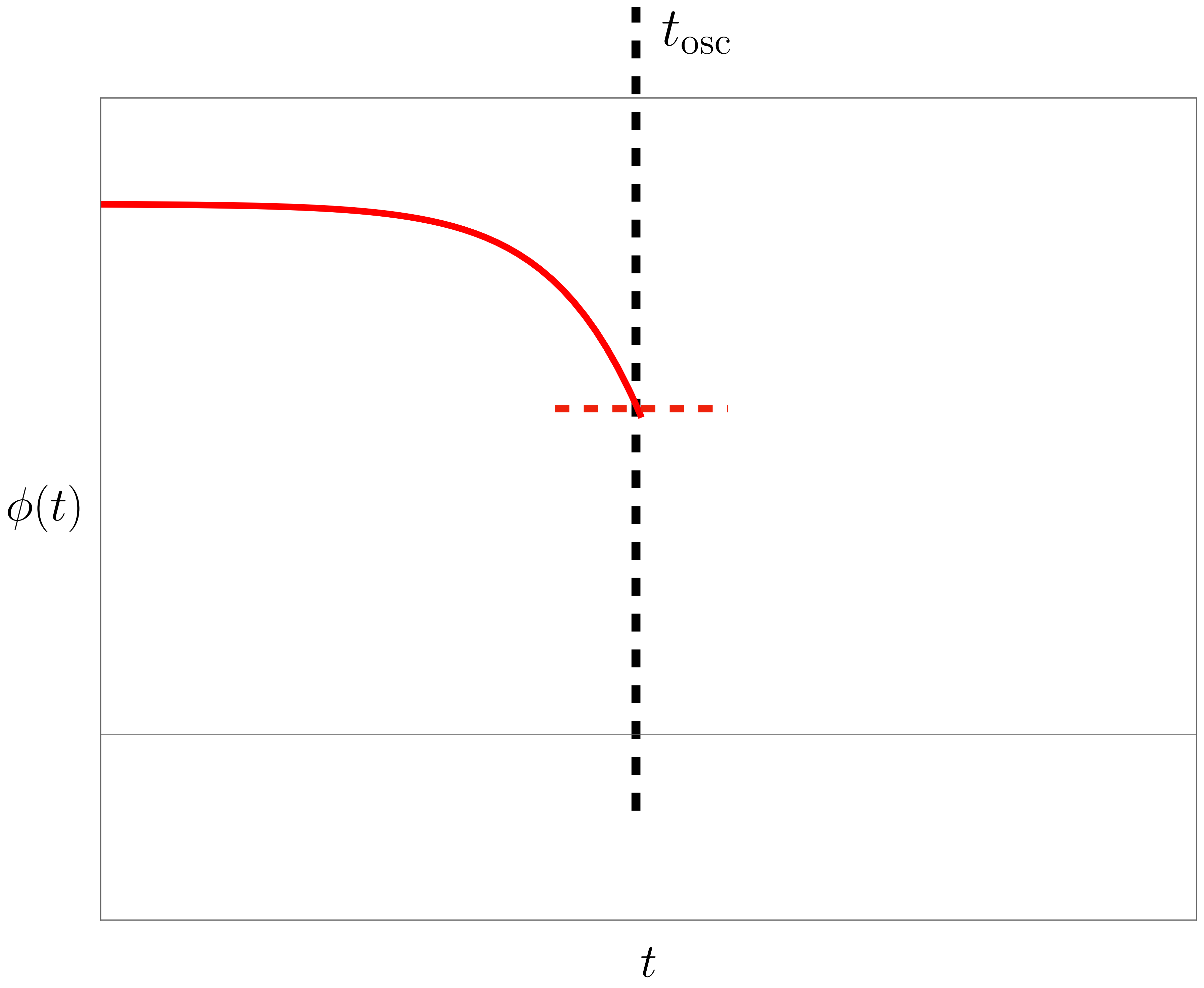
$$H \gg m_\phi$$



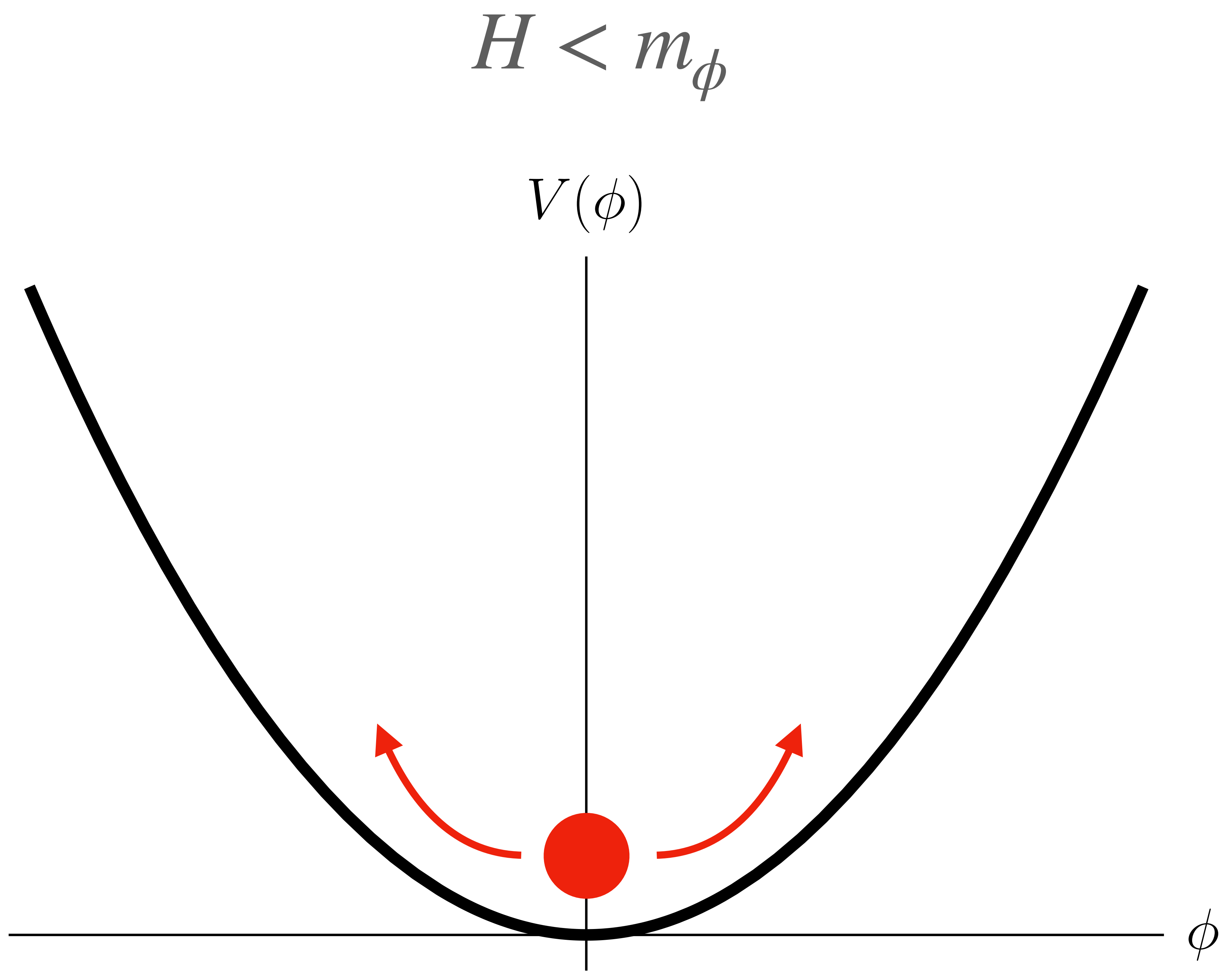
Standard Misalignment

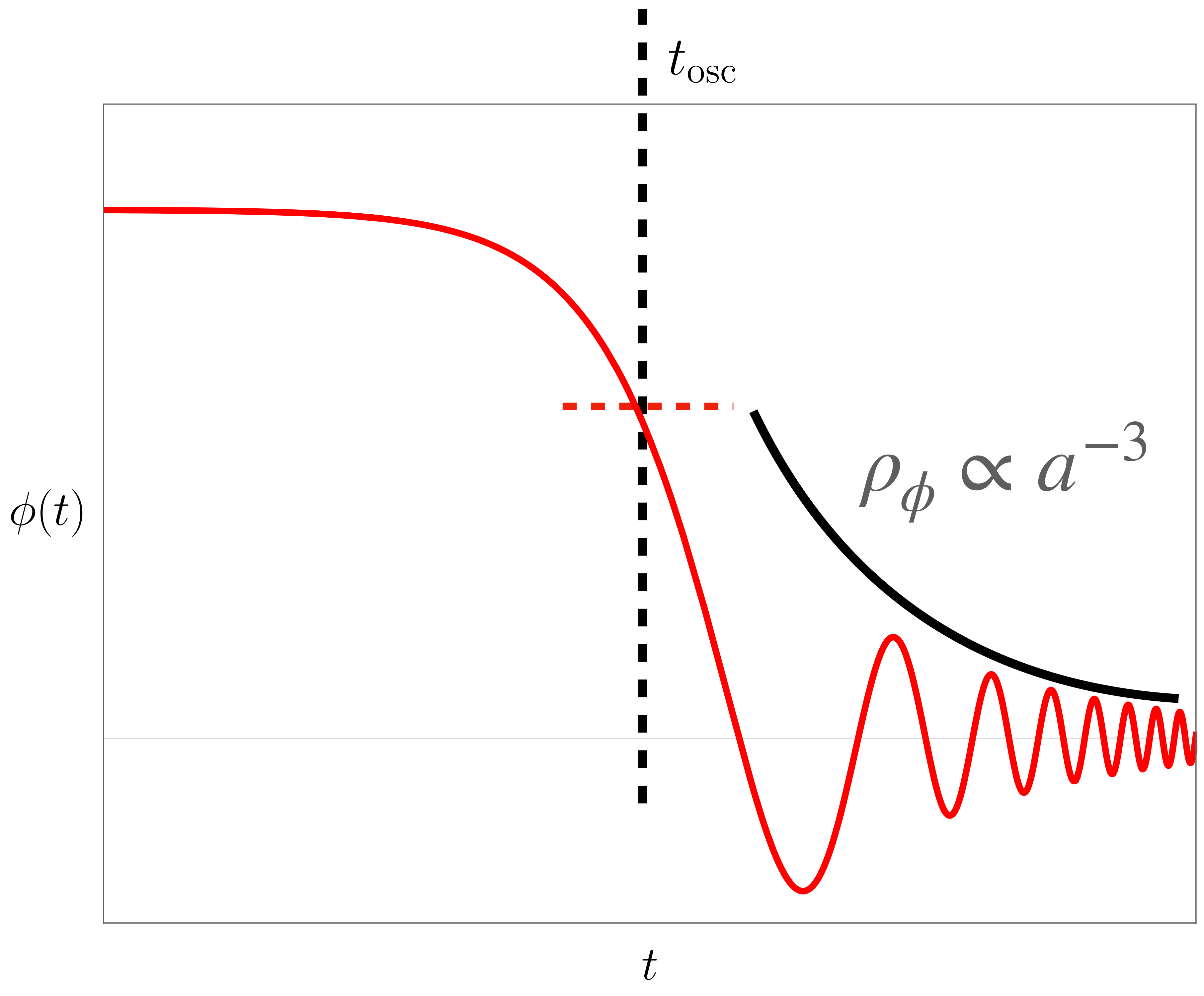
$H \simeq m_\phi$





Standard Misalignment

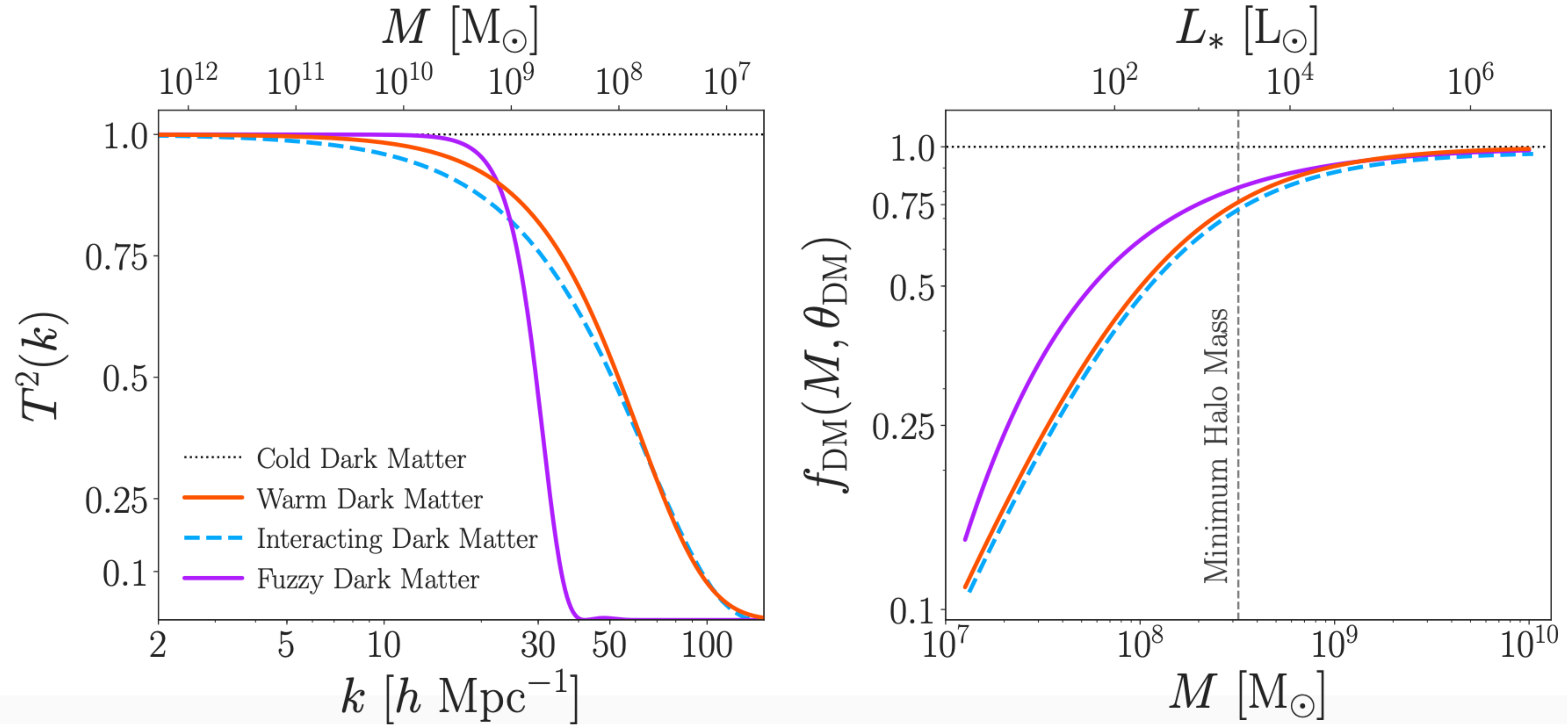




ULDM “Nightmare Scenario”

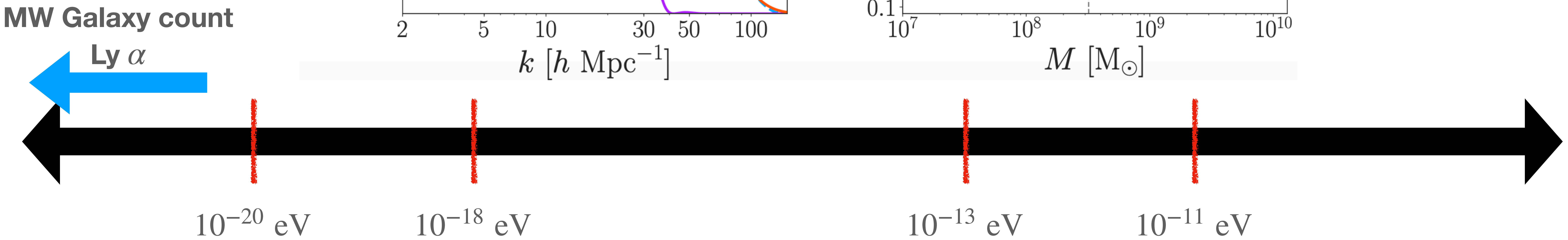
What if ULDM interacts only gravitationally?

