Coleman Weinberg Dynamics Of Dark Matter And Right-Handed Neutrinos

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Caltech

Neutrino Theory Network

BASED ON ARXIV:2306.13799

Motivation

- Embed ultralight Higgs portal DM in extended dark sector.
- Include necessary ingredients for leptogenesis and neutrino masses.
- Interesting new features emerge with seemingly benign ingredients.

Executive Summary

- Focus on radiatively generated parameter space (CW-dynamics).
- Correlation between DM and RHN mass (~few GeV).
- Predictive mass range for DM, $1\ \mu\text{eV} \lesssim m_\phi \lesssim 10\ \text{meV}$.

✓ **PART 1**

BACKGROUND

- Ultralight Higgs portal dark matter.
- Thermal misalignment.

✓ **PART 2**

ADDING RHNS

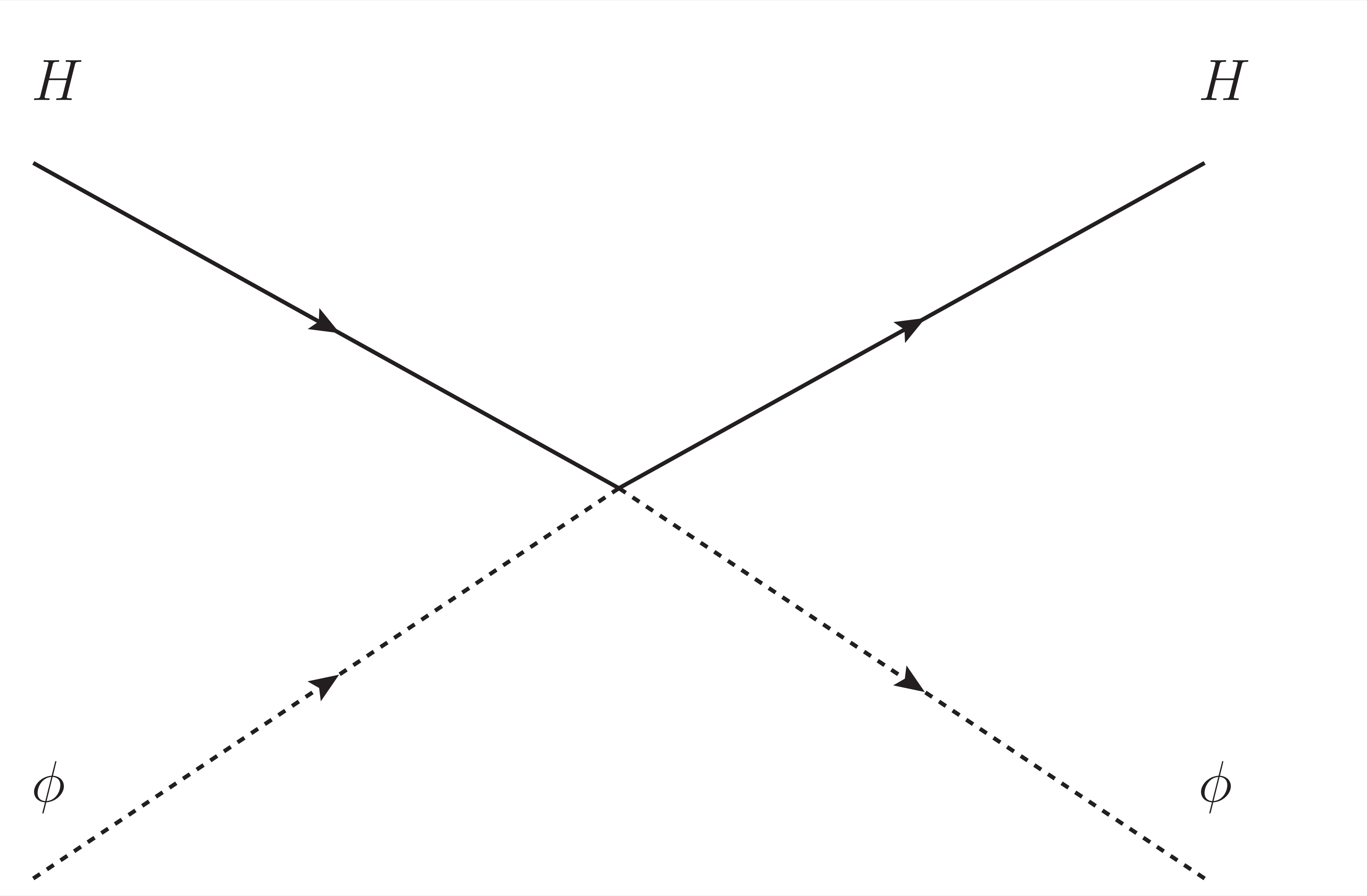
- Interfacing with a neutrino mass mechanism.
- New radiative corrections & scalar dynamics.
- "Predicting" the RHN mass.

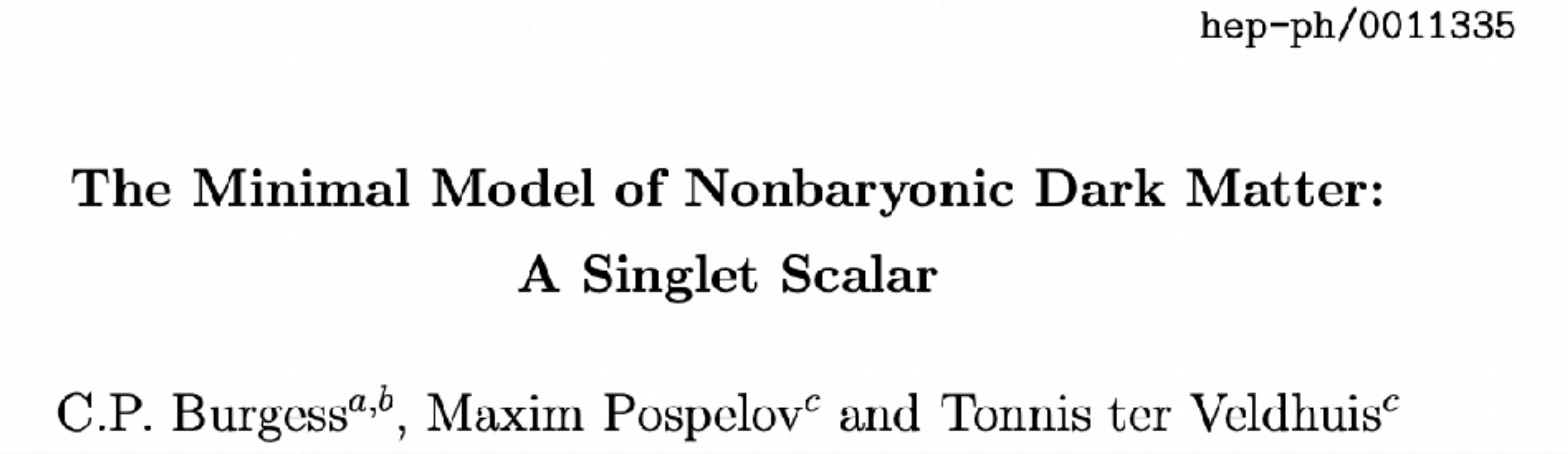
✓ **PART 3**

COSMOLOGY

- Thermal misalignment & dynamics in the early universe.
- Relic abundance prediction.
- Initial conditions and preheating.

Minimal Scalar Dark Matter




hep-ph/0011335

The Minimal Model of Nonbaryonic Dark Matter:
A Singlet Scalar

C.P. Burgess[a,b], Maxim Pospelov[c] and Tonnis ter Veldhuis[c]

$$m_\phi \sim 10 - 100\ \mathrm{GeV}$$

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{\lambda}{4!}\phi^4 + B\phi^2|H|^2 + \mathscr{L}_{\mathrm{SM}}$$

$\mathbb{Z}_2$ SYMMETRY

Ultralight Scalar Dark Matter

FRIEDMAN EQUATION

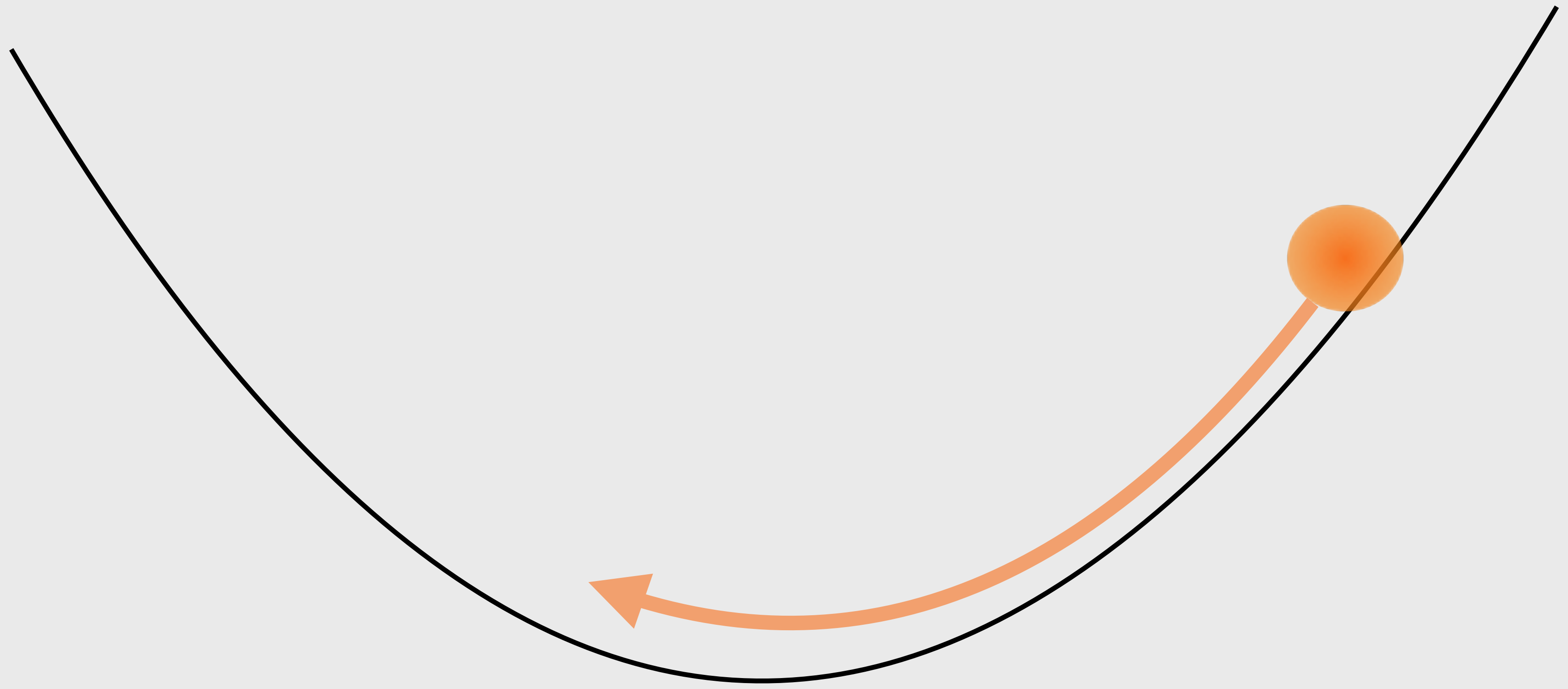
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