- Lyman α constraints the matter power spectrum $k \simeq 1 - 10\ \mathrm{Mpc}^{-1}$
- MW Satellite counts also constraint the linear matter power spectrum



Nadler et. al.

See talk by Vera, Renee

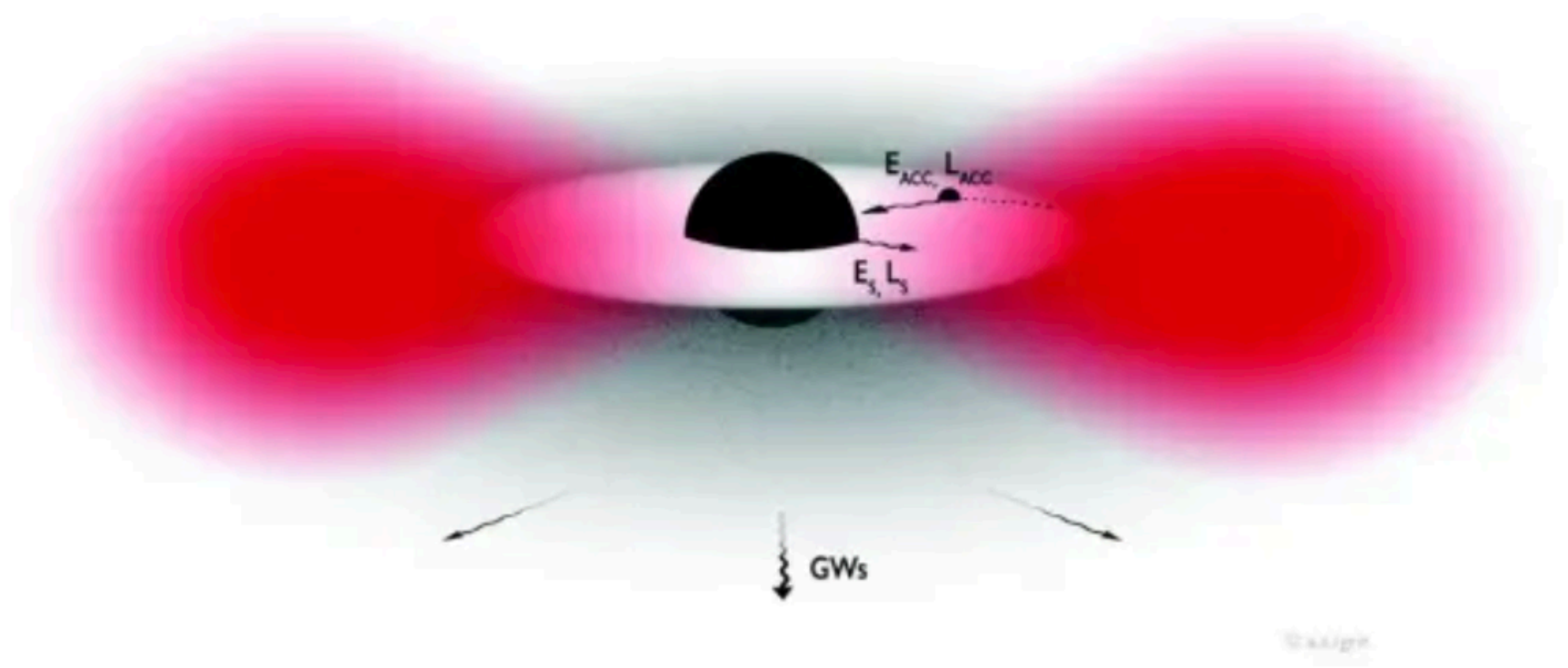


ULDM "Nightmare Scenario"

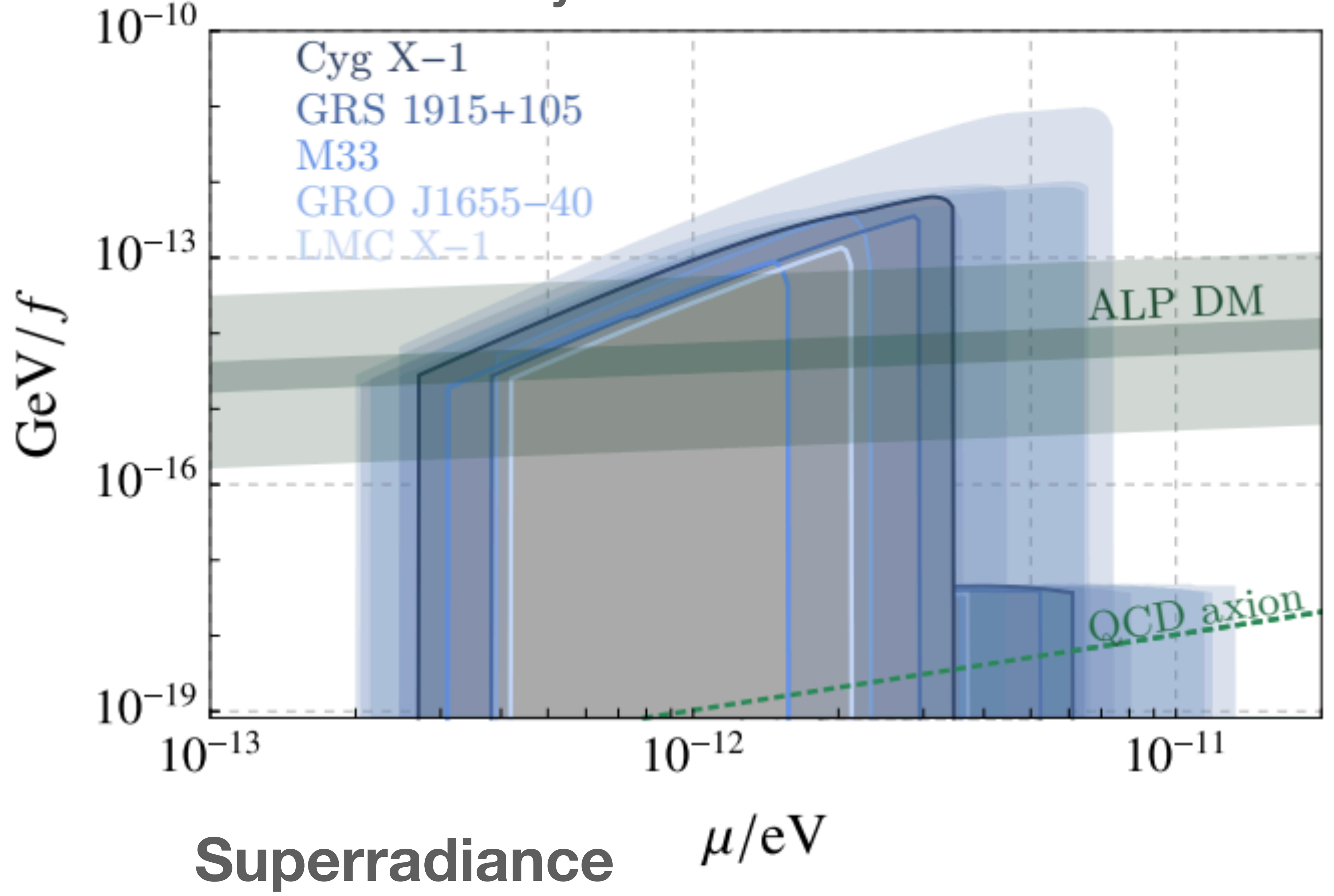
What if ULDM interacts only gravitationally?

Arvanitaki et. al.

- A massive boson $m_\phi^{-1} \simeq R_{\rm sch}$ can extract angular momentum from BH



Baryakhtar et. al.



ULDM-SM Interactions

ULDM can interacts with standard model particles

- Coupling to photons

$$\frac{1}{4\sqrt{2}}\frac{d_e}{M_{\rm pl}}\phi F^{\mu\nu}F_{\mu\nu}\ ;\ \alpha \to \alpha(1+\frac{d_e}{\sqrt{2}M_{\rm pl}}\phi)$$

- Coupling to fermions (leptons or quarks)

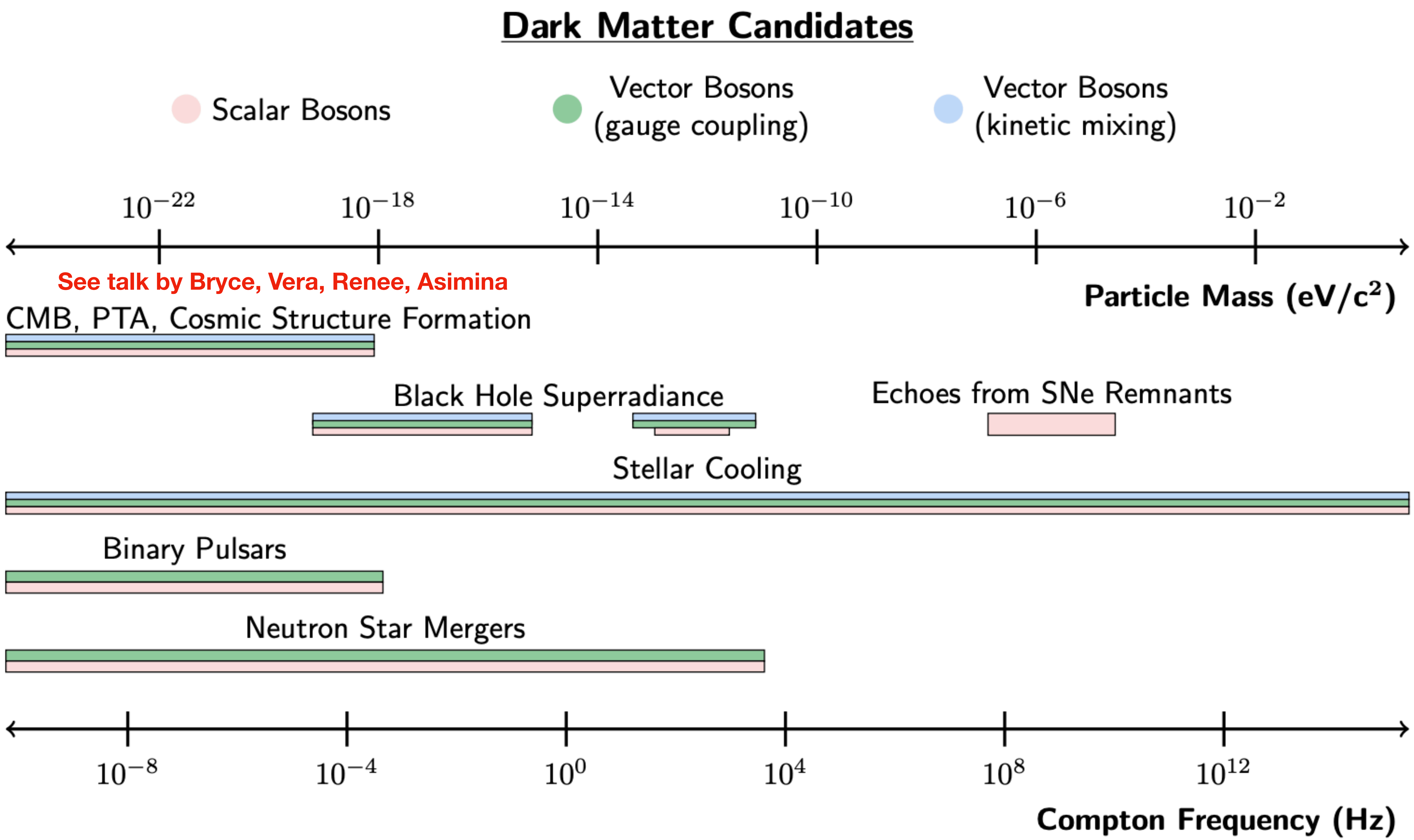
$$\frac{d_{m_f}}{\sqrt{2}M_{\rm pl}}\phi m_f \bar{f}f\ ;\ m_f \to m_f\left(1+\frac{d_{m_f}\phi}{\sqrt{2}M_{\rm pl}}\right)$$

- Coupling to Higgs

$$A\phi H^2\ ;\ v \to v\left(1+\frac{A\phi}{m_H^2}\right)$$

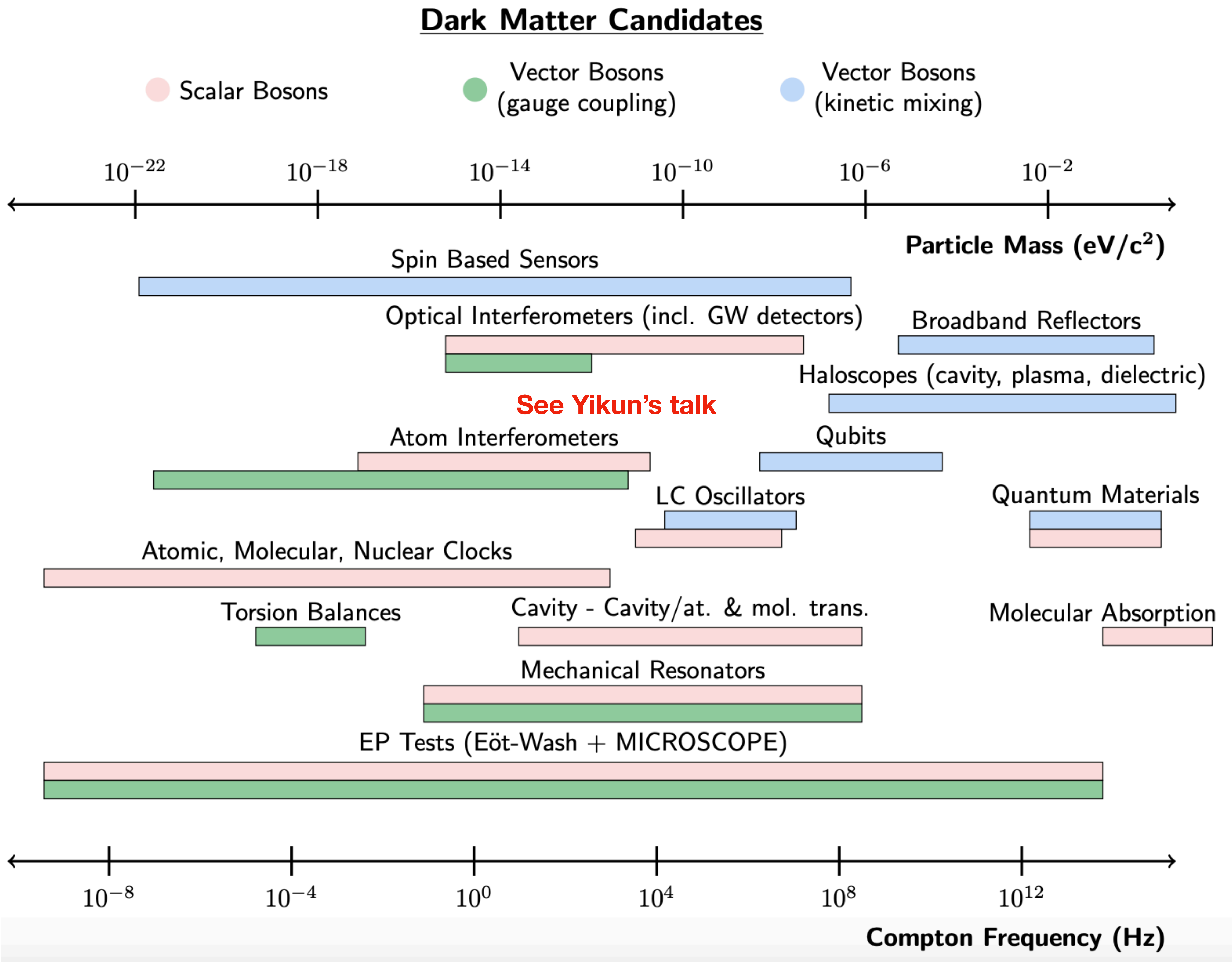
ULDM SM Interactions

Astrophysical Constraints



ULDM SM Interactions

Experimental constraints



Experimental Constraints

Long Range Forces

$$V(r) = -\frac{G m_A m_B}{r}\left(1 + \alpha_A \alpha_B e^{-m_\phi r}\right) \;\; ; \alpha_A \propto \frac{1}{m_A}\frac{\partial m_A}{\partial \phi}$$

- Equivalence principle (acceleration due to gravity is independent of mass)
- EP tests dominate for for $m_\phi \lesssim 10^{-6}$ eV
- For $m_\phi \gtrsim 10^{-6}$ eV Inverse Square Law tests dominate

Experimental Constraints

Atomic/Nuclear Clocks

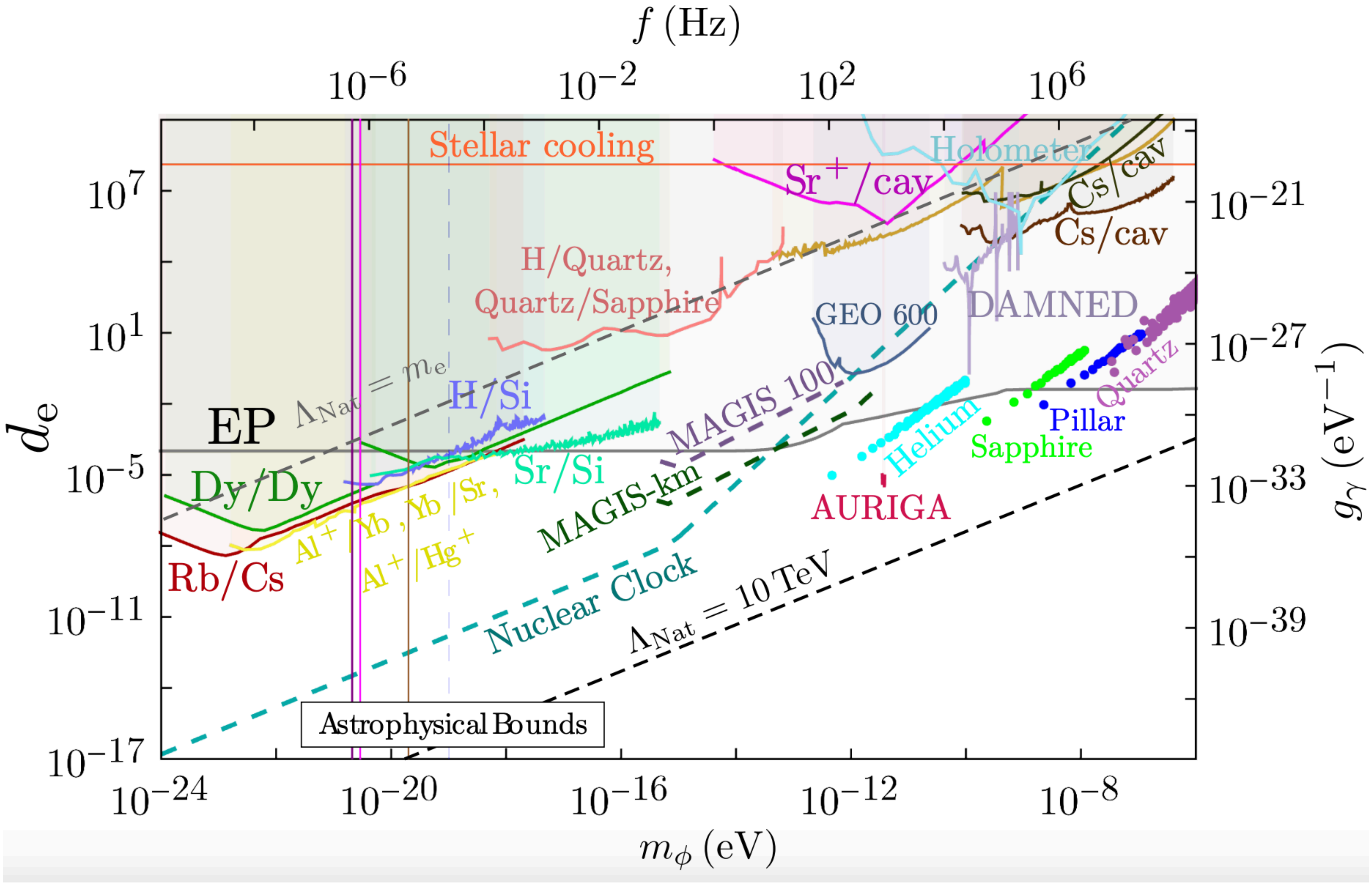
Arvanitaki, Huang, Tilburg

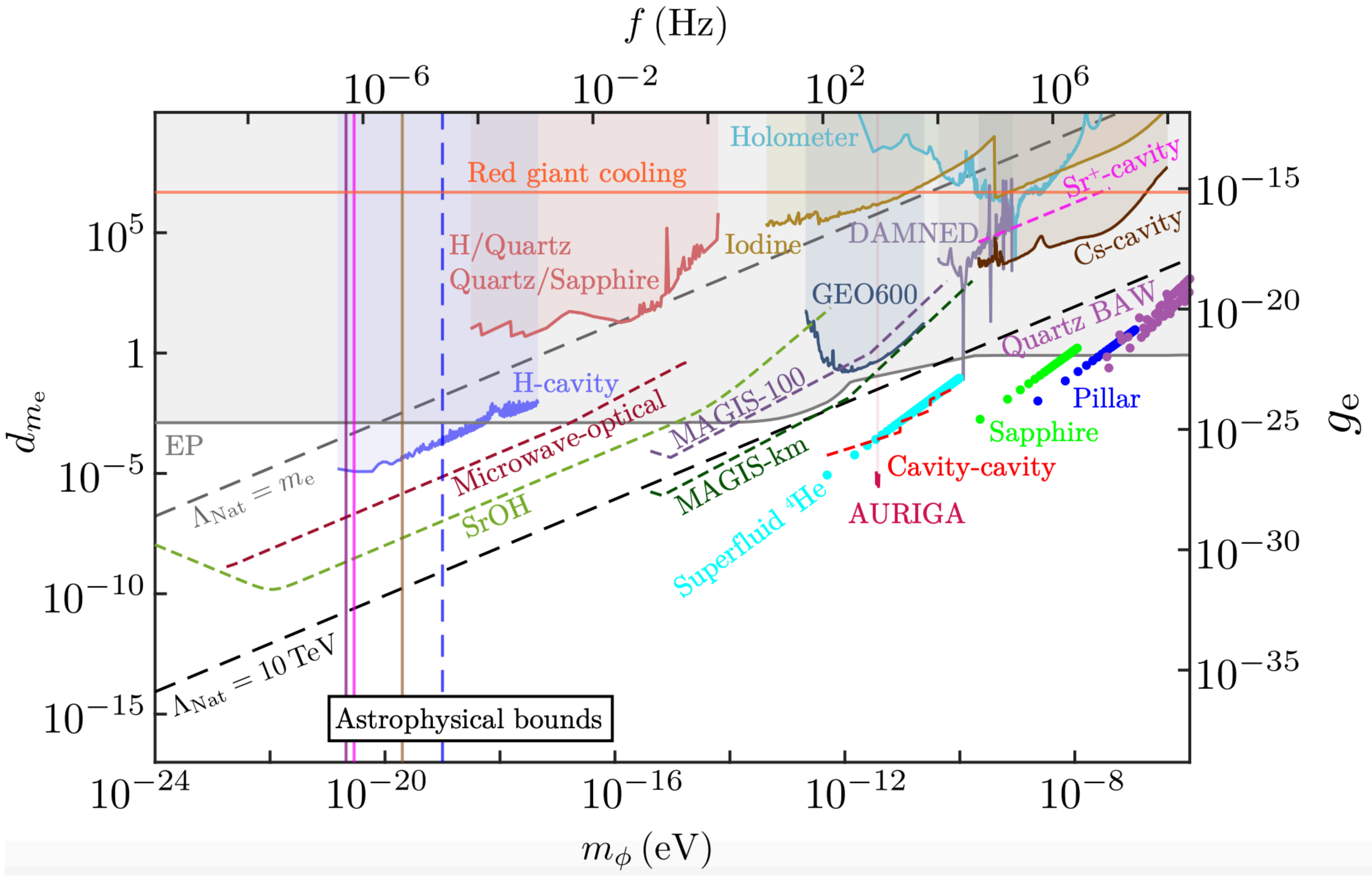
$$\phi(t) \simeq 10^9\text{GeV}\left(\frac{10^{-20}\text{eV}}{m_\phi}\right)\cos(m_\phi t) \to \frac{\delta\alpha}{\alpha} \simeq 10^{-9} d_e \left(\frac{10^{-20}\text{eV}}{m_\phi}\right)$$

- Atomic clocks are tuned to specific transitions of atoms
- Compare two frequencies that have different dependences on α

$$\frac{d}{dt}\left(\frac{\nu_2}{\nu_1}\right) = \left(K_2 - K_1\right)\frac{1}{\alpha}\frac{d\alpha}{dt}$$

All Constraints

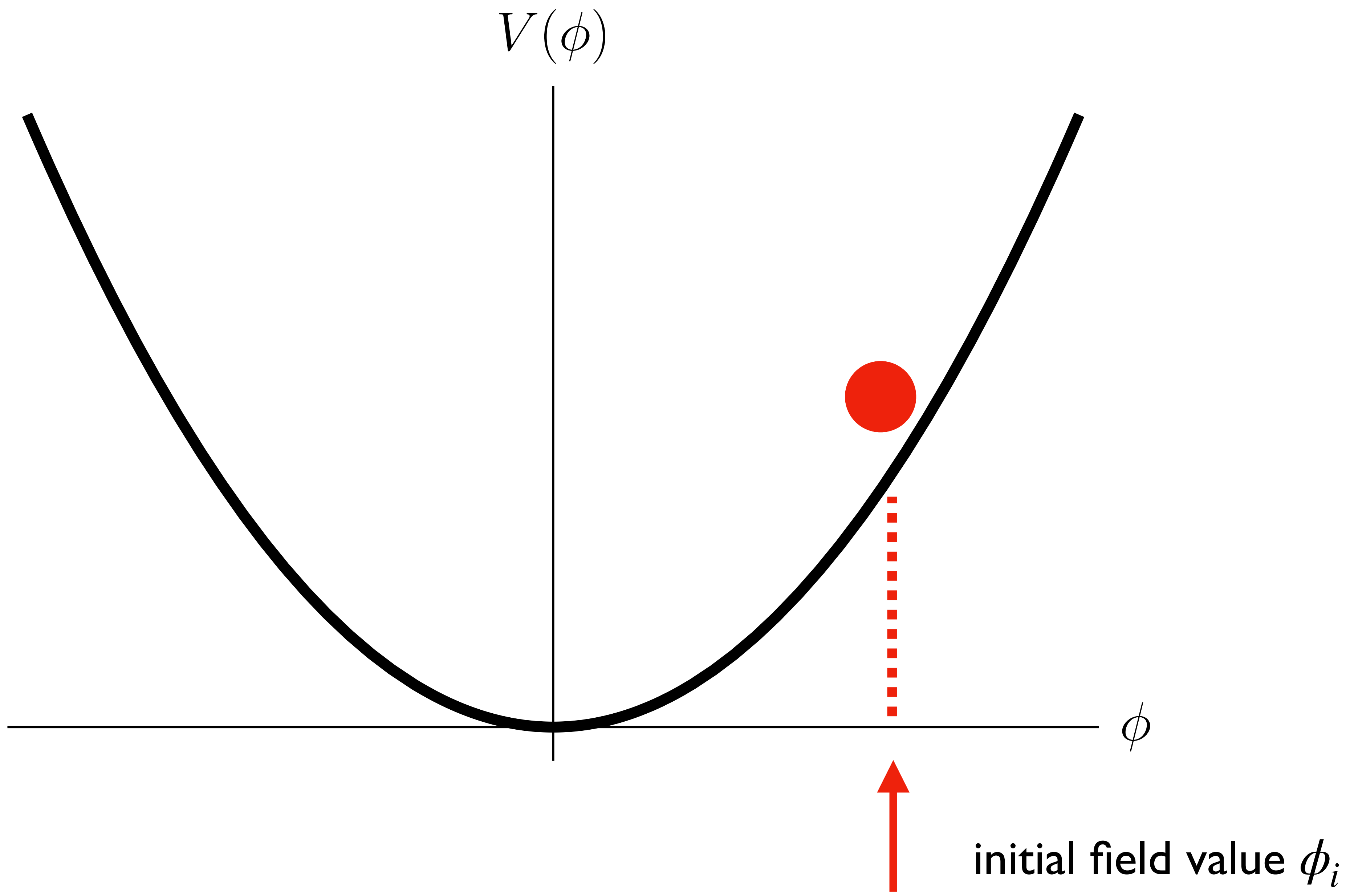




Effects in early universe cosmology

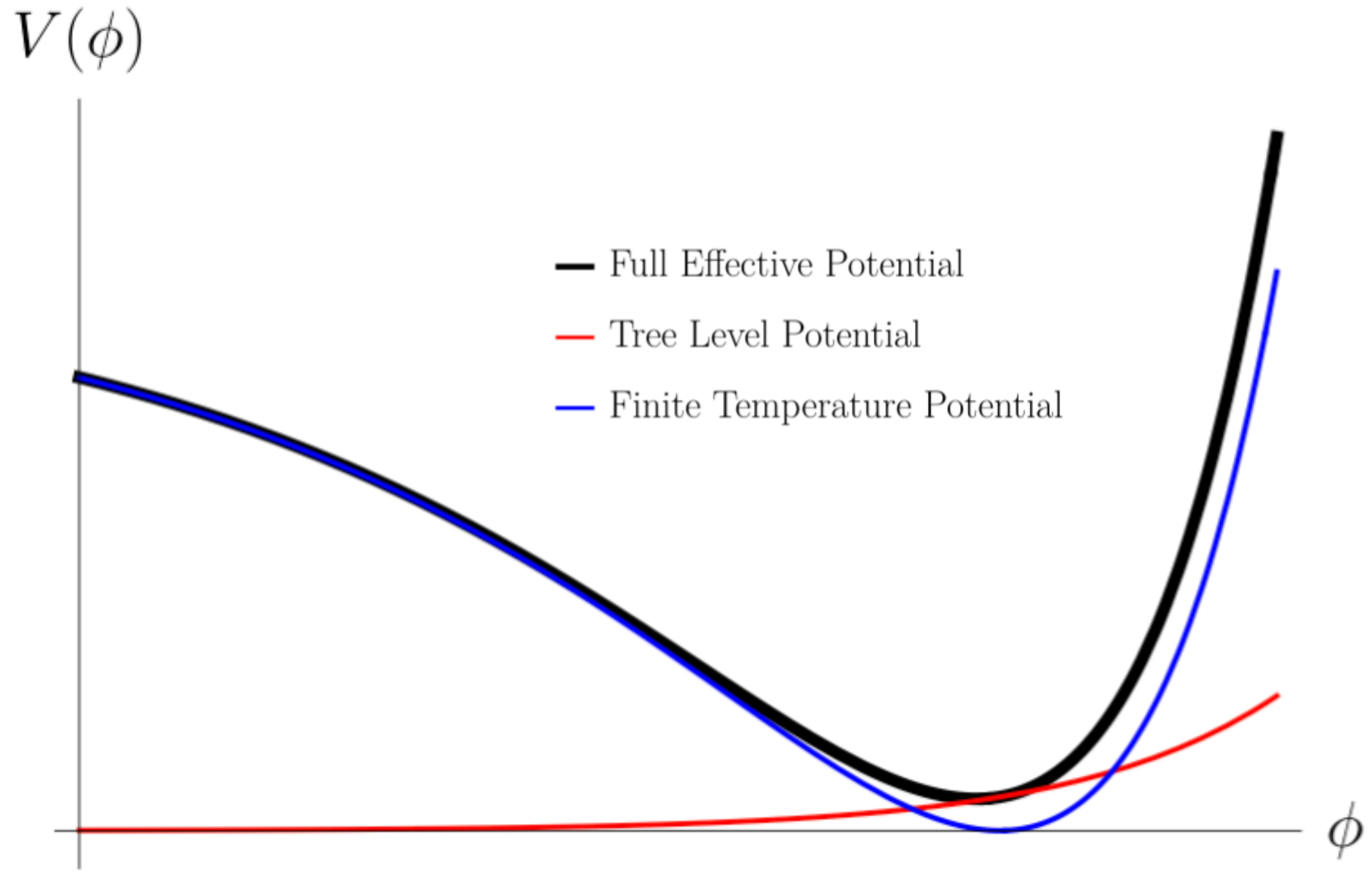
$$\mathscr{L} \supset -\left[m_f \left(1 - \frac{\beta \phi}{M_{\rm pl}} \right) \bar{\mu}\mu + {\rm h.c.} \right] + \frac{1}{2} m_\phi^2 \phi^2$$