INITIAL CONDITIONS

$$\phi(t_0) = \phi_i \quad \dot{\phi}(t_0) = 0$$

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2$$

$$\rho = \frac{1}{2}m_\phi^2\phi^2$$



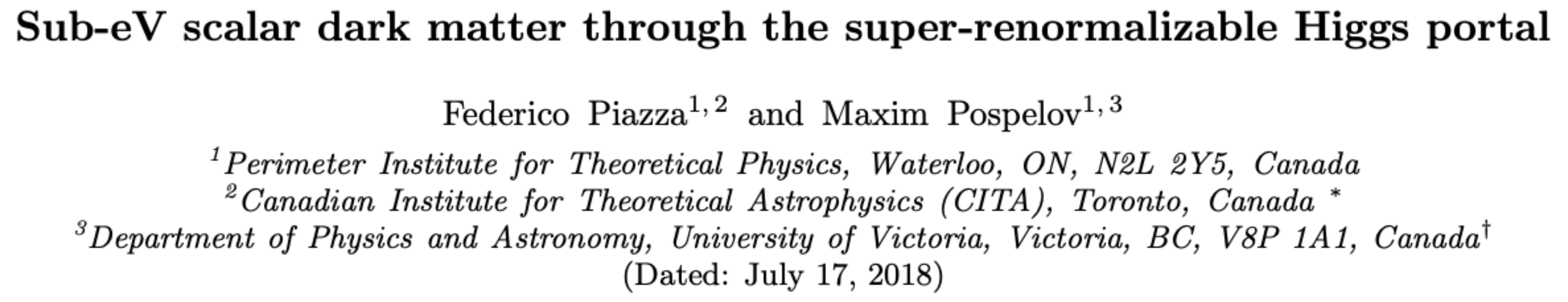
John Preskill, Mark B. Wise, Frank Wilczek (1983)

COMPLETELY SECLUDED

Super-Renormalizable Higgs Portal

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \boxed{A\phi\,|H|^2} + B\phi^2\,|H|^2 + \mathscr{L}_{\mathrm{SM}}$$

NO $\mathbb{Z}_2$ SYMMETRY



Sub-eV scalar dark matter through the super-renormalizable Higgs portal

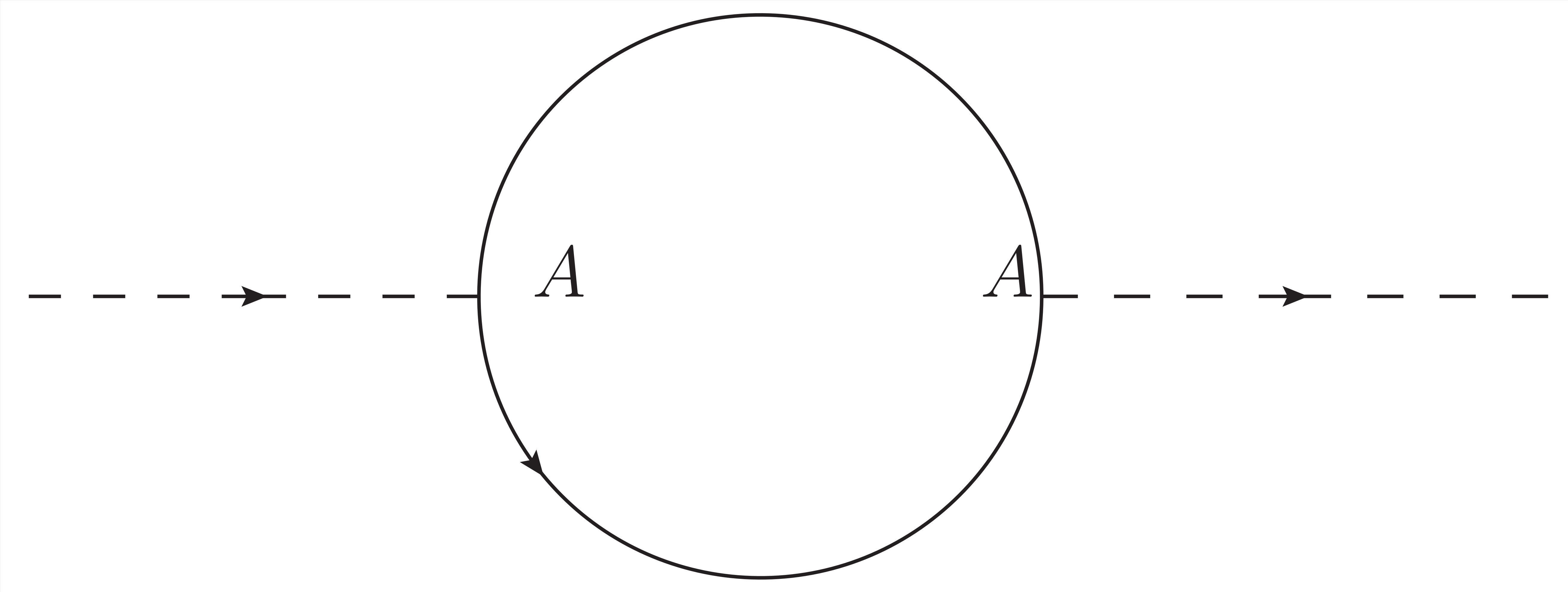
Federico Piazza[1,2] and Maxim Pospelov[1,3]

[1] *Perimeter Institute for Theoretical Physics, Waterloo, ON, N2L 2Y5, Canada*
[2] *Canadian Institute for Theoretical Astrophysics (CITA), Toronto, Canada* *
[3] *Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 1A1, Canada*†
(Dated: July 17, 2018)

Scalar Mass & Fine Tuning

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \boxed{A\phi|H|^2} + \cancel{B\phi^2}|H|^2 + \mathscr{L}_{\mathrm{SM}}$$

NO $\mathbb{Z}_2$ SYMMETRY



$$\delta m_\phi^2 \sim A^2 \times \log(\ldots)$$

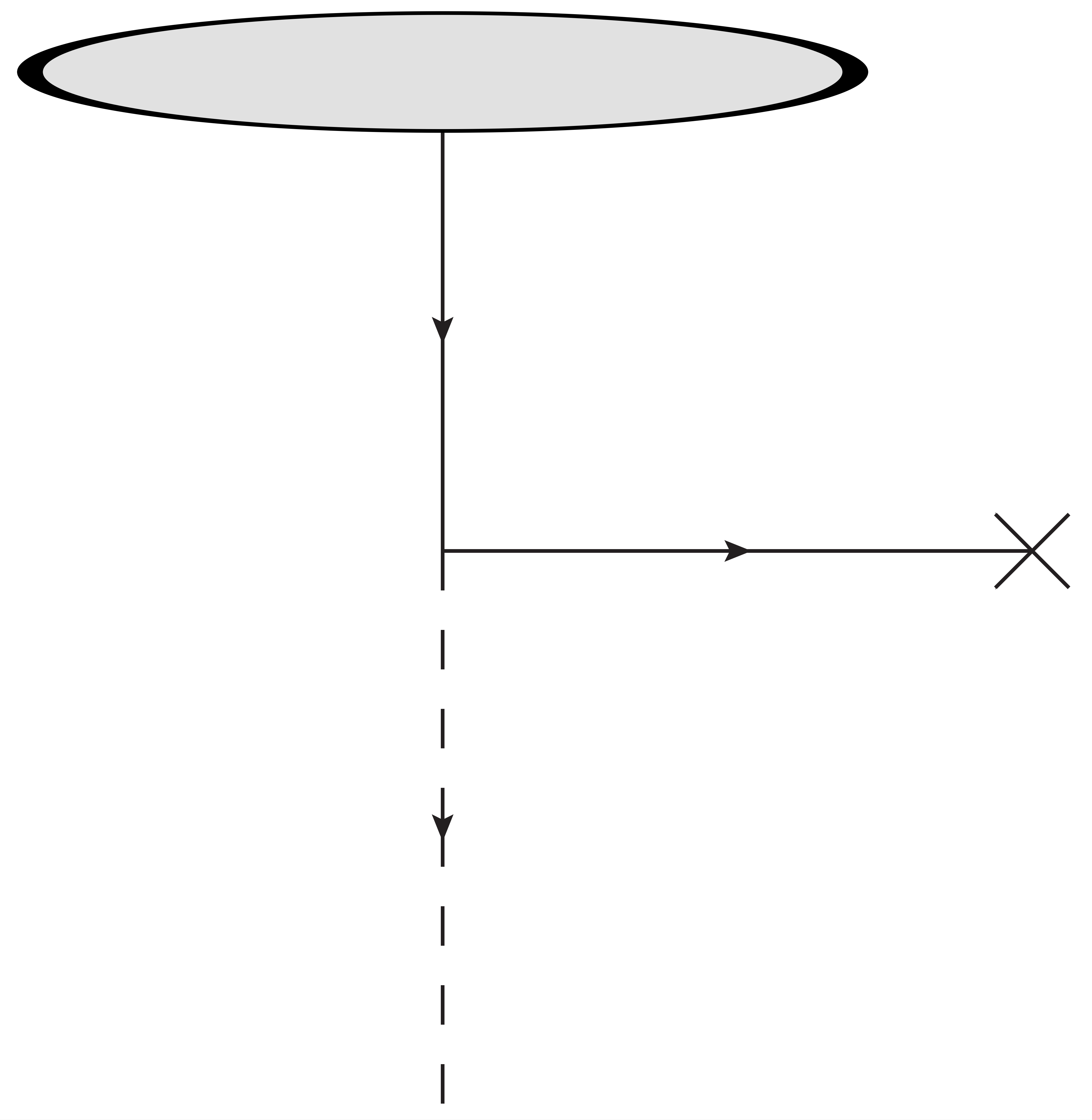
- If $B < m_H^2/m_\phi^2$ then small scalar mass is technically natural within IR theory

Interactions With Matter

- Electroweak symmetry breaking leads to mixing with the Higgs.
- This induces coupling to matter.