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$



$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi + \frac{\partial V_T(m_\mu(\phi))}{\partial \phi}$$

$$T = 10\, m_\psi$$



Evolution of potential with increasing temperature

Slide by BB

$$V_{\text{eff}}(\phi, T) \simeq V_0(\phi) + V_1^T(\phi) \quad \Rightarrow$$

$$V_0(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$

$$V_1^T(\phi) = -\frac{g_\psi}{2\pi^2} T^4 \int_0^\infty dx\, x^2 \log\left[1 + \exp\left(-\sqrt{x^2 + \frac{m_\psi(\phi)^2}{T^2}}\right)\right]$$

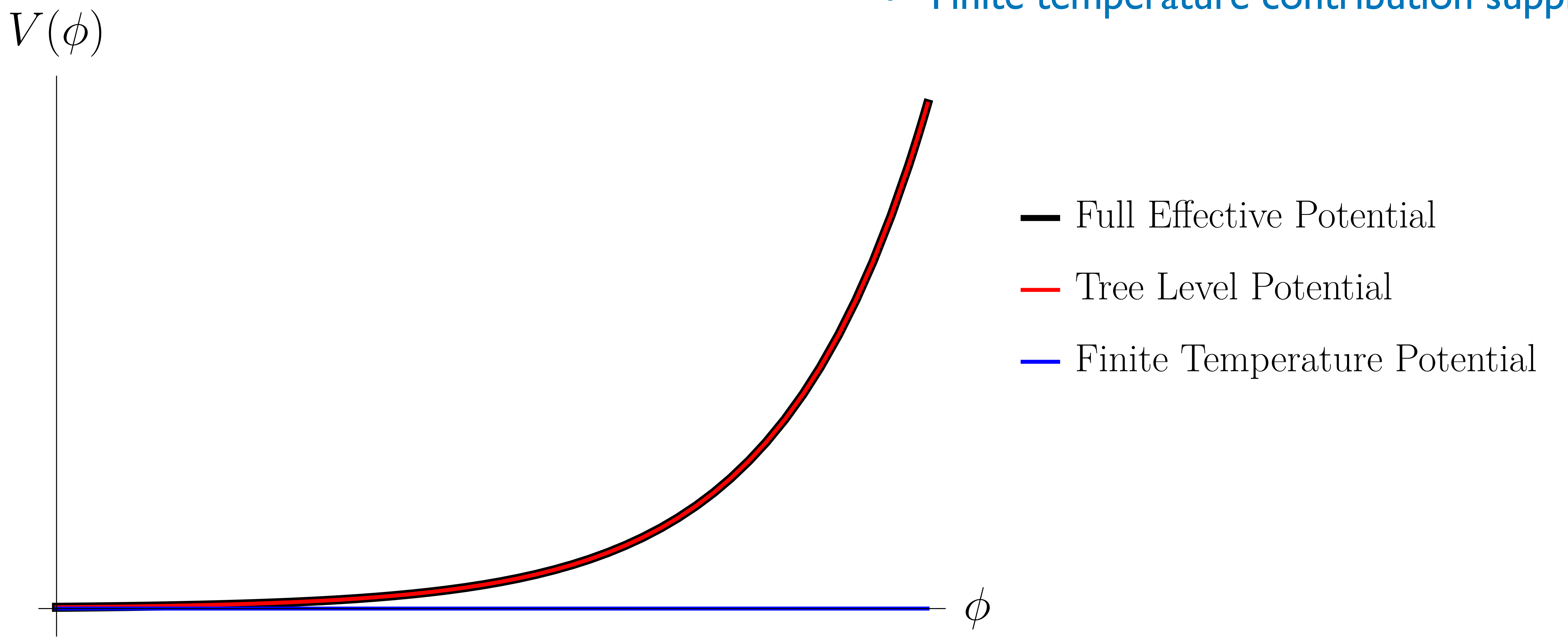
$$\sim e^{-m_\psi/T} \quad \text{for} \quad T \ll m_\psi$$

Boltzmann suppressed

Low temperature

- Tree level dominates at low temperature
- Finite temperature contribution suppressed

$T = 0.1\, m_\psi$



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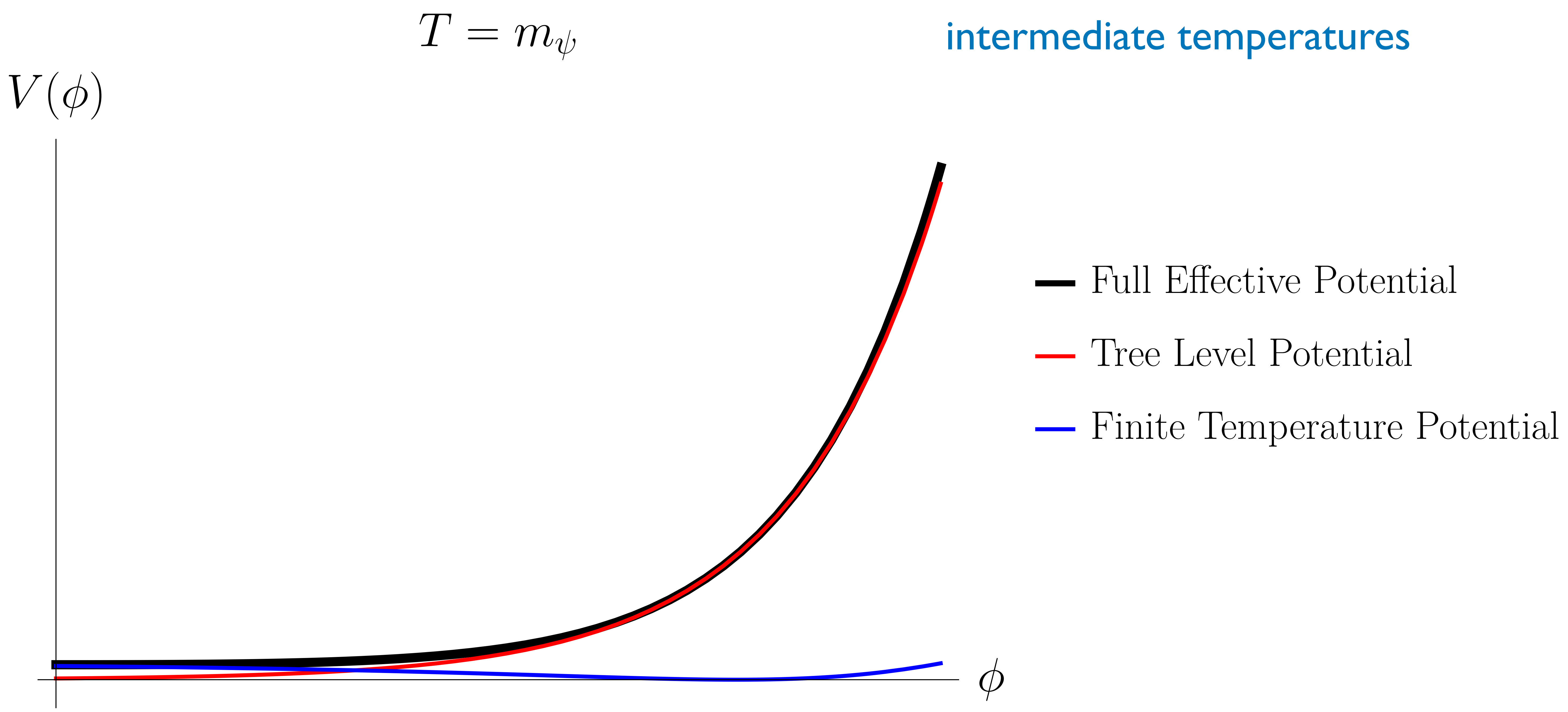
<u>Intermediate temperature</u>

- Finite temperature contribution grows at intermediate temperatures



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$$V_{\rm eff}(\phi, T) \simeq V_0(\phi) + V_1^T(\phi)$$ ➡

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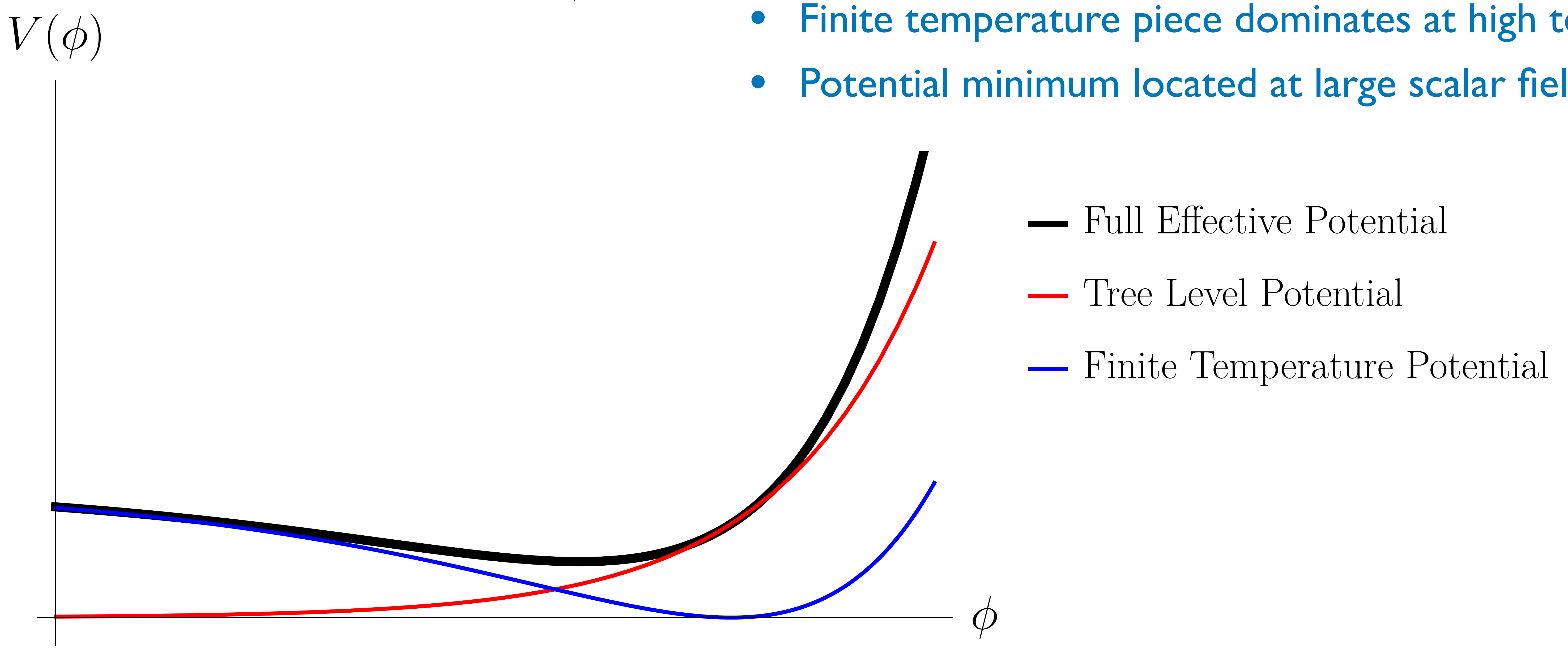
$$\sim \frac{T^2 m_\psi^2}{12}\left(1 - \frac{\beta\,\phi}{M_{\rm pl}}\right)^2 \quad \text{for} \quad T \gg m_\psi$$

↳ Minimum at $\phi \sim M_{\rm pl}/\beta$

High temperature

$T = 3\, m_\psi$

- Finite temperature piece dominates at high temperatures
- Potential minimum located at large scalar field values



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$T = 10\, m_\psi$

- Finite temperature piece dominates at high temperatures
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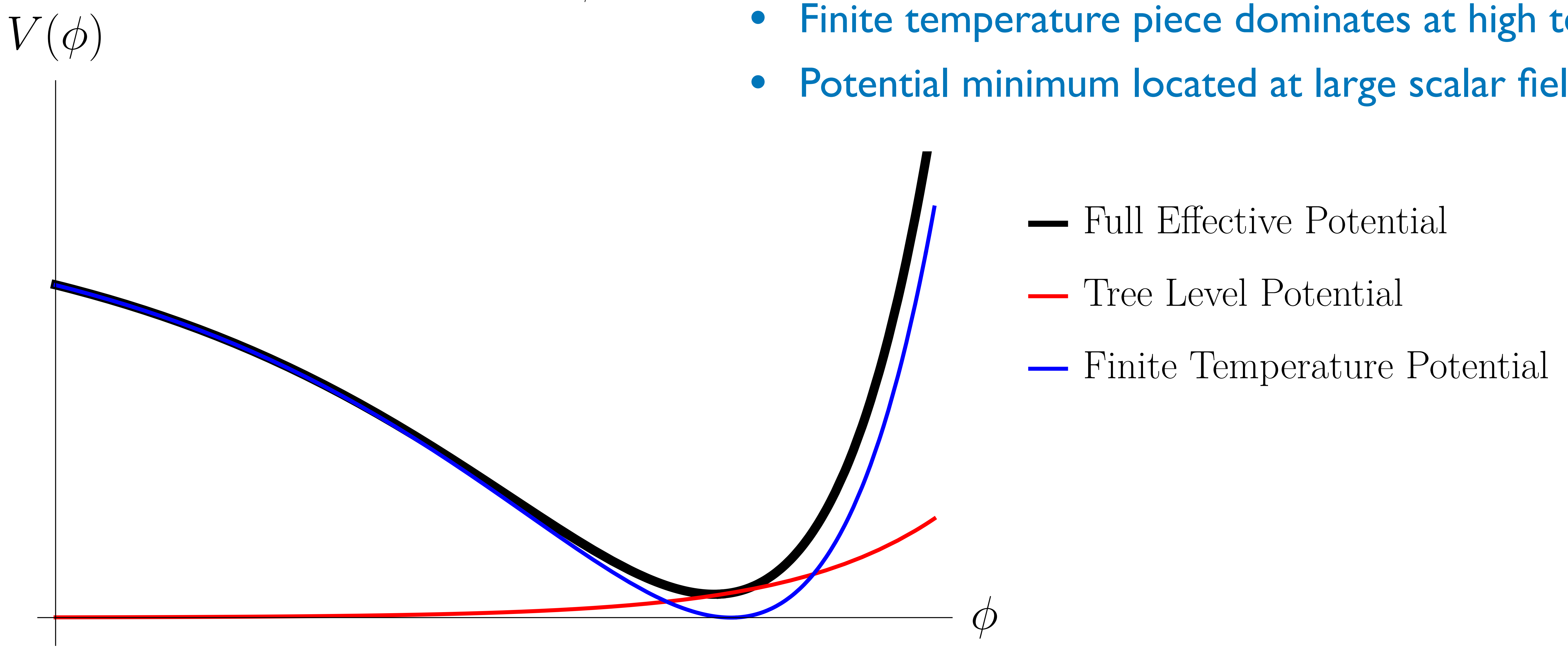
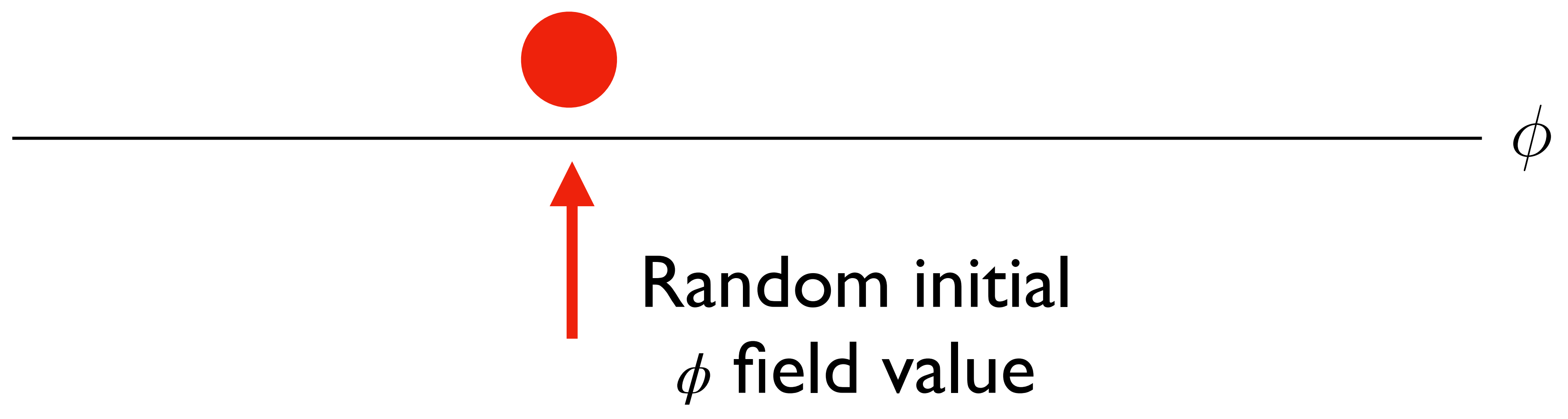