$$\mathscr{L}_{\text{int}} = g_{\text{eff}}\ \phi\ \bar{N}N$$

$$g_{\text{eff}} \sim A\,\frac{(500\ \text{MeV})}{m_h^2}$$

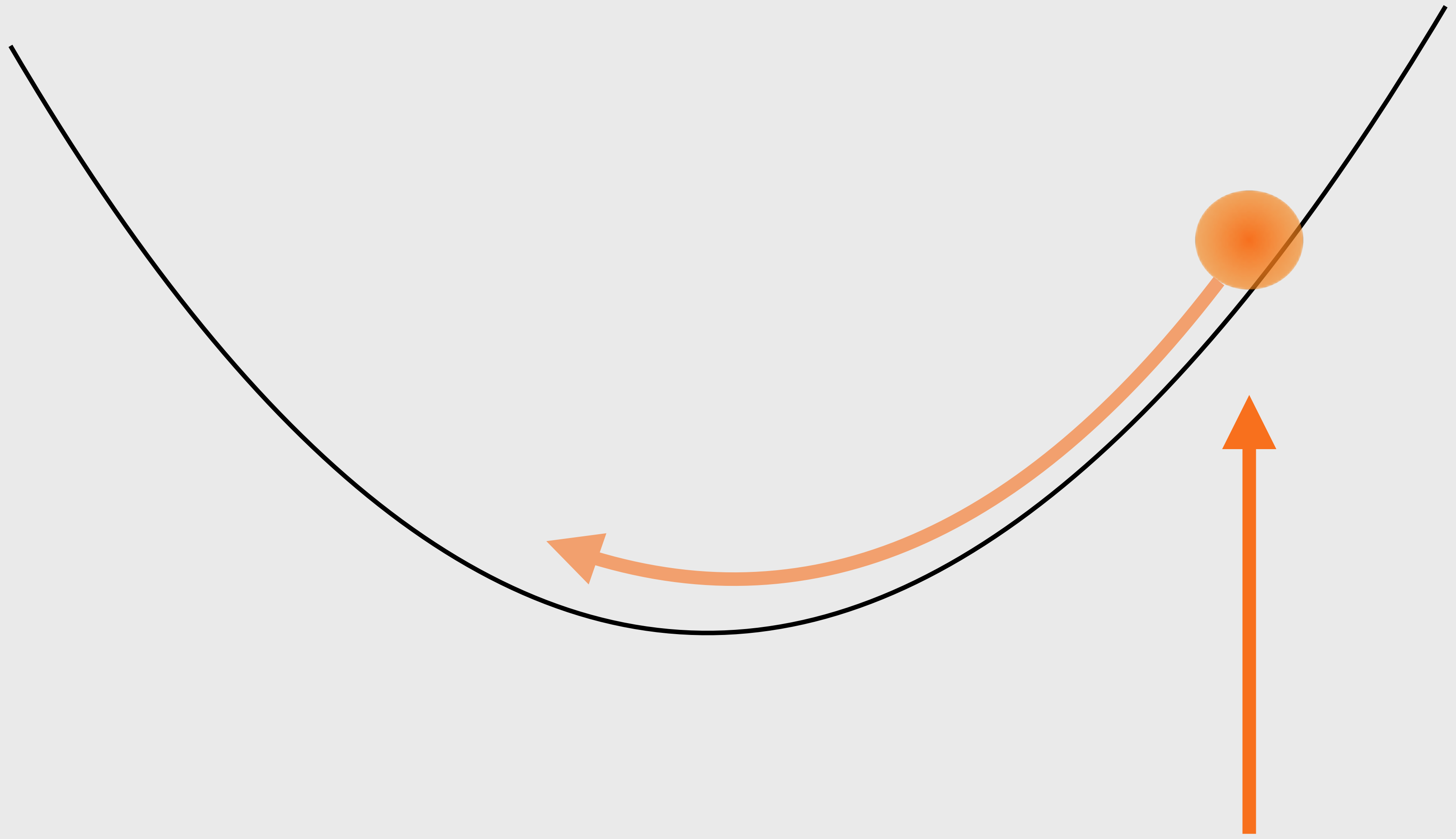


Misalignment & Relic Abundance

$$\rho = \rho_0 \times \left(\frac{T}{T_{\rm osc}}\right)^3 \frac{g_*(T)}{g_*(T_{\rm osc})}$$

SET BY INITIAL CONDITIONS

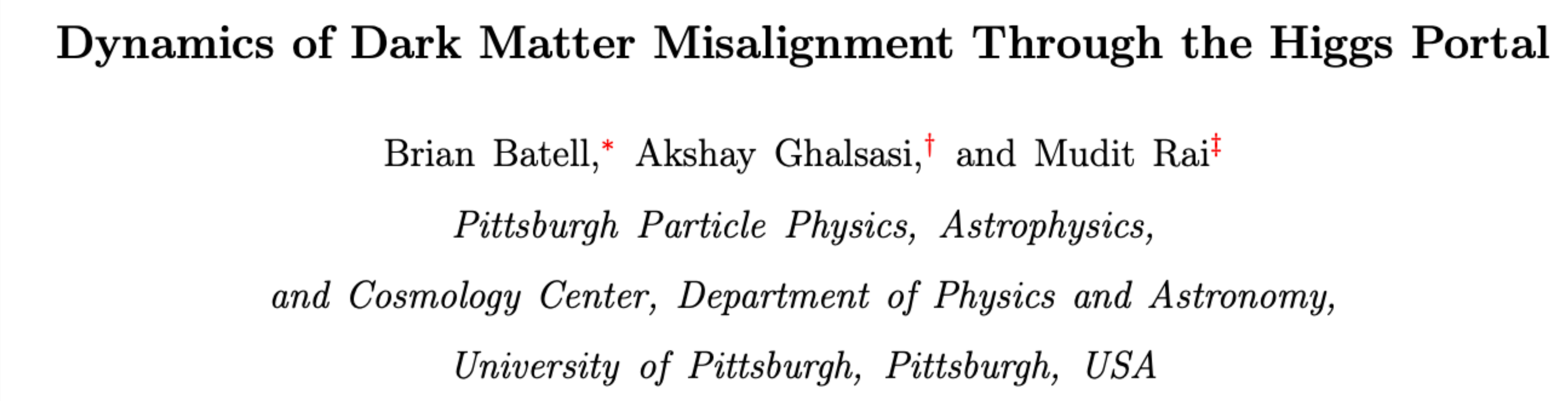
$$\rho = \frac{1}{2}m_\phi^2\phi^2$$



$$3H(T_{\rm osc}) = m_\phi$$

- Mechanism is simple, and entirely secluded.
- Initial conditions leave open questions.

Thermally Driven Misalignment



Dynamics of Dark Matter Misalignment Through the Higgs Portal

Brian Batell,[*] Akshay Ghalsasi,[†] and Mudit Rai[‡]

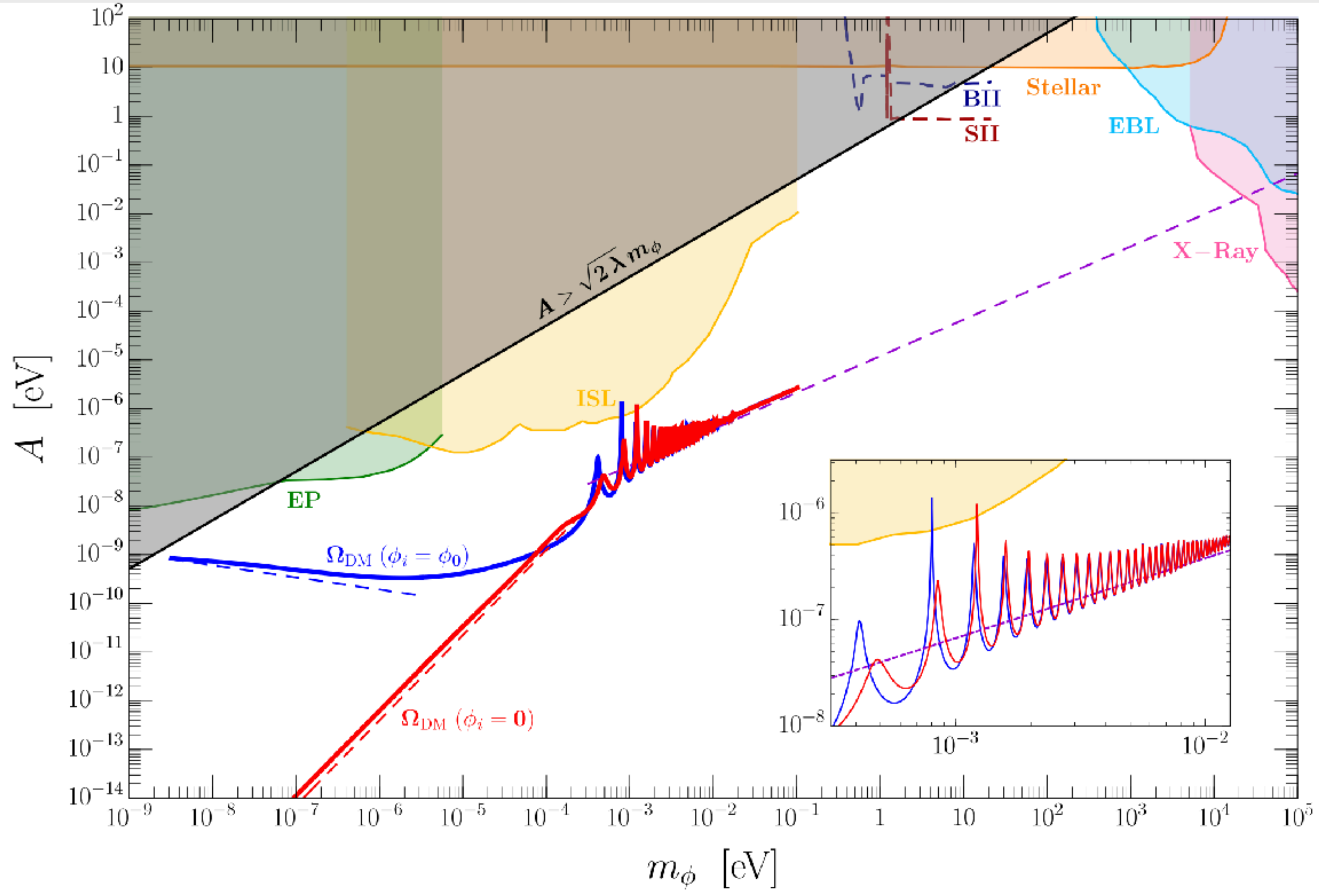
Pittsburgh Particle Physics, Astrophysics,
and Cosmology Center, Department of Physics and Astronomy,
University of Pittsburgh, Pittsburgh, USA

$$V_{\mathrm{eff}}(\varphi, T) \sim A\ T^2\ \varphi \qquad T \gg T_{\mathrm{EW}}$$

- Linear tilt from thermal effects misaligns field to negative values.
- Can supply necessary misalignment for dark matter.

Thermally Driven Misalignment

- Relic abundance is predictable in terms of (A, m_ϕ).
- Relies on small initial field fluctuations.
- Can be translated into low inflationary scale.



☑ **PART 1**

BACKGROUND

- Ultralight Higgs portal dark matter.
- Thermal misalignment.

☑ **PART 2**

ADDING RHNS

- Interfacing with a neutrino mass mechanism.
- New radiative corrections & scalar dynamics.
- "Predicting" the RHN mass.

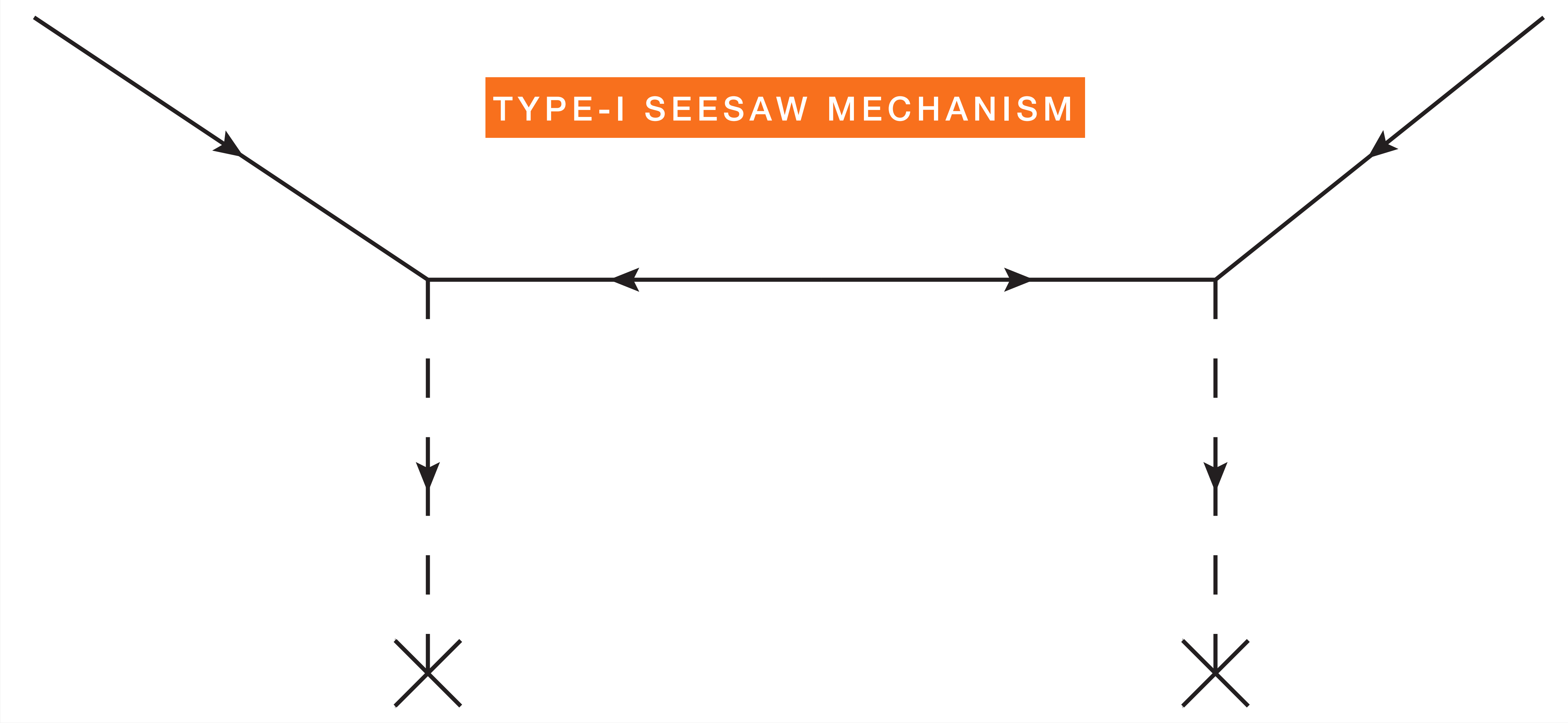
☑ **PART 3**

COSMOLOGY

- Thermal misalignment & dynamics in the early universe.
- Relic abundance prediction.
- Initial conditions and preheating.

Including A Neutrino Mass Mechanism

- Gauge singlets in neutrino mass models will couple to ϕ.
- Lets consider the simplest option and add a family of right-handed neutrinos.



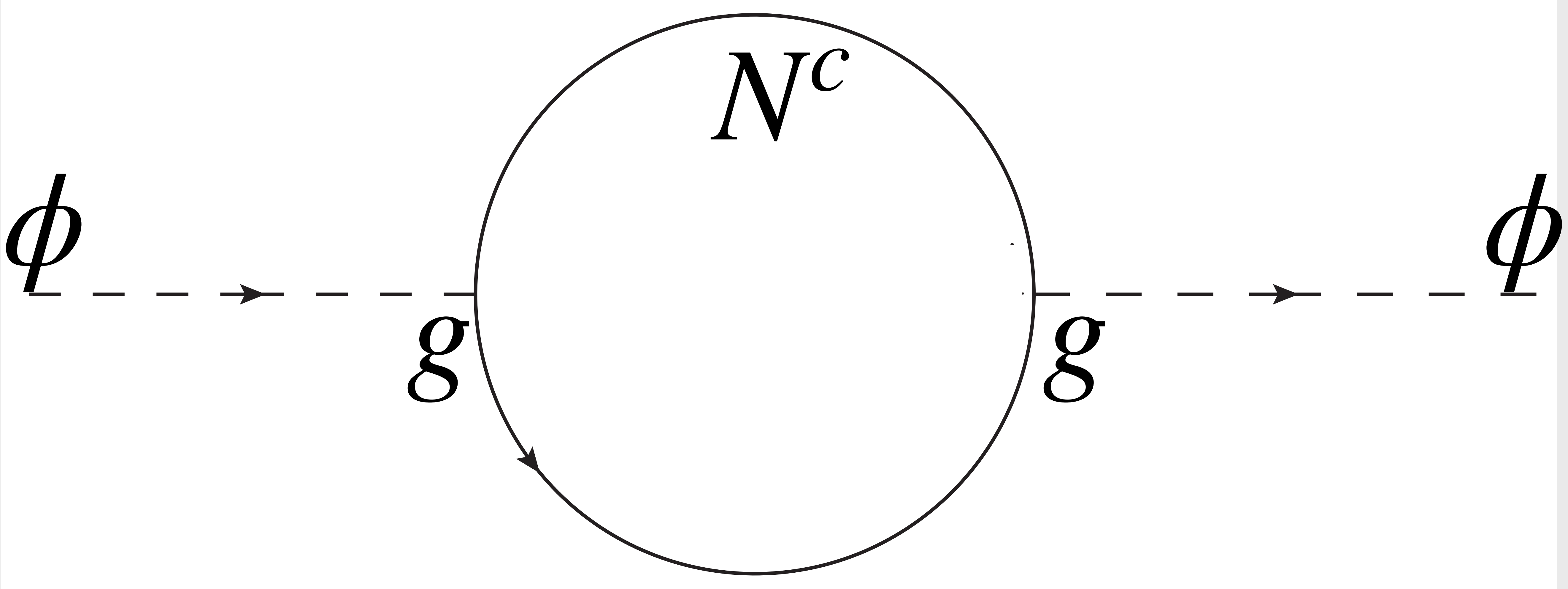
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \overline{N}^c \sigma_\mu \partial^\mu N^c - \tfrac{1}{2} M_{ij} N_i^c N_j^c - \tfrac{1}{2} g_{ij} \phi N_i^c N_j^c$$
$$- Y_{ij} \tilde{H} L N^c - A\phi |H|^2 - \tfrac{1}{2} B\phi^2 |H|^2 \; + \; \text{h.c.},$$

$$V(\phi) = \tfrac{1}{2} c_2 \phi^2 + \tfrac{1}{6} c_3 \phi^3 + \tfrac{1}{24} c_4 \phi^4$$