Cartoon sketch of the mechanism

- Assume nonzero homogeneous scalar field with arbitrary* initial condition after inflation
- In the case of a Standard Model fermion, initial condition set after electroweak phase transition



* Caveats will be discussed below

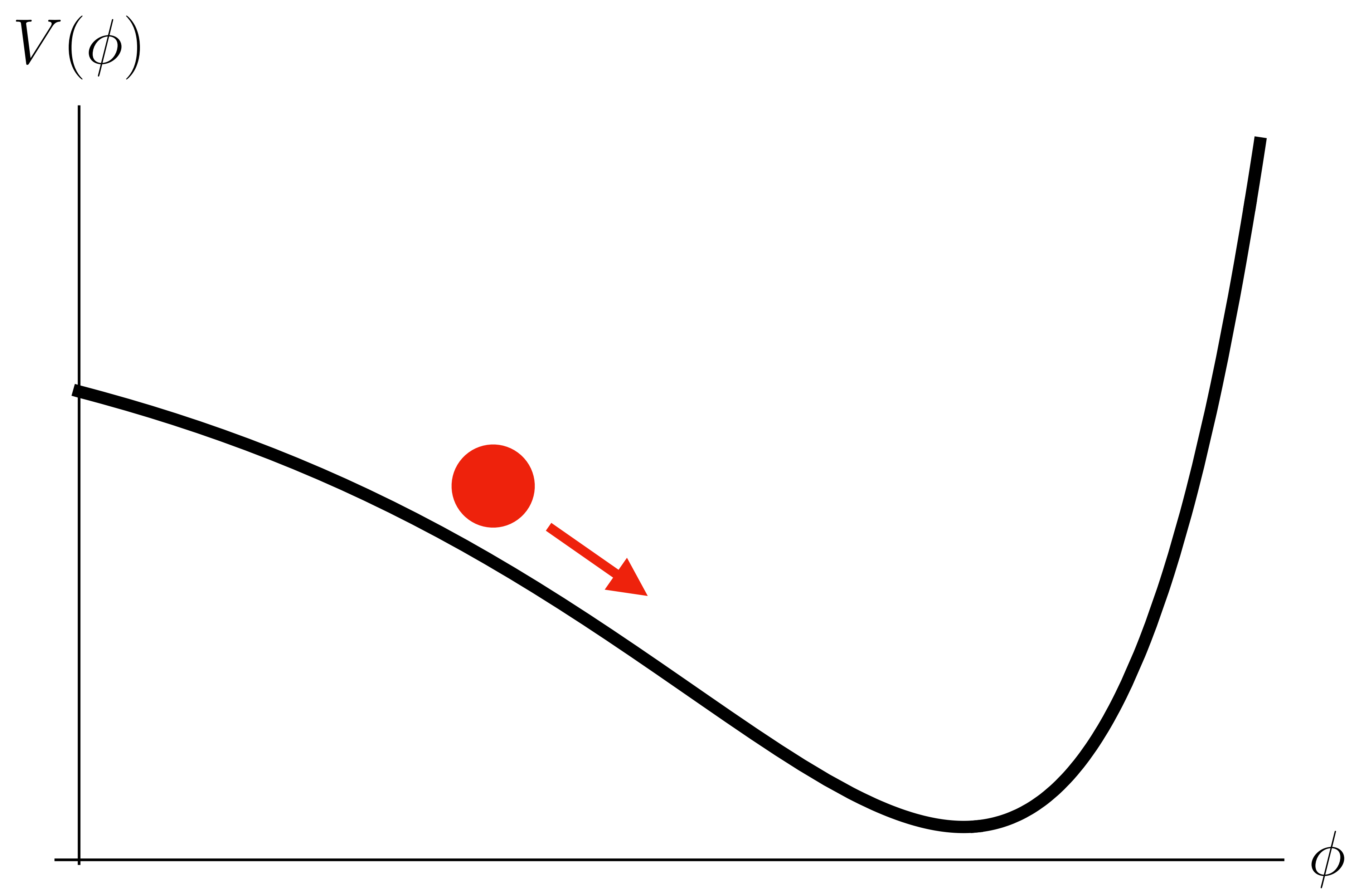
Cartoon sketch of the mechanism

Slide by BB

- Inflation ends and reheating occurs, creating the thermal plasma.
- The finite temperature potential dominates at this stage.
- ϕ rolls toward the minimum at large field values, generating misalignment

<u>High temperature</u>

$T \gg m_f$



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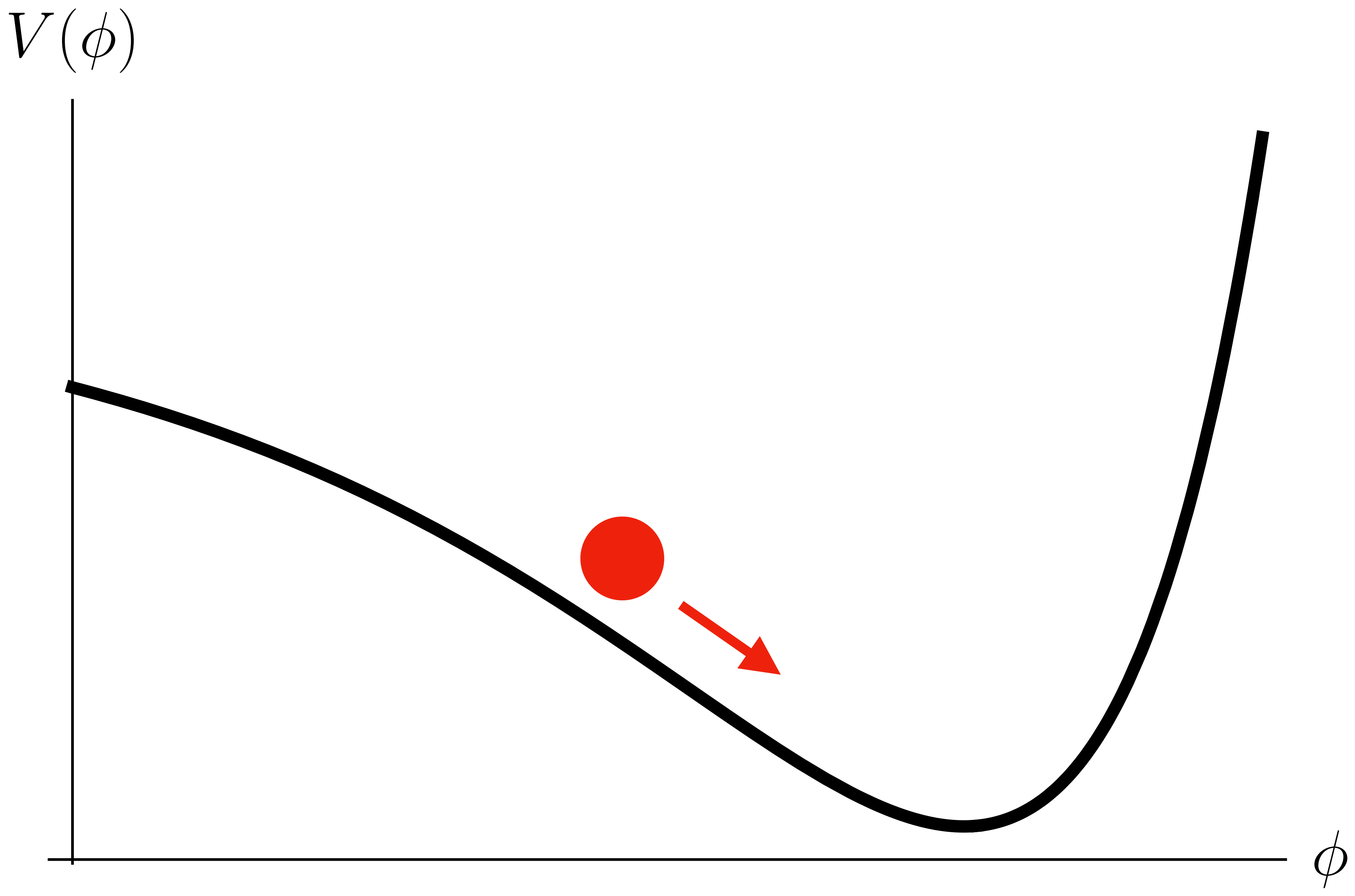

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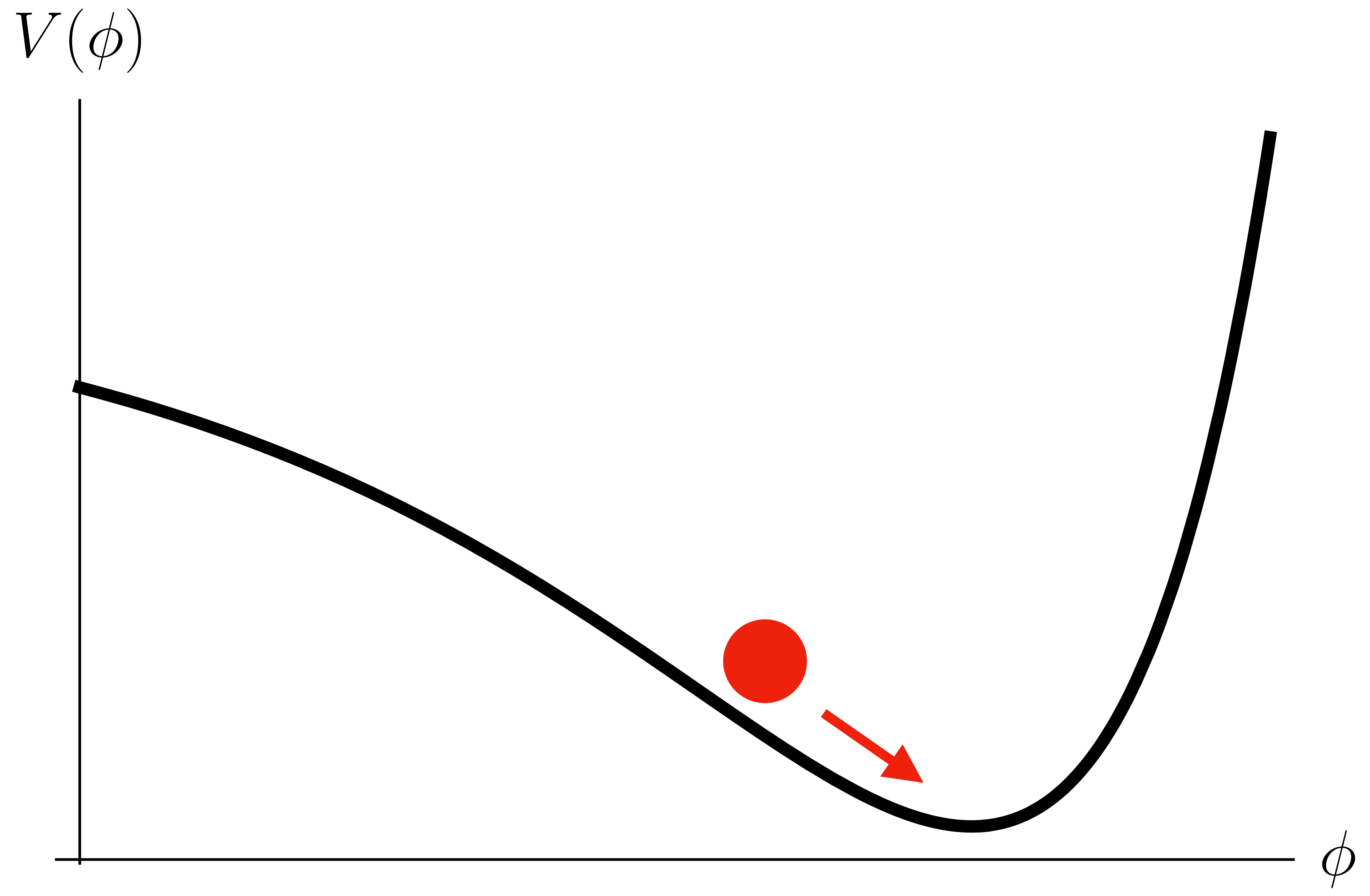
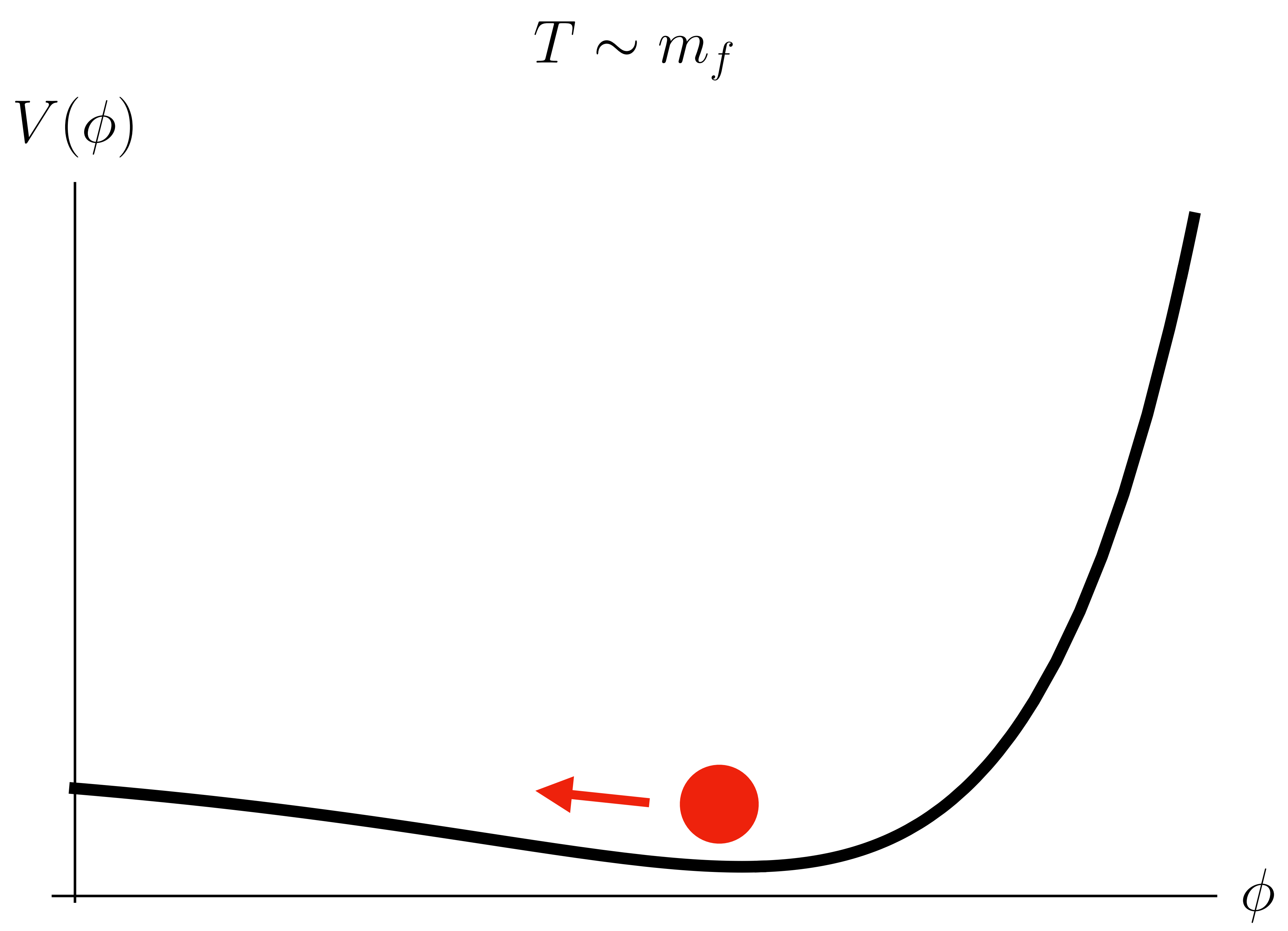