Keeping Dark Matter (Ultra)Light

- Right-handed neutrino loops will induce a new correction to the scalar mass

$$\delta m_\phi^2 \sim \frac{1}{16\pi^2} g^2 M_N^2 \times \log(\ldots)$$



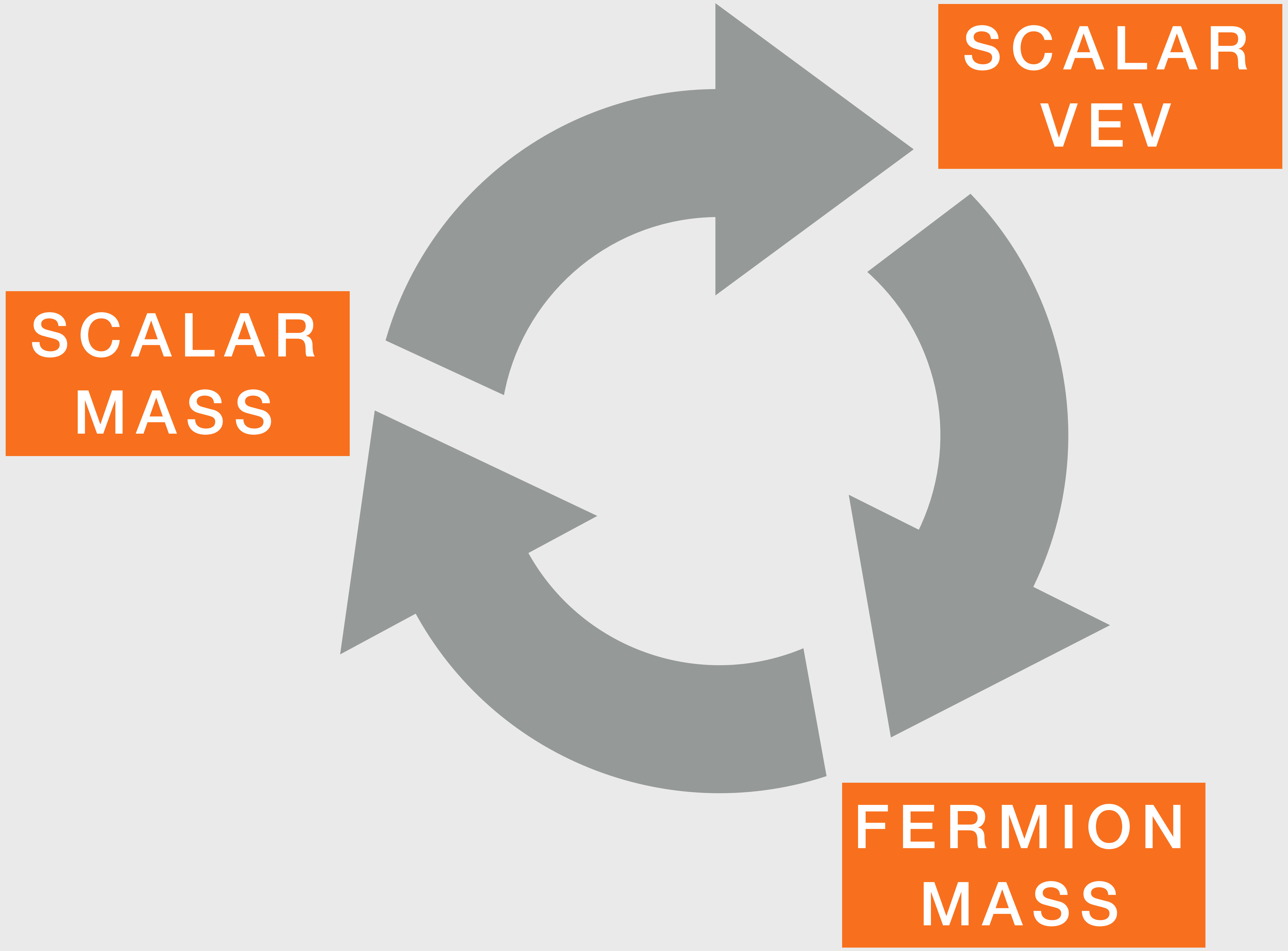
Keeping Dark Matter (Ultra)Light

- A small scalar masses leads to a large scalar vev

$$\langle\phi\rangle \sim A\frac{v_{\mathrm{EW}}^2}{m_\phi^2}$$

- Large vev leads to large RHN masses

$$\delta M_N = g\langle\phi\rangle$$



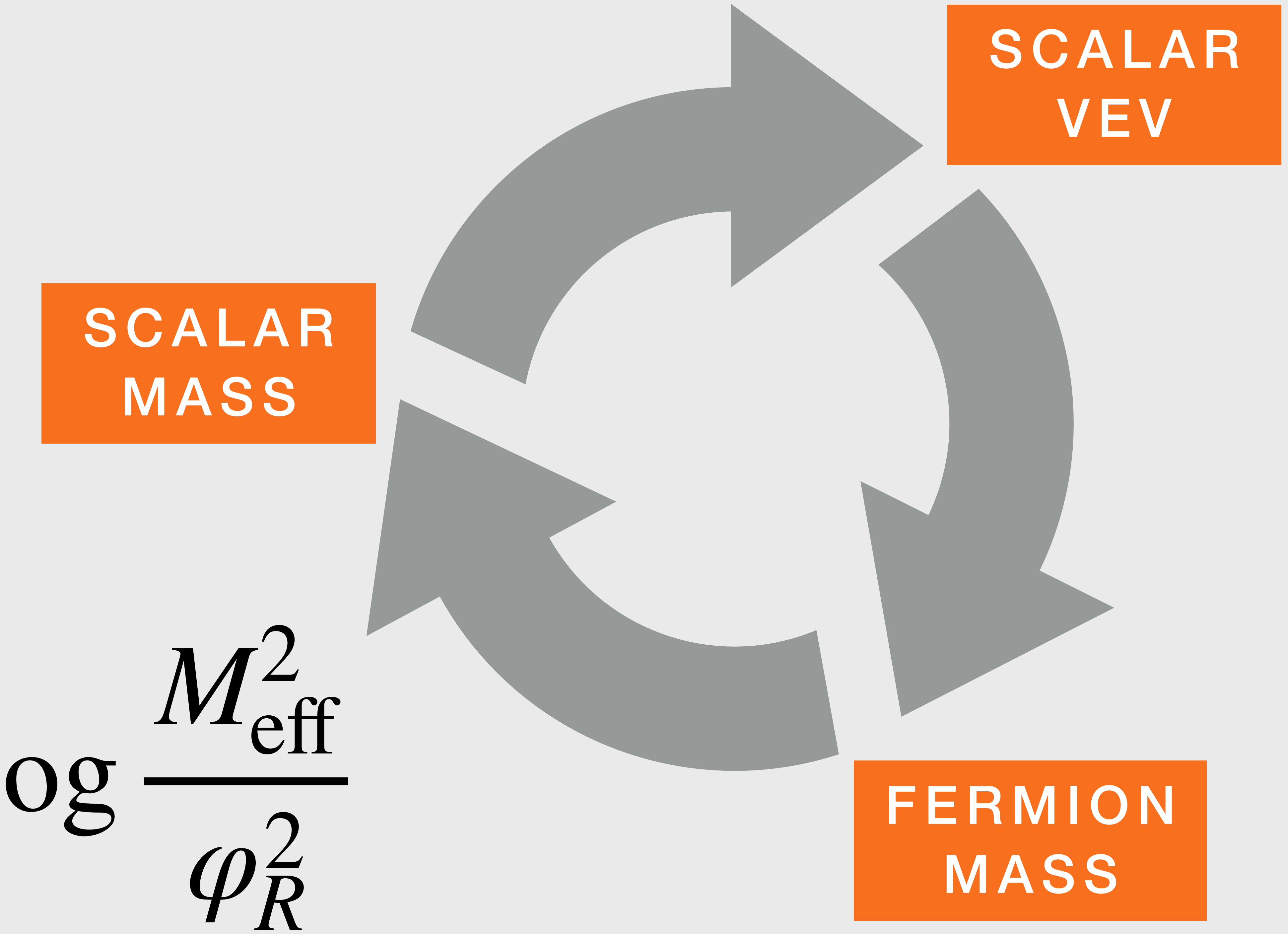
Coleman-Weinberg Dynamics

Coleman-Weinberg Potential

- This has just been a clumsy discussion of scalar dynamics w/ radiative corrections

$$M_{\text{eff}} = M_N + g\langle \phi \rangle$$

$$V_{\text{CW}}(\phi) = V_{\text{tree}}(\phi) + (-1)^S \frac{M_{\text{eff}}^4}{64\pi^2}(2S+1)\ \log \frac{M_{\text{eff}}^2}{\varphi_R^2}$$



- Large corrections from fermion loops show up as a quartic-like potential.

Radiatively Generated Parameters

- It is natural to ask if parameters are "fine-tuned".
- One way to guarantee natural size of parameters is to generate almost all of them radiatively.

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \overline{N}^c\sigma_\mu\partial^\mu N^c - \cancel{\tfrac{1}{2}M_{ij}}N_i^cN_j^c - \tfrac{1}{2}g_{ij}\phi N_i^cN_j^c$$
$$- Y_{ij}\tilde{H}LN^c - A\phi|H|^2 - \cancel{\tfrac{1}{2}\lambda_3}\phi^2|H|^2 \; + \; \text{h.c.},$$

$$V(\phi) = \cancel{\tfrac{1}{2}\mu^2}\phi^2 + \cancel{\tfrac{1}{6}\kappa_3}\phi^3 + \cancel{\tfrac{1}{24}\kappa_4}\phi^4$$