Cartoon sketch of the mechanism

Slide by BB

- At intermediate temperatures of order the fermion mass, the finite temperature pieces becomes smaller.
- The minimum moves toward the origin

Intermediate temperature



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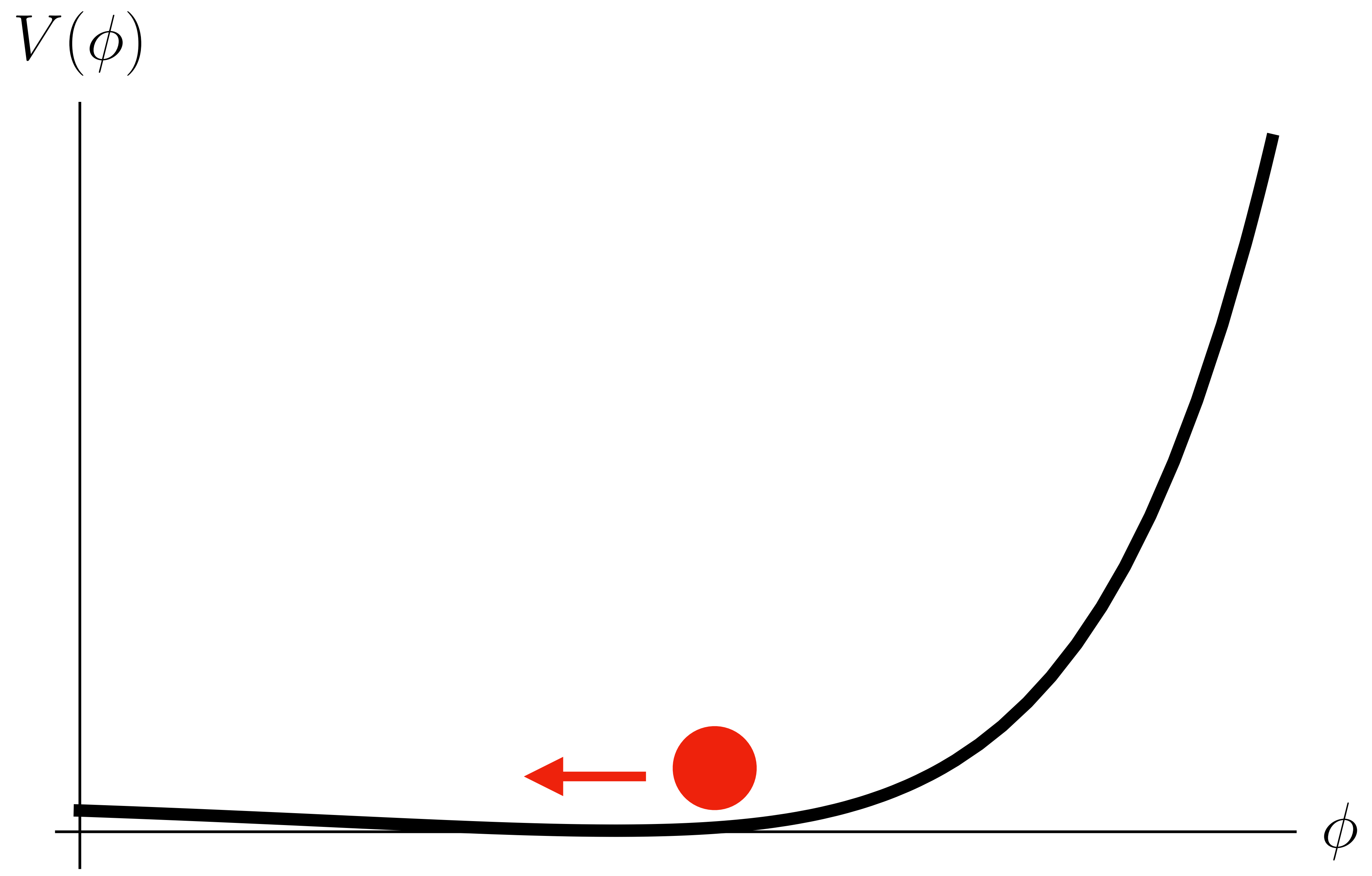
$T \sim m_f$

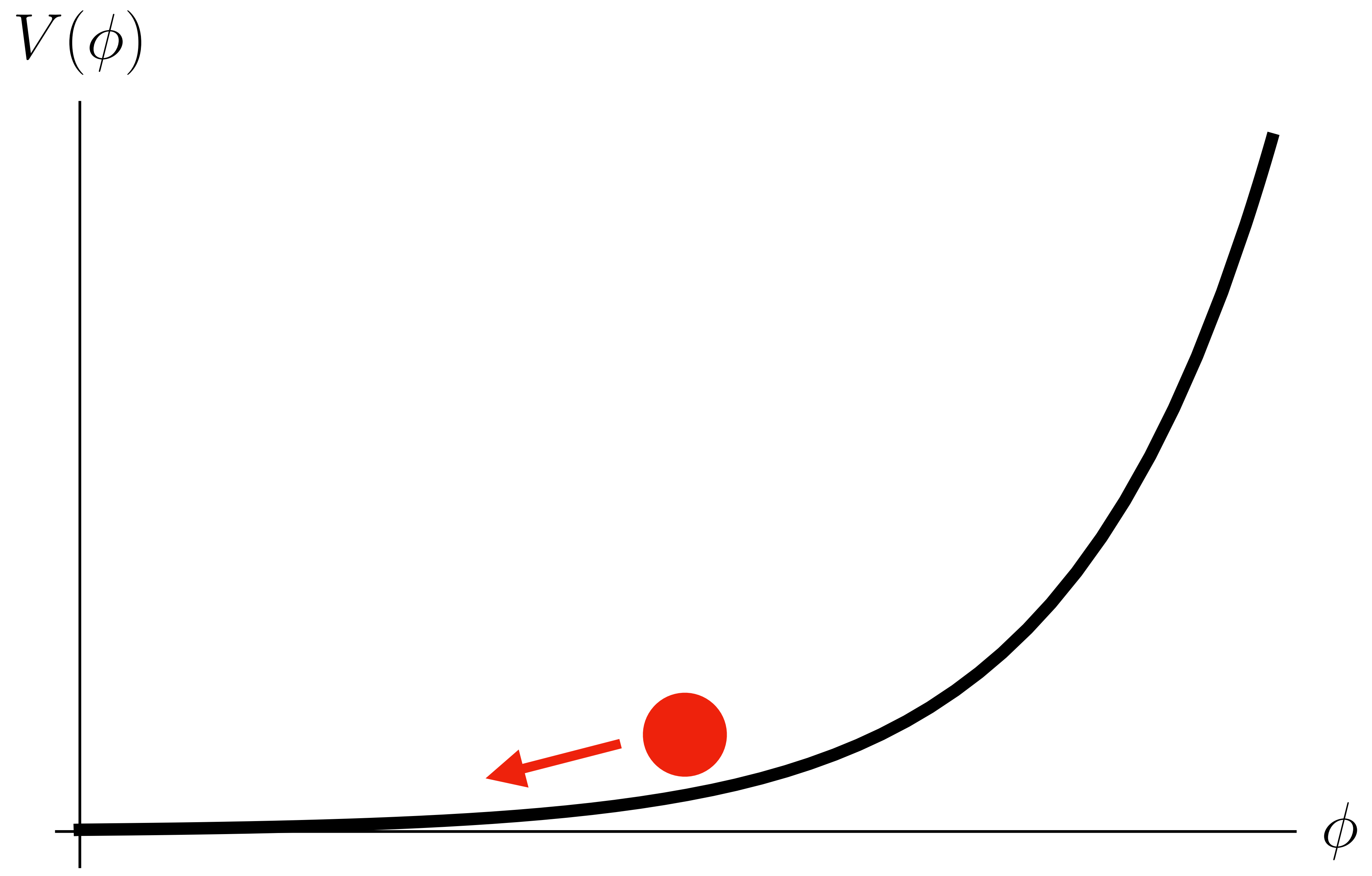


Cartoon sketch of the mechanism

Slide by BB

- At low temperatures the tree level potential dominates
- The minimum is located at the origin
- Eventually ϕ oscillates and behaves as dark matter

$T \ll m_f$



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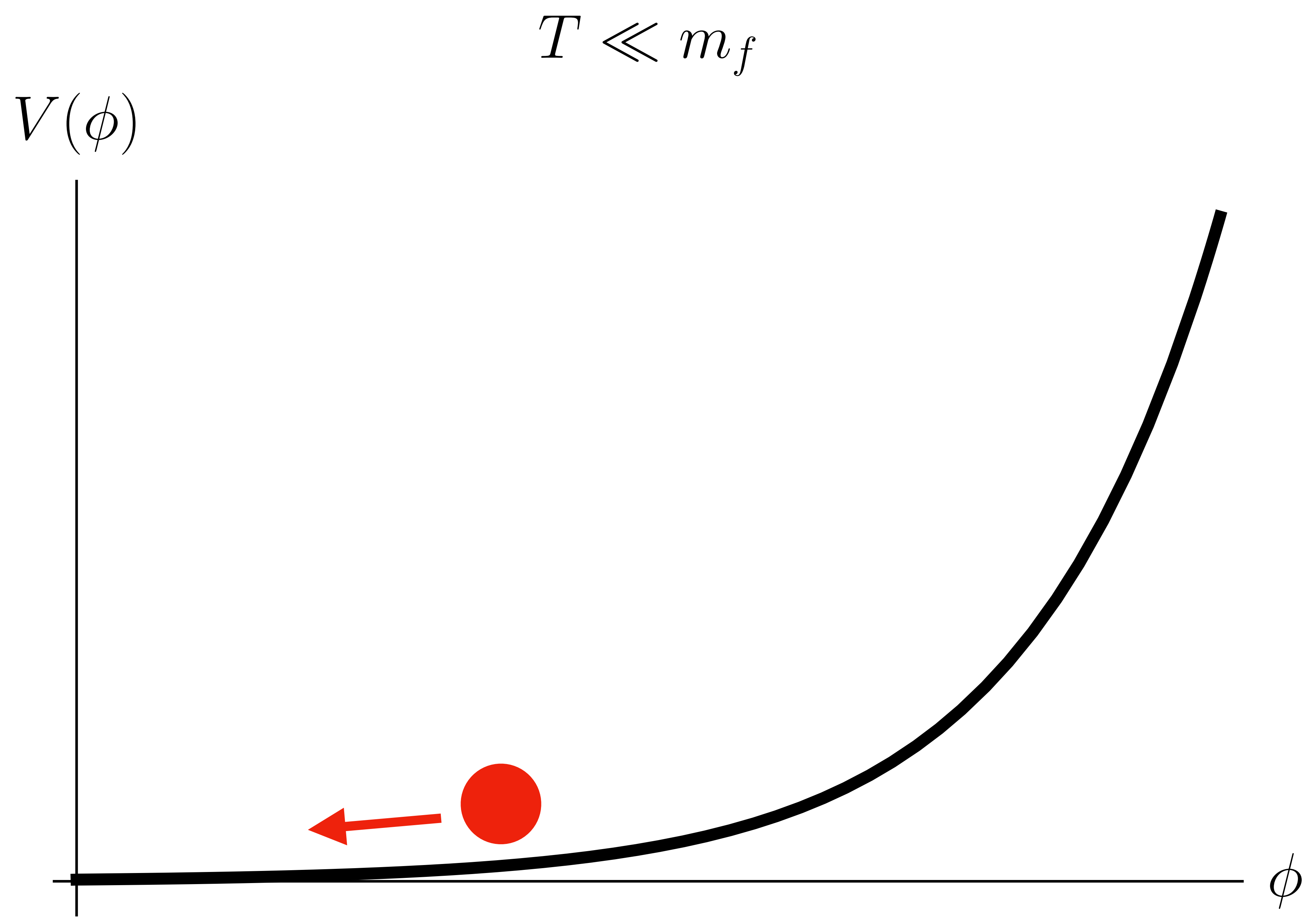

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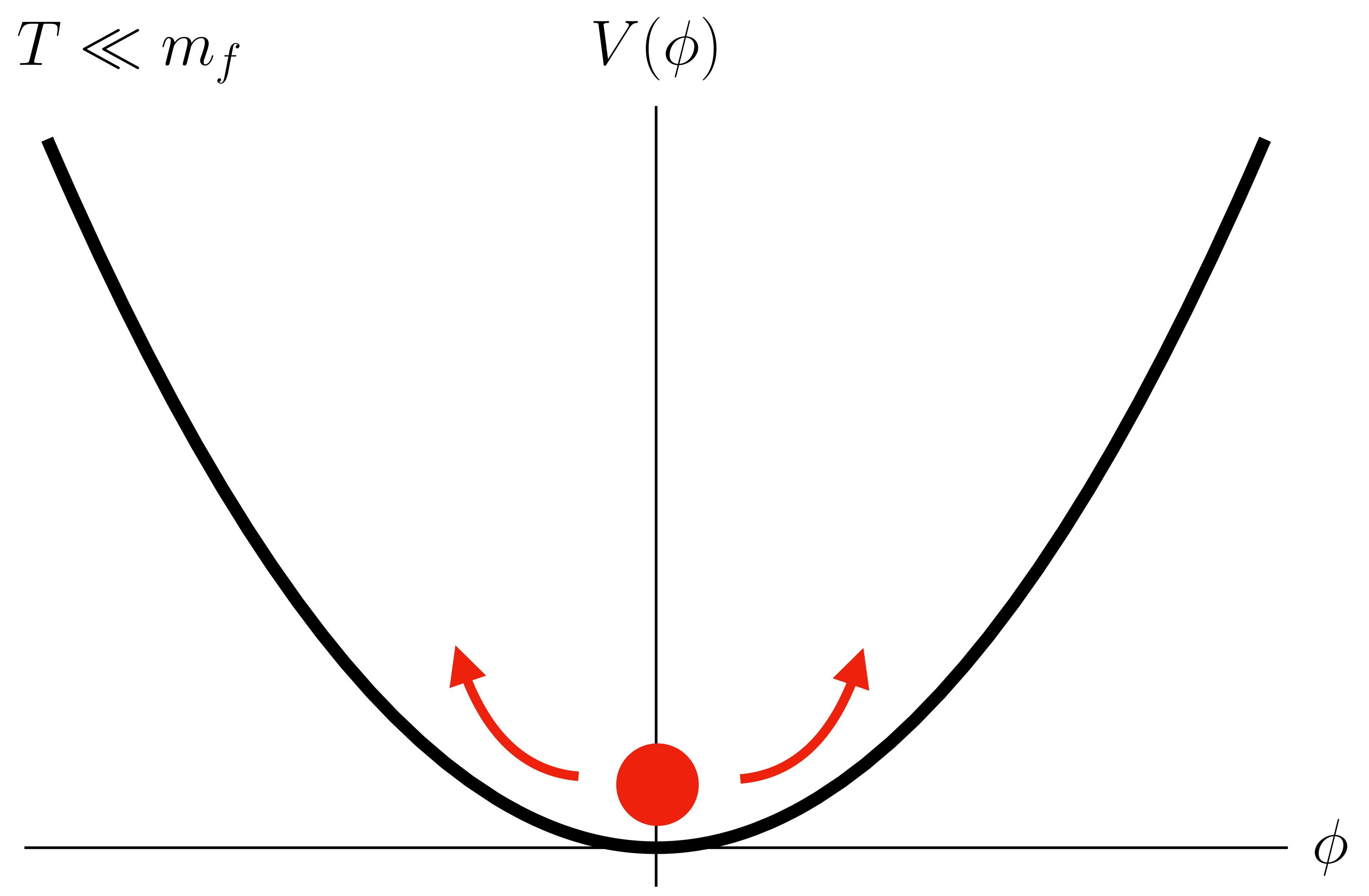
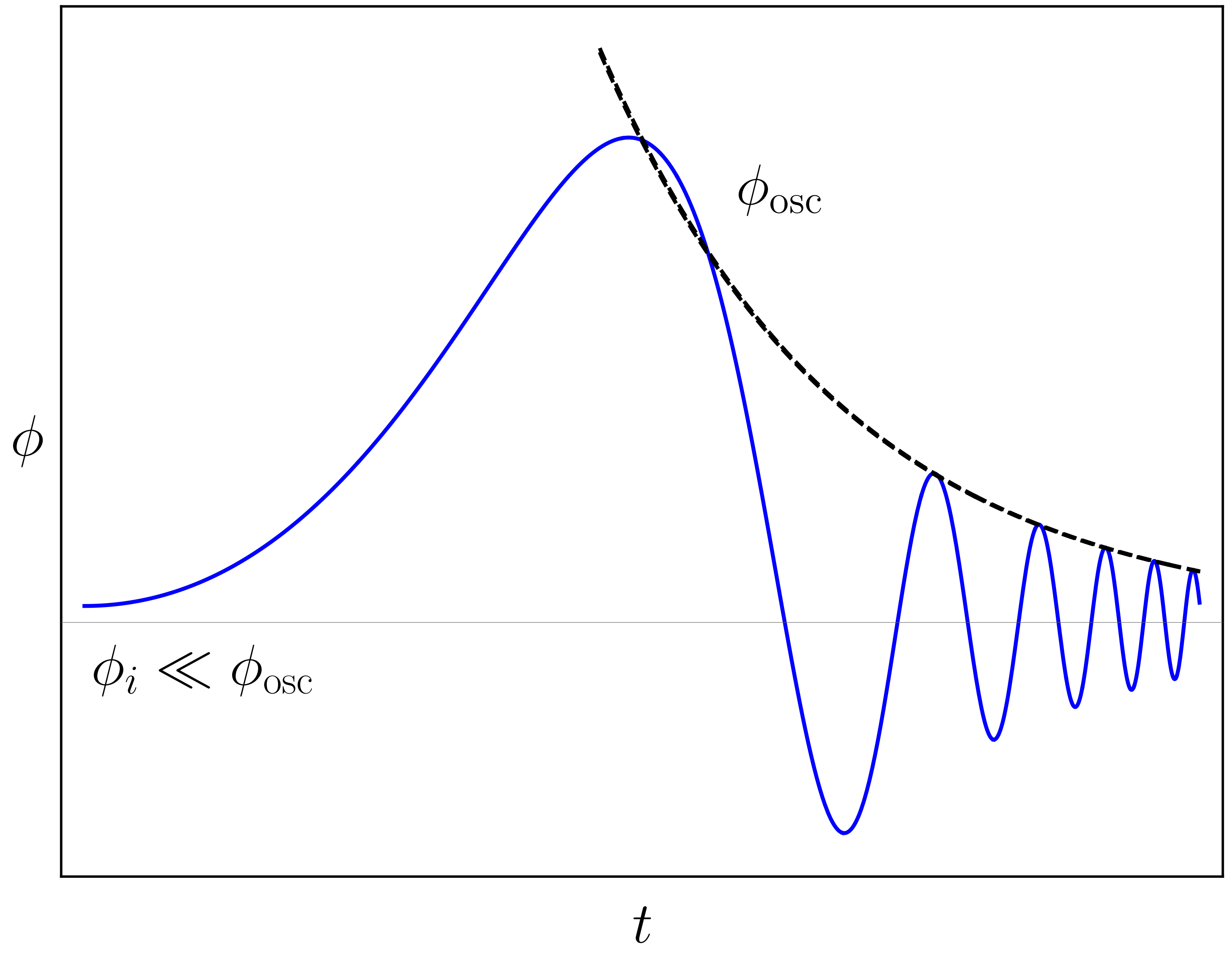


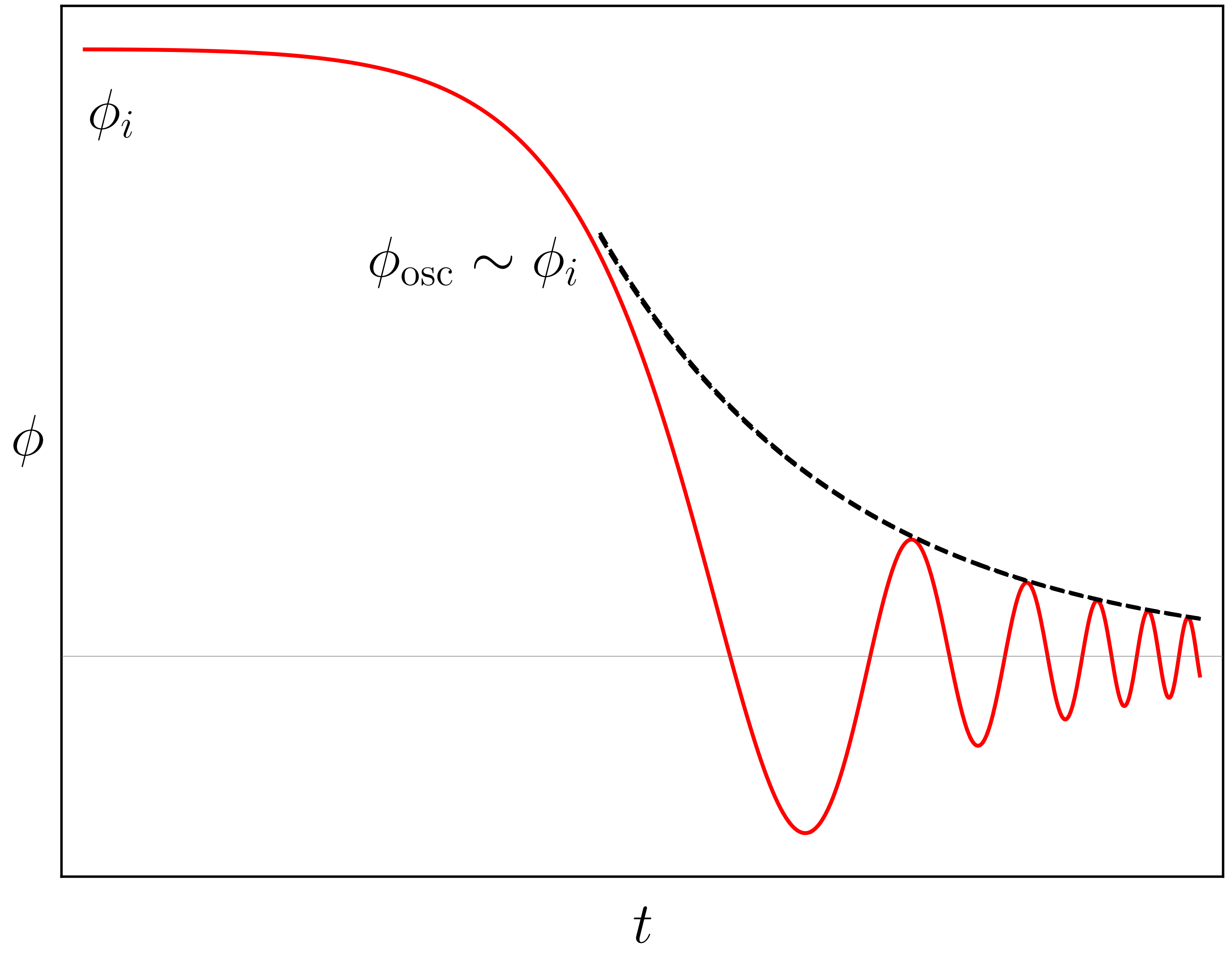
Thermal misalignment mechanism

Thermal Misalignment



- At high temperatures, ϕ is dynamically misaligned from a small initial value to its oscillation amplitude

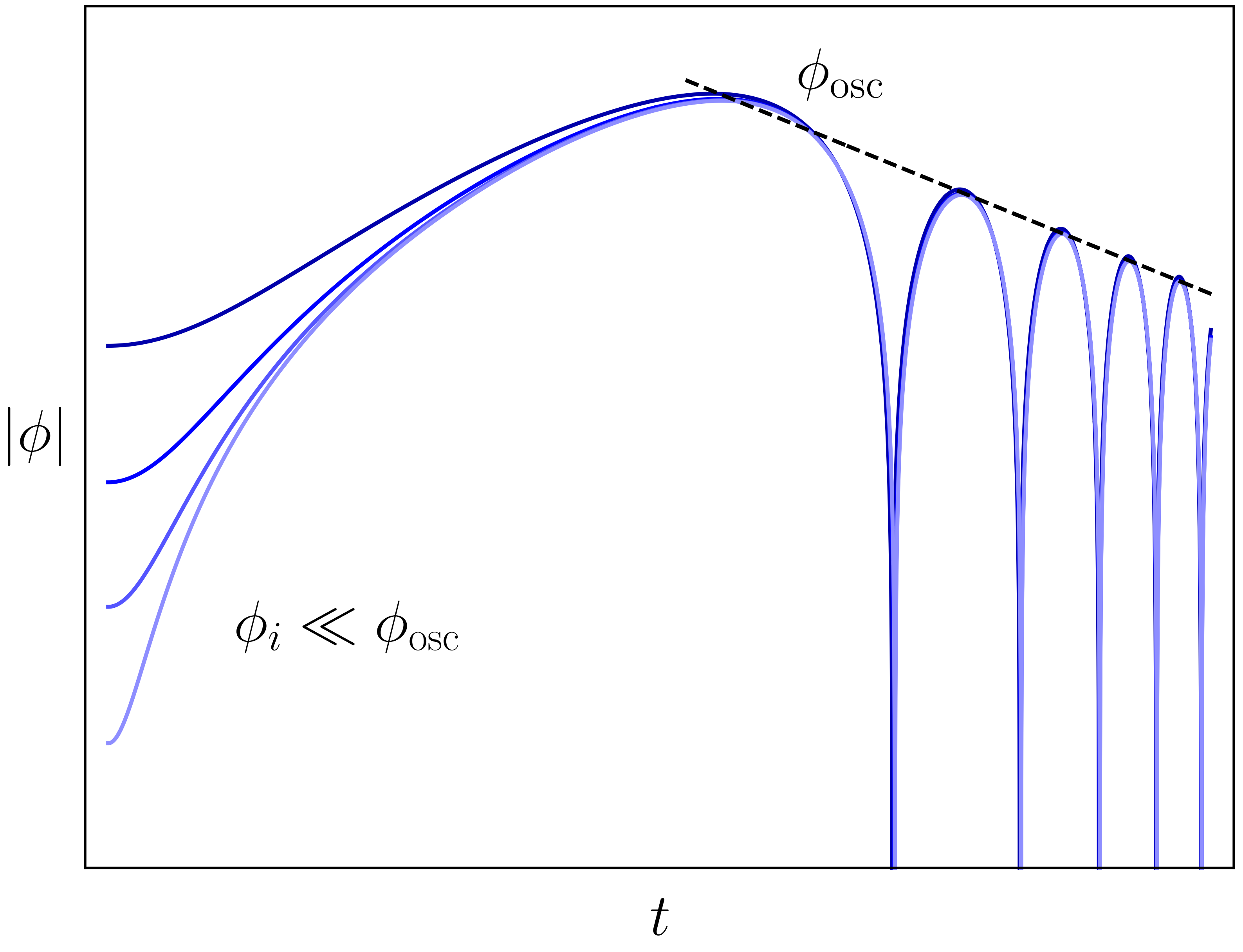
Classic Misalignment



- ϕ oscillation amplitude and abundance dictated by initial conditions

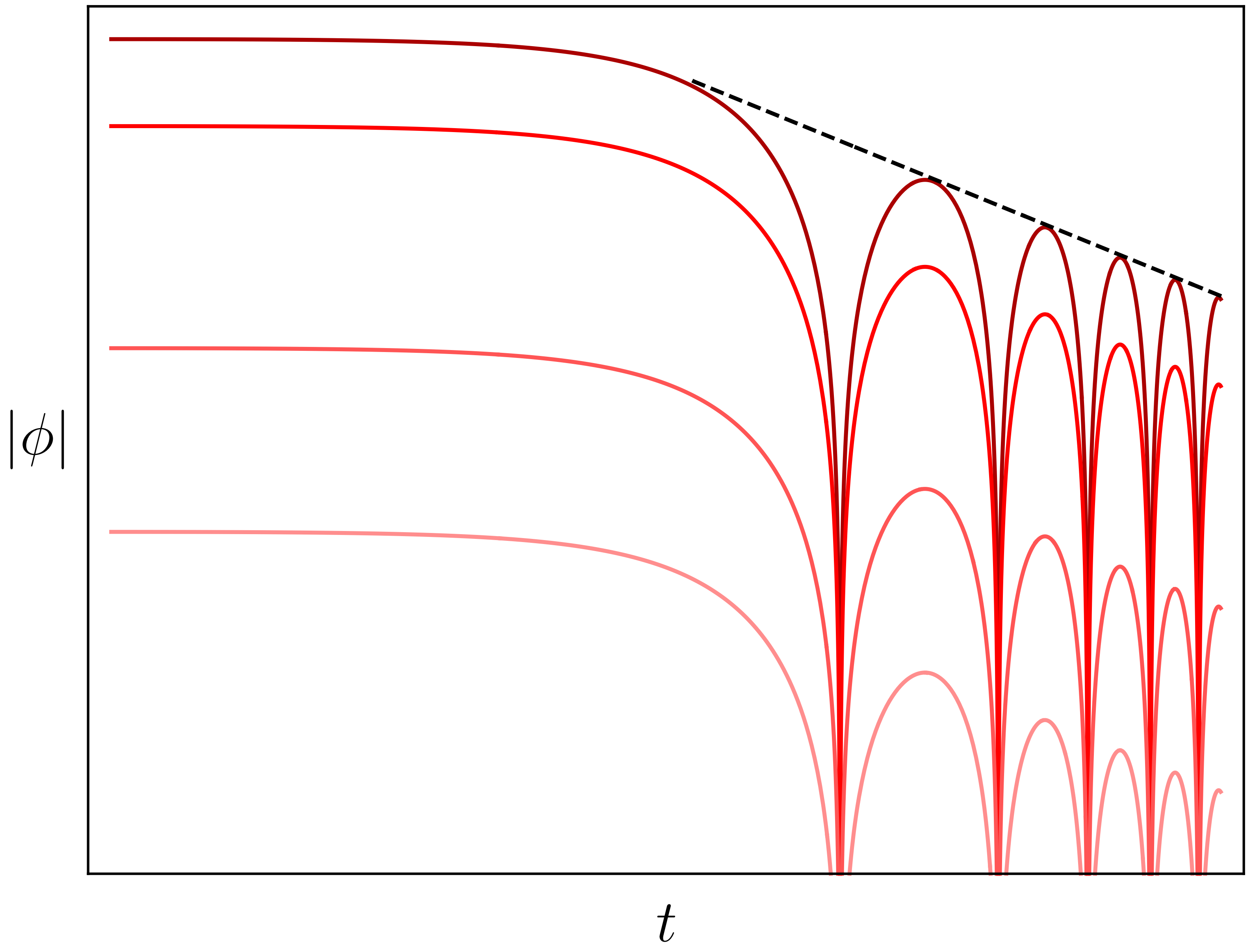
Thermal misalignment mechanism

Thermal Misalignment



- At high temperatures, ϕ is dynamically misaligned from a small initial value to its oscillation amplitude
- The oscillation amplitude is an attractor for $\phi_i \ll \phi_{\rm osc}$ - insensitive to initial conditions