$\mathbb{Z}_4$ IN DARK SECTOR

SOFT BREAKING BY PORTALS

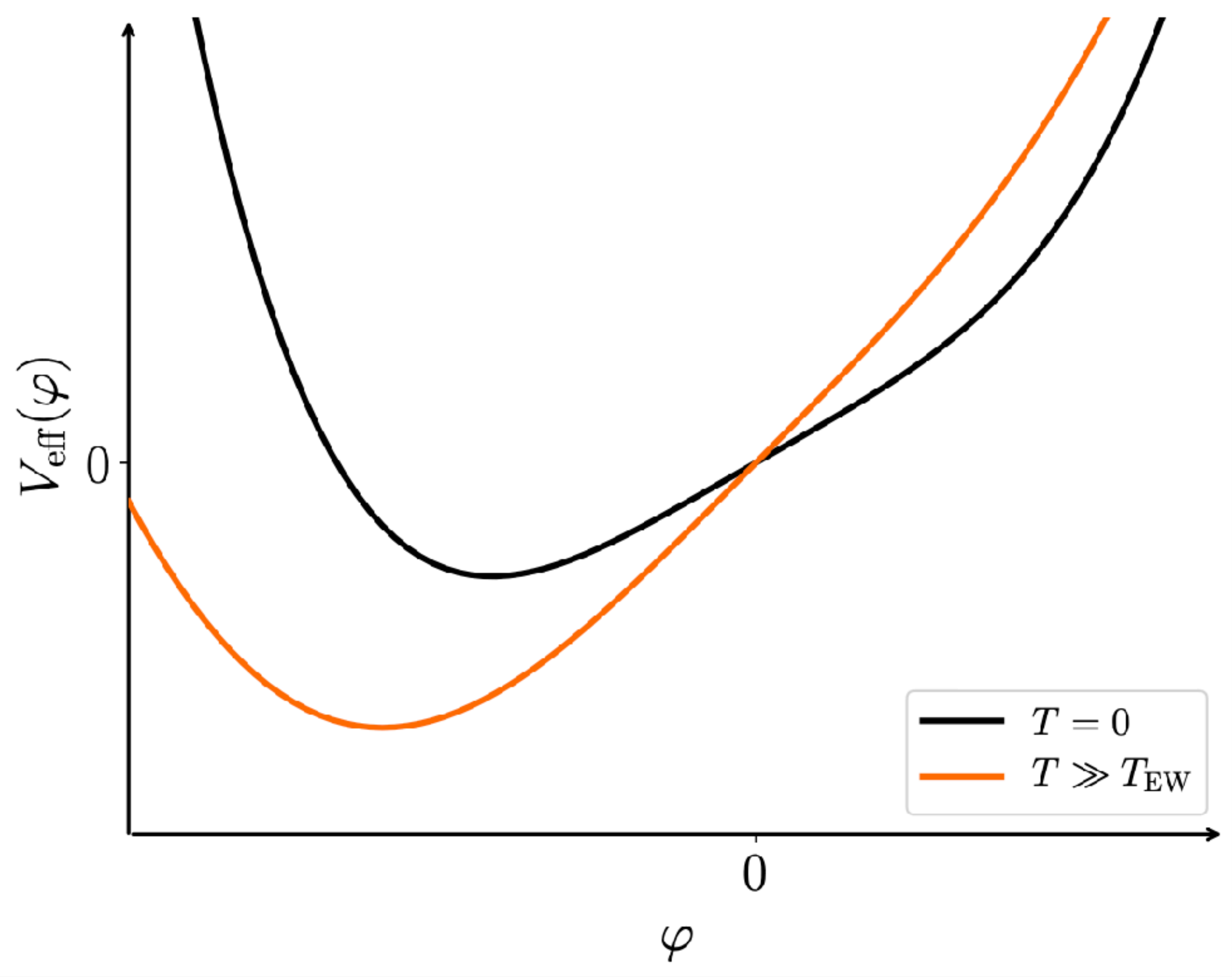
Stabilization Of The Field

$$[V_{\mathrm{CW}}]_{\varphi_0=0} = \Lambda \,,$$

$$[V''_{\mathrm{CW}}]_{\varphi_0=0} = 0 \,,$$

$$[V''''_{\mathrm{CW}}]_{\varphi_0=\varphi_R} = 0 \,,$$

Free Parameters $= (g, A)$



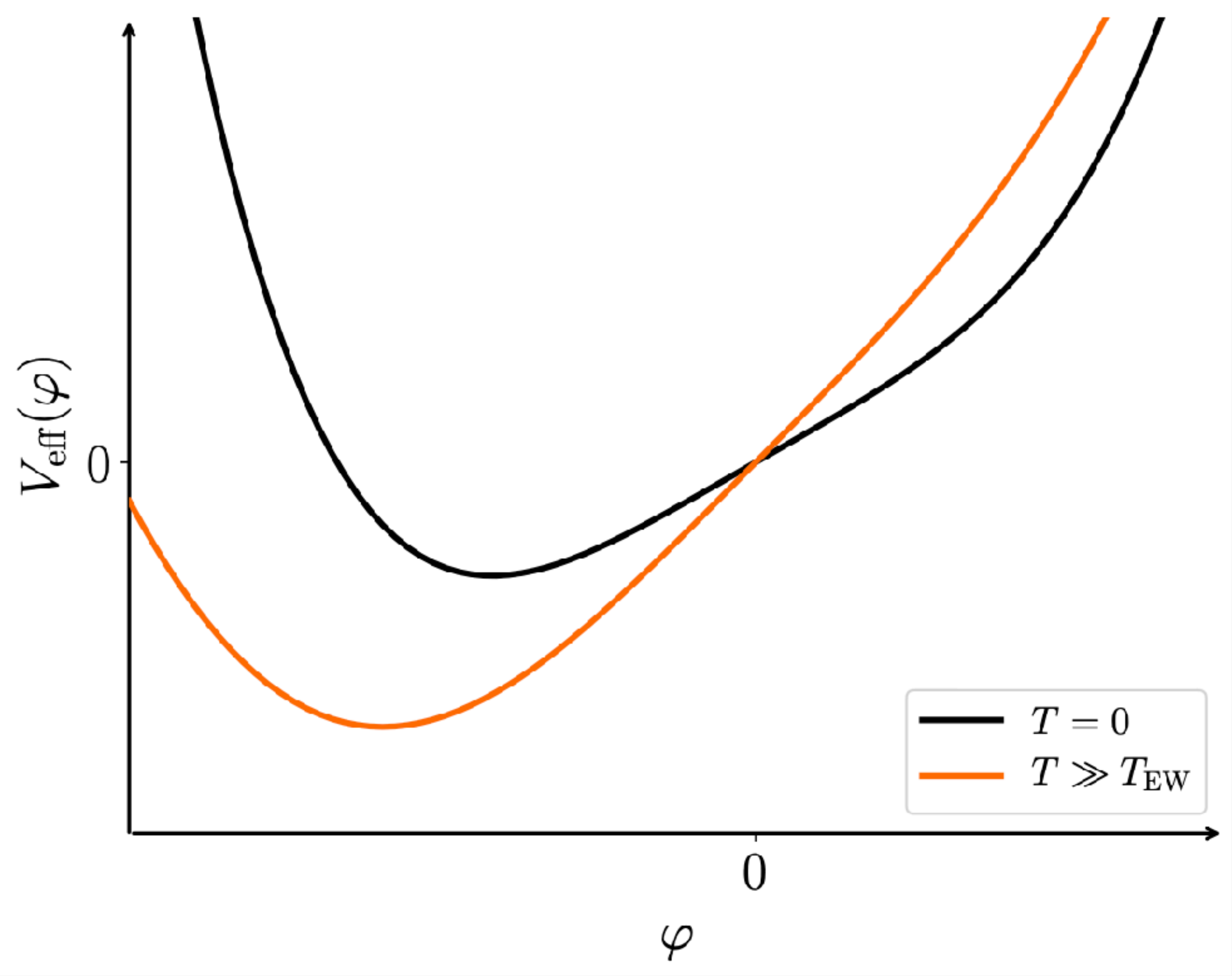
Theory At Zero Temperature

Zero Temperature Dynamics

$$\varphi_0 = -\left(\frac{8\pi^2 A\mathrm{v}^2}{11 g^4}\right)^{1/3}$$

$$m_\phi^2 = \left[V''(\varphi)\right]_{\varphi=\varphi_0} = \frac{27}{2}\left(\frac{A\mathrm{v}^2 g^2}{11\pi}\right)^{2/3}$$

Free Parameters $= (g, A) \leftrightarrow (m_\phi, A)$



FOR THE REST OF THE TALK WE WILL USE (m_ϕ, A)

Right-Handed Neutrino Mass

$$\varphi_0 = \varphi_R = -\frac{27}{11}\frac{A\mathrm{v}^2}{m_\phi^2}$$

$$M_N = g|\varphi_0| = 6^{3/4}\sqrt{\frac{\pi}{11}}\left(\frac{A}{m_\phi}\right)^{1/2} \mathrm{v}$$

$$m_N < \mathrm{v}_{\mathrm{EW}}$$

$$m_N \sim \text{few GeV}$$

WELL SUITED FOR ACCELERATORS

- The RHN mass depends only on the ratio of A/m_N.
- This ratio is always less than one!

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- Relic abundance prediction.
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``Heavy'' Scalars

$$m_\phi \gtrsim 1 \text{ meV}$$

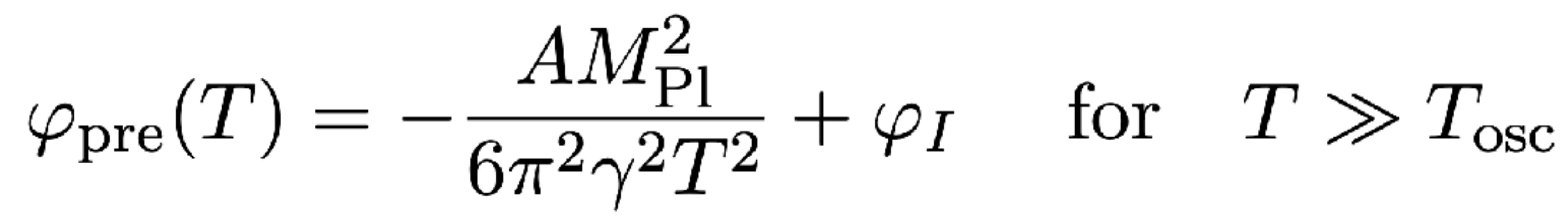
Dynamics At Very Early Times

STANDARD MISALIGNMENT

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

THERMAL MISALIGNMENT

$$\ddot{\varphi} + 3H\dot{\varphi} + \partial_\varphi V_{\rm CW} = -\frac{AT^2}{\pi^2}$$

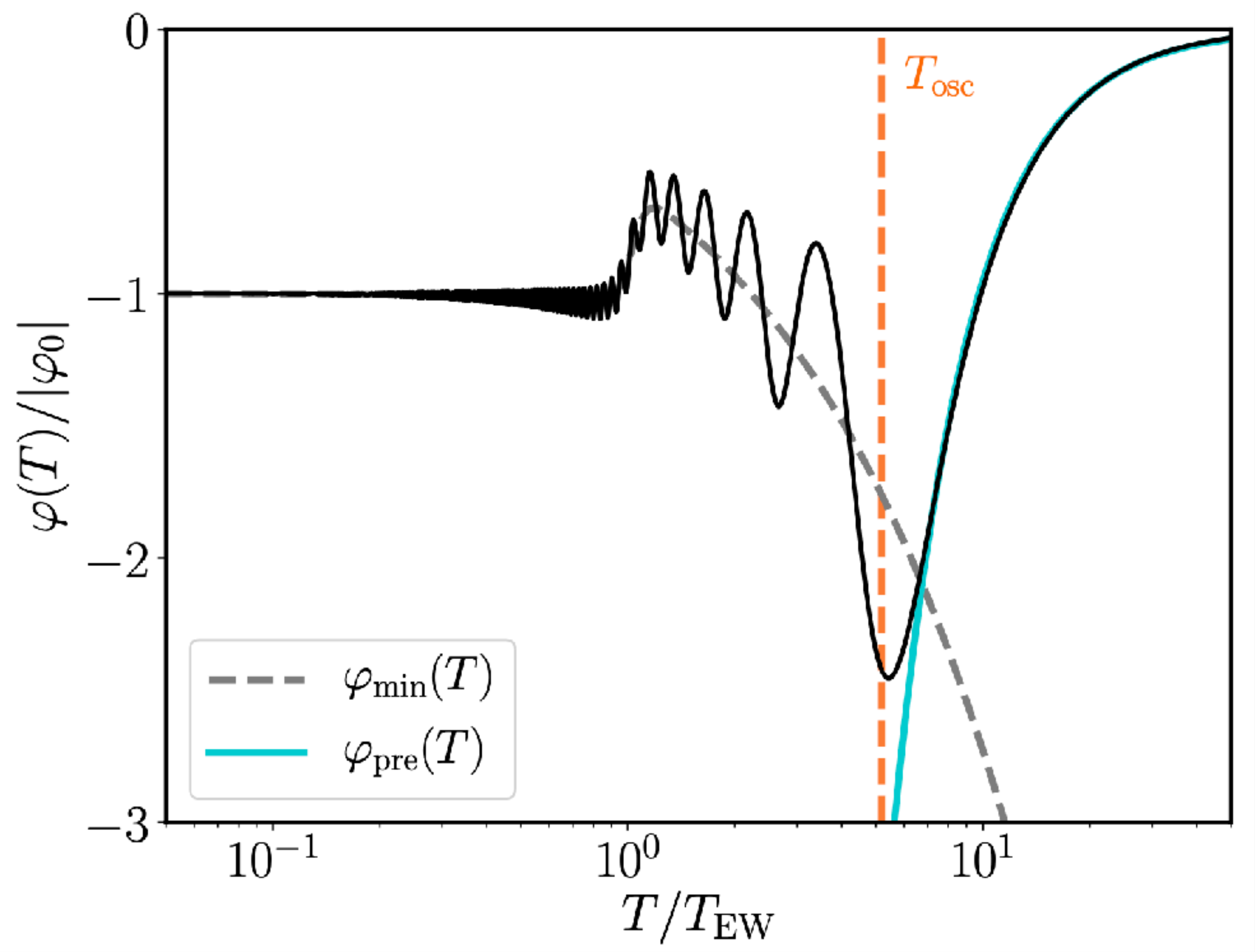


$$\varphi_{\rm pre}(T) = -\frac{AM_{\rm Pl}^2}{6\pi^2\gamma^2T^2} + \varphi_I \quad \text{for} \quad T \gg T_{\rm osc}$$

$$m_{\rm eff}(\varphi) = \partial_\varphi V_{\rm CW}/\varphi \qquad 3H(T_{\rm osc}) = m_{\rm eff}\left(\varphi_{\rm pre}(T_{\rm osc})\right)$$

Onset Of Oscillations

- Oscillation onset is well estimated.
- Oscillations always start close to the minimum of the potential.
- Electroweak phase transition provides quick "jump" in field space.