Classic Misalignment



- ϕ oscillation amplitude and abundance dictated by initial conditions

Thermal misalignment mechanism

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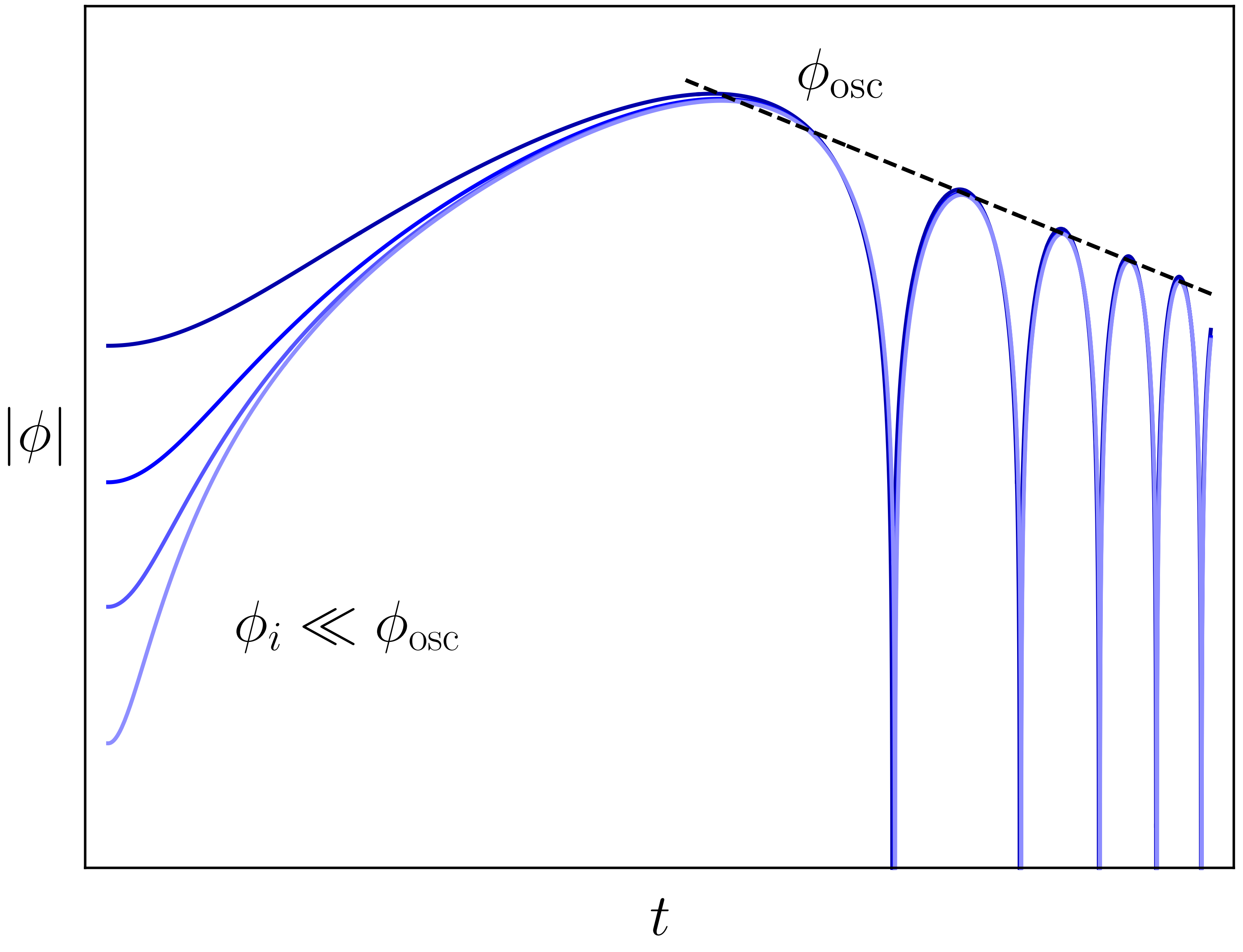
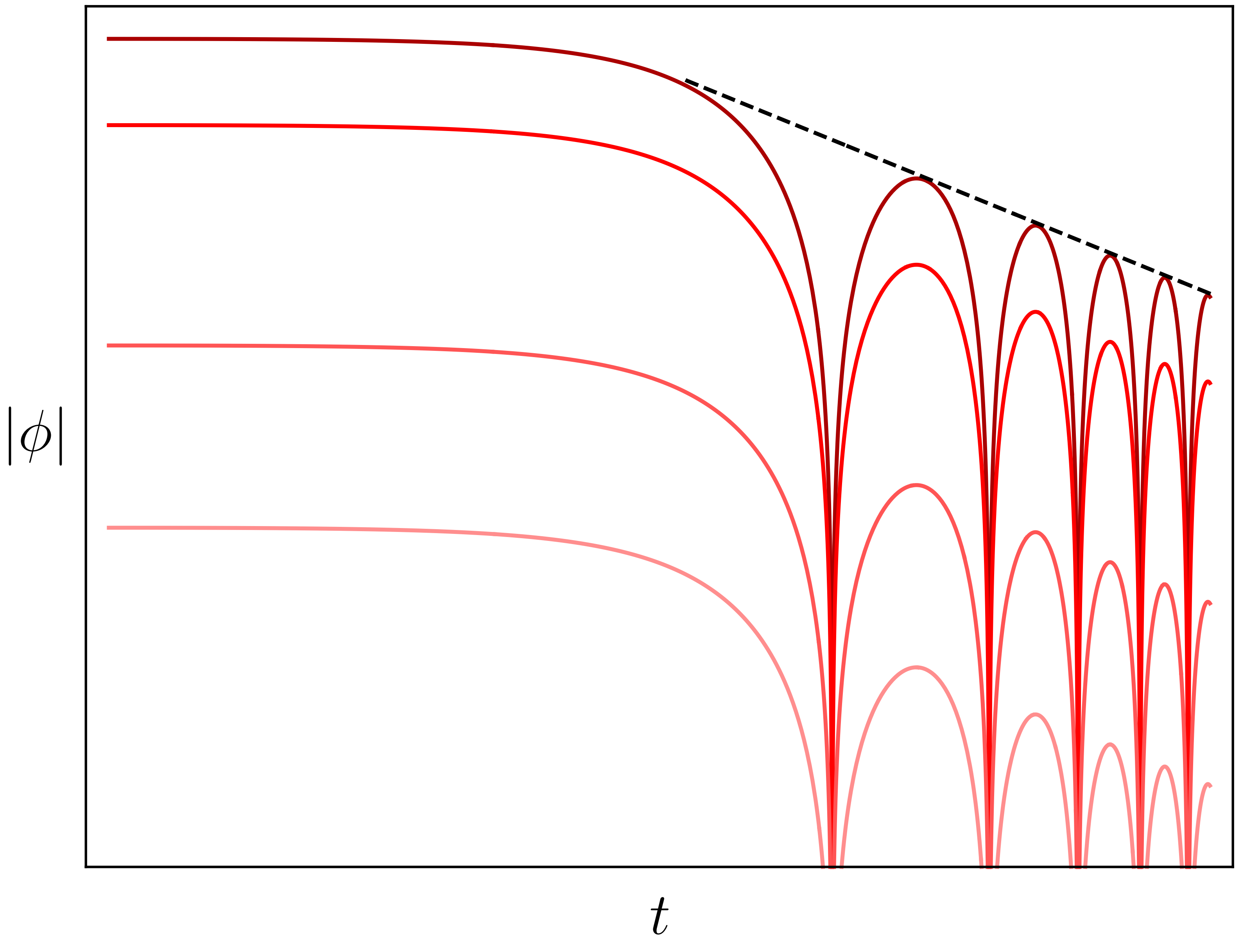


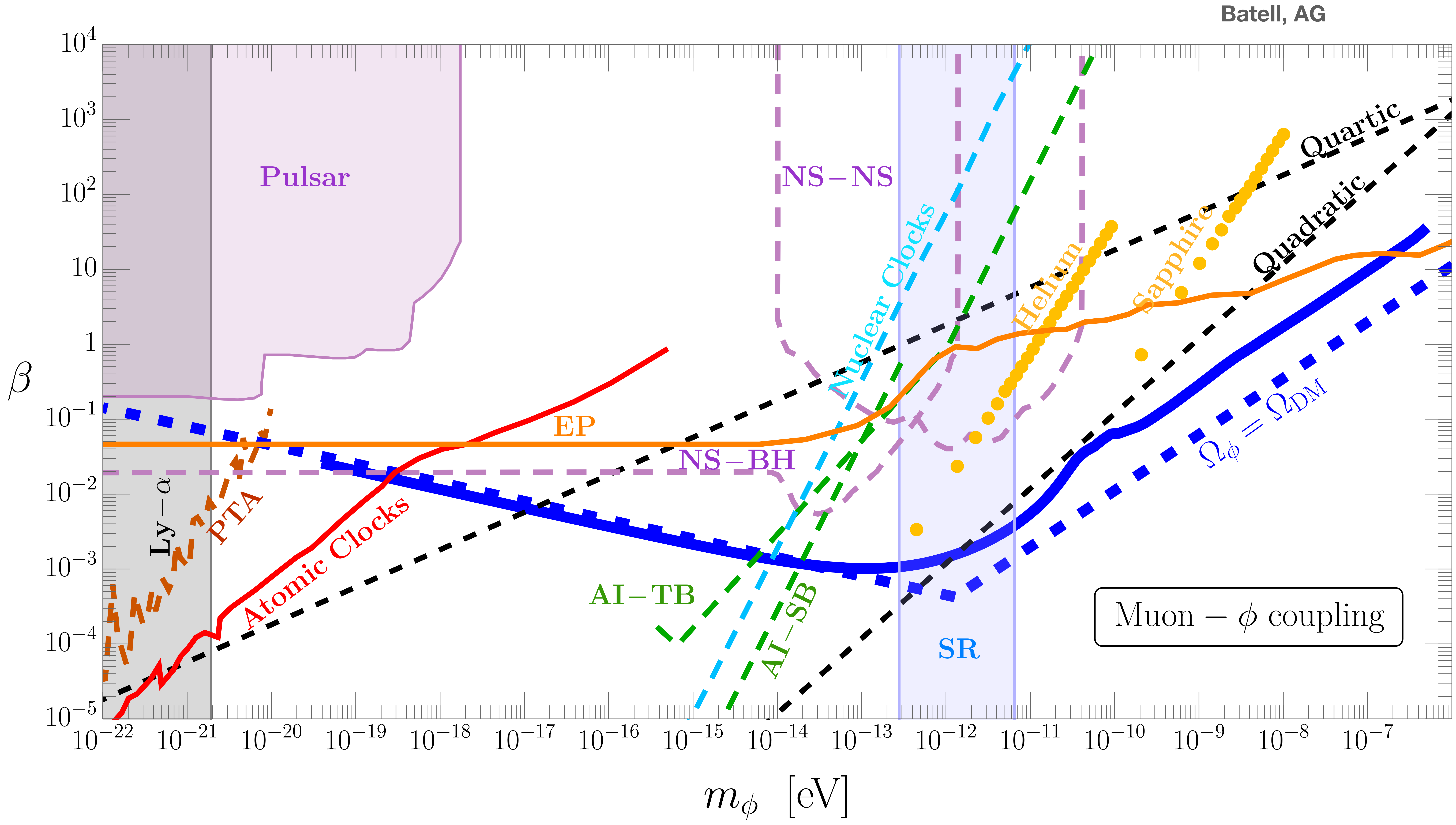
Classic Misalignment



- At high temperatures, ϕ is dynamically misaligned from a small initial value to its oscillation amplitude
- The oscillation amplitude is an attractor for $\phi_i \ll \phi_{\rm osc}$ - insensitive to initial conditions
- The oscillation amplitude and resulting abundance is dictated by microscopic particle physics

- ϕ oscillation amplitude and abundance dictated by initial conditions

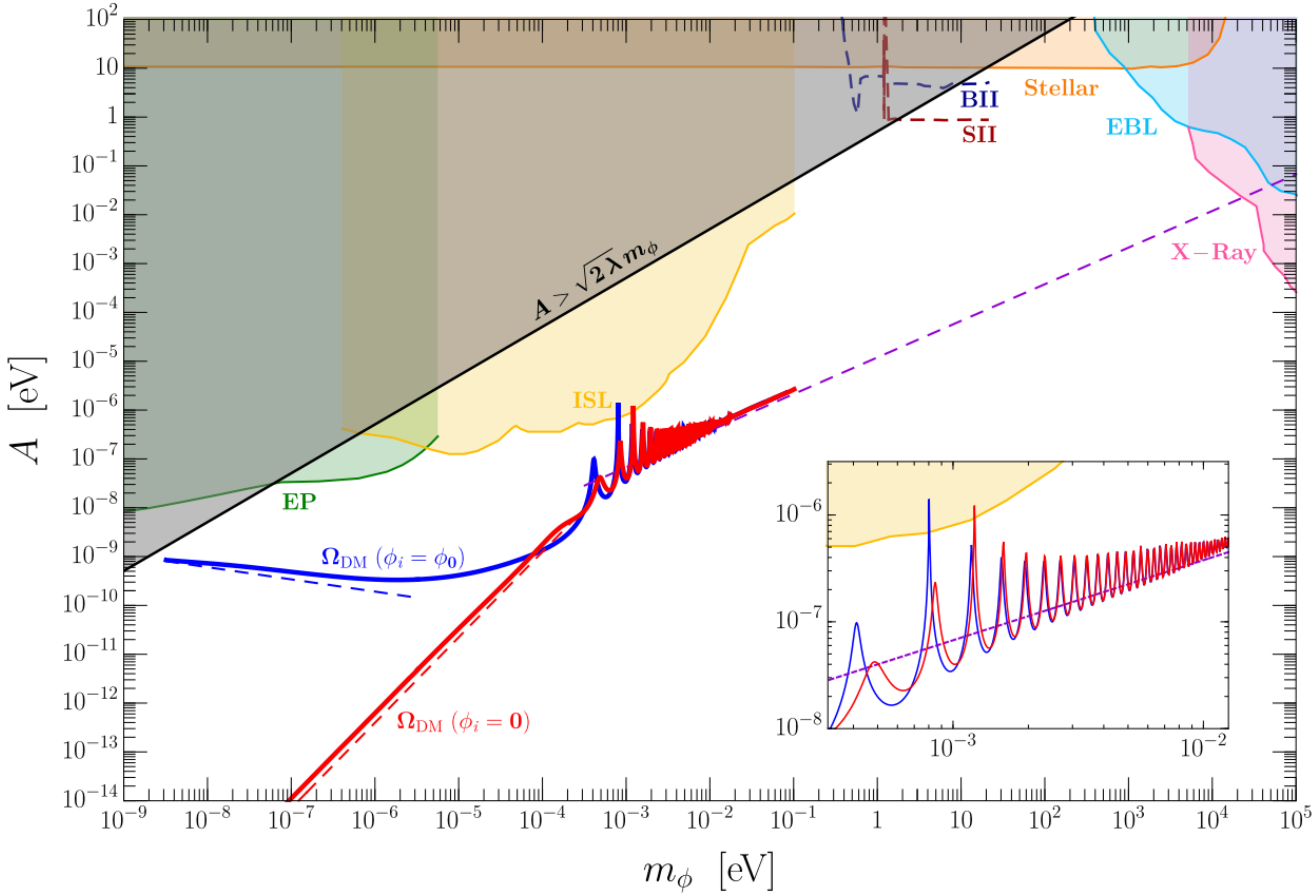
Constraints from Thermal Misalignment



Thermal Misalignment of Higgs portal scalar

$$V \supset -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + A\phi H^\dagger H + \frac{1}{2} m_\phi^2 \phi^2$$

Batell, AG, Rai



Summary

- Ultralight bosons can be DM.
- Purely gravitational interactions constraint $m_\phi \gtrsim 10^{-20}\text{eV}$ (and intermediate masses from superradiance)
- Couplings with SM mediate long range forces which can be detected
- Large number of Ultralight bosons can modify fundamental constants/ masses
- Increasingly precise ways to measure time/distance has allowed us to put strong constraints on ULDM-SM coupling
- Presence of large amount of SM particles in the early universe modifies the ULDM scalar potential, modifying ULDM dynamics, sourcing misalignment