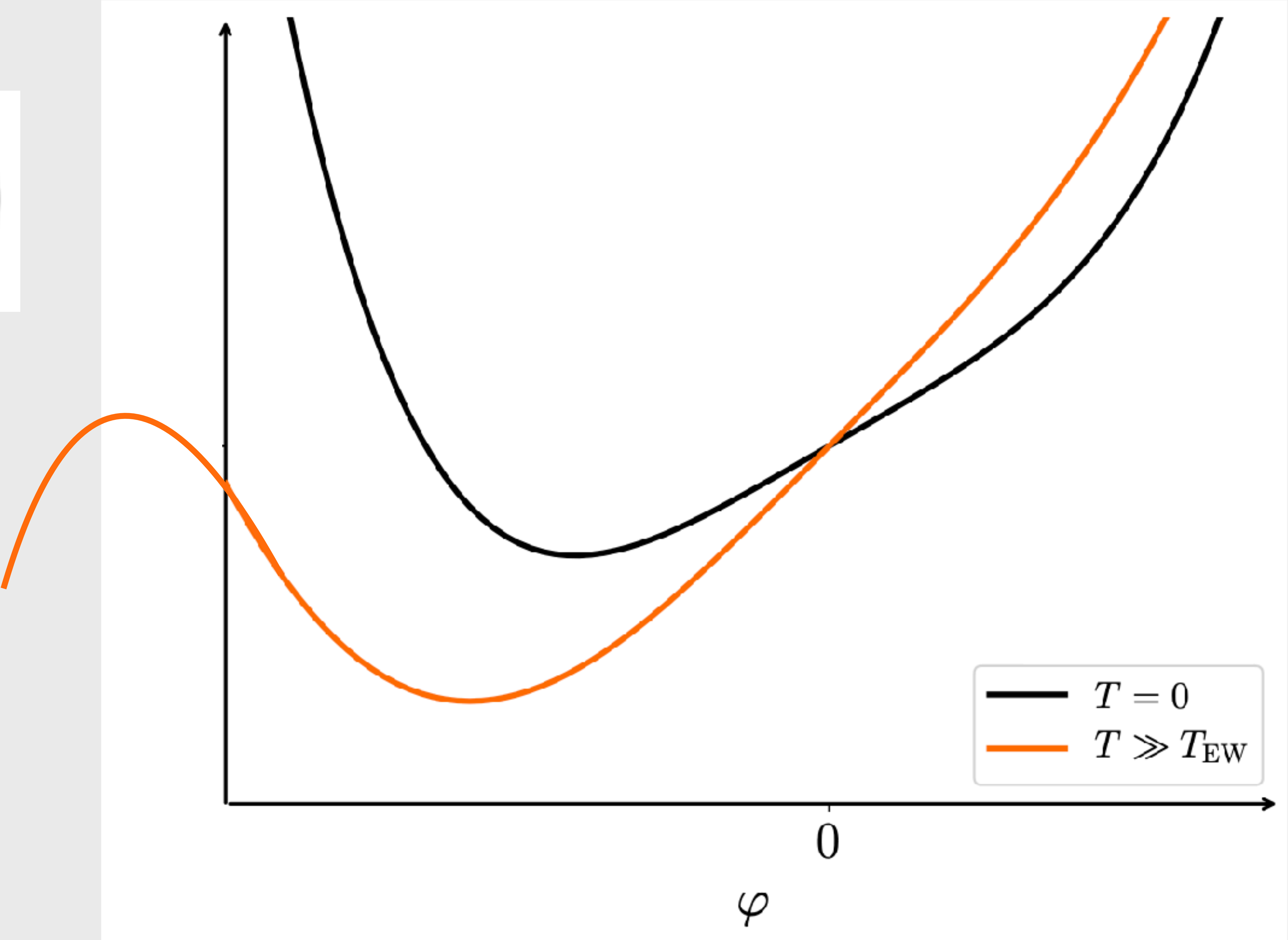


Maximum Dark Matter Mass

$$\varphi_{\rm pre}(T) = -\frac{A M_{\rm Pl}^2}{6\pi^2\gamma^2 T^2} + \varphi_I \qquad \text{for} \quad T \gg T_{\rm osc}$$

$$T_{\rm osc} = \frac{\rm v}{3}\left(\frac{M_{\rm Pl}\, m_\phi}{\gamma {\rm v}^2}\right)^{3/4}\left(\frac{11^{1/4}(11-3\mathsf{L}_{\rm osc})^{1/8}}{3^{5/8}\;2^{1/4}\;\pi^{1/2}}\right)$$

- If $T_{\rm osc}$ is too large CW-log can turn over potential.
- Sets maximum mass for DM.

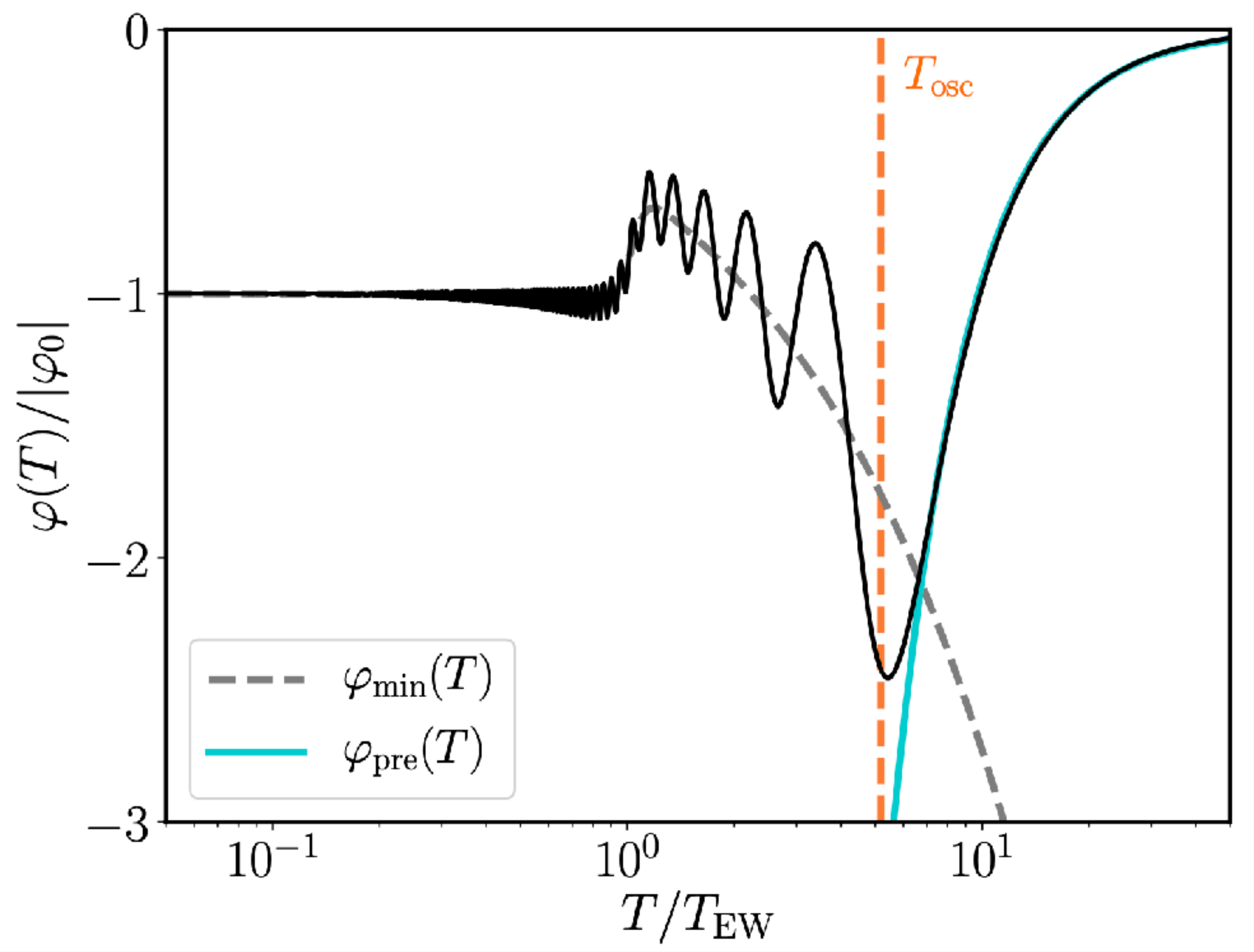


Adiabatic Transport

- We find adiabatic dynamics.
- Stems from scaling of potential minimum.

$$\varphi_{\min}(T) \sim T^{2/3}$$

$$H \sim T^2$$



- Very different than with tree-level mass

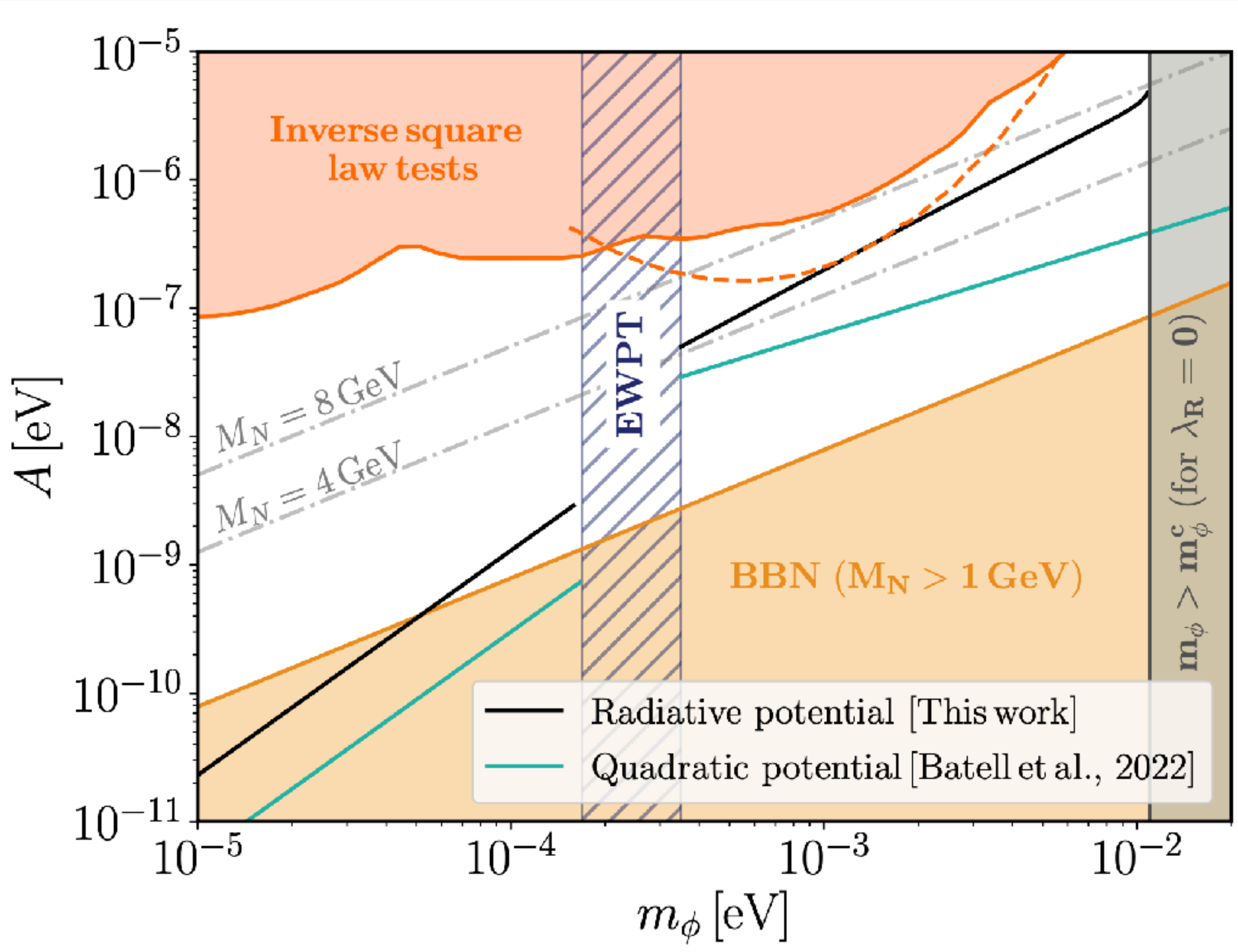
Relic Abundance Estimate

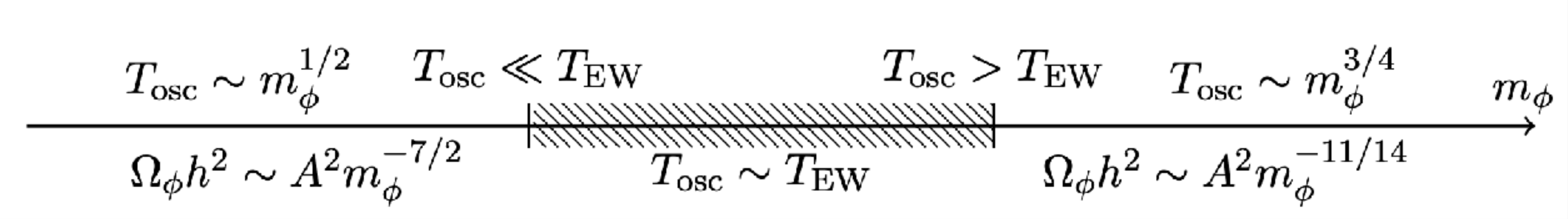
- Dynamics are adiabatic.
- Comoving number density is conserved.

$$\Omega_\phi h^2 = \frac{\rho(T_{\mathrm{osc}})}{\rho_c}\left(\frac{m_\phi}{\mu(T_{\mathrm{osc}})}\right)\left(\frac{T_0}{T_{\mathrm{osc}}}\right)^3 \frac{g_*(T_0)}{g_*(T_{\mathrm{osc}})} = 0.15\left(\frac{A}{1\ \mu\mathrm{eV}}\right)^2\left(\frac{3\ \mathrm{meV}}{m_\phi}\right)^{11/4}$$

- Mass is time-dependent.
- Straightforward estimate of relic density.

- Coleman-Weinberg dynamics fix $M_N(m_\phi, A)$
- Reproducing DM relic abundance predicts $A(m_\phi)$
- At high masses ISL test offer discovery prospects.
- At low mass search for RHNs with accelerators.





$T_{\rm osc} \sim m_\phi^{1/2}$ $T_{\rm osc} \ll T_{\rm EW}$ $T_{\rm osc} > T_{\rm EW}$ $T_{\rm osc} \sim m_\phi^{3/4}$ m_ϕ

$\Omega_\phi h^2 \sim A^2 m_\phi^{-7/2}$ $T_{\rm osc} \sim T_{\rm EW}$ $\Omega_\phi h^2 \sim A^2 m_\phi^{-11/14}$

Summary

Summary

- We considered RHNs and light scalar DM coupled to the SM via the Higgs portal.
- RHNs radiatively "lift" the scalar mass.
- We studied regions of parameter space where the DM mass comes ***only*** radiative corrections.
- Resulting cosmology differs from quadratic case because of non-linearities in the CW-potential.
- Mechanism exists to drive scalar field to origin after inflation.

Backup Slides

``Light'' Scalars

$$m_\phi \lesssim 100\ \mu\text{eV}$$

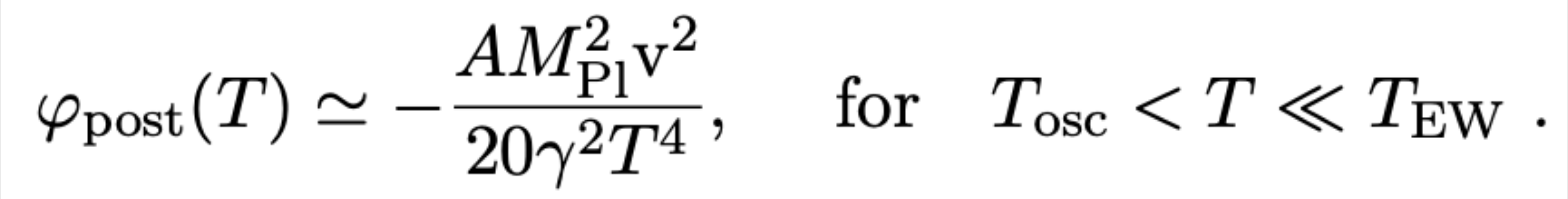
Dynamics Below The Electroweak Scale

STANDAR MISALIGNMENT

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

THERMAL MISALIGNMENT

$$\ddot{\varphi} + 3H\dot{\varphi} + \partial_\varphi V_{\mathrm{CW}} = -Av^2$$



$$\varphi_{\mathrm{post}}(T) \simeq -\frac{AM_{\mathrm{Pl}}^2 \mathrm{v}^2}{20\gamma^2 T^4}, \qquad \text{for} \quad T_{\mathrm{osc}} < T \ll T_{\mathrm{EW}} \,.$$

- After Higgs vev turns on mass is constant and agrees w/ $T = 0$.

$$3H(T_{\mathrm{osc}}) = m_\phi$$

Right-Handed Neutrino Thermalization

- Assuming standard type-I see-saw couplings GeV scale neutrinos thermalize around $T \sim 10\ \mathrm{GeV}$.
- These contribute to the thermal effective potential.
- Thermalization is slow compared to scalar oscillations.
- Adiabatic shift in minimum.

RIGHT-HANDED NEUTRINO THERMALIZATION DOES NOT AFFECT RELIC ABUNDANCE

Relic Abundance Estimate

- Dynamics are adiabatic.
- Comoving number density is conserved.

$$\Omega_\phi h^2 \simeq \frac{\rho(T_{\rm osc})}{\rho_c}\left(\frac{T_0}{T_{\rm osc}}\right)^3 \frac{g_*(T_0)}{g_*(T_{\rm osc})} \simeq 0.1\left(\frac{A}{1\ \rm neV}\right)^2\left(\frac{90\ \mu\rm eV}{m_\phi}\right)^{7/2}$$

- Mass is fixed.
- Straightforward estimate of relic density.

- Coleman-Weinberg dynamics fix $M_N(m_\phi, A)$
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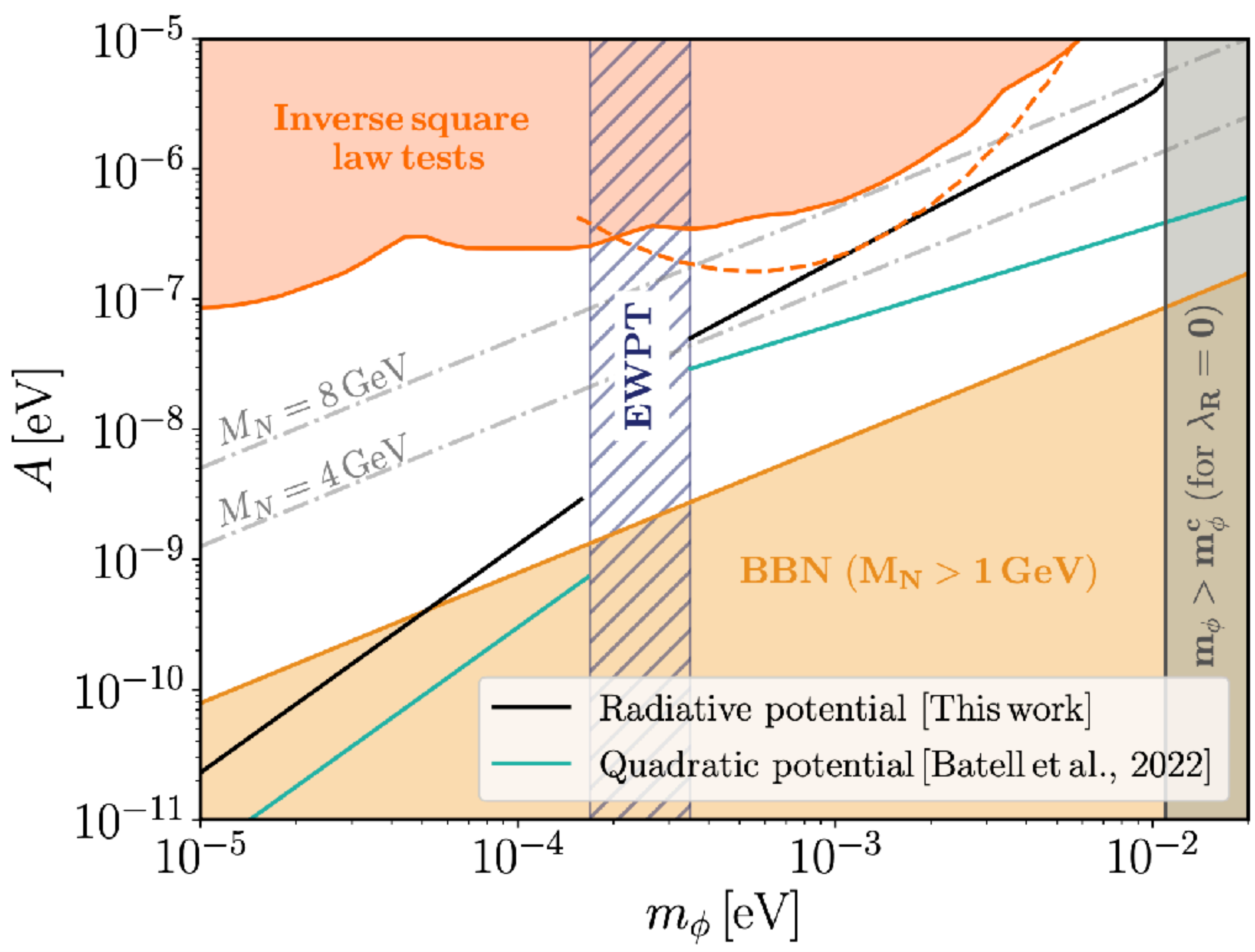
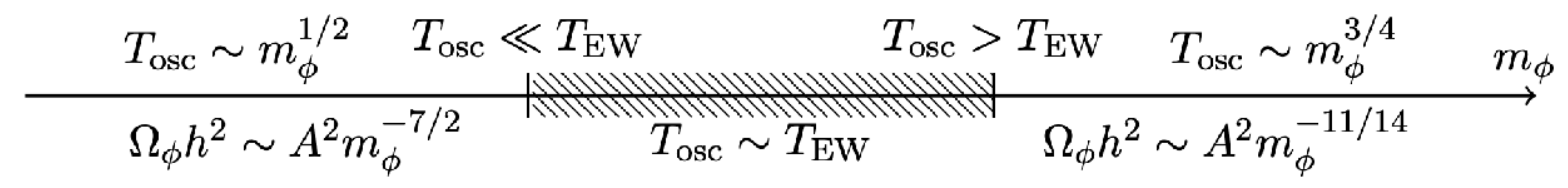
- At high masses ISL test offer discovery prospects.
- At low mass search for RHNs with accelerators.





Speculations About Initial Conditions

Who's Afraid Of Initial Conditions?

- A generic concern with light fields during inflation is that they will get "knocked around".

- If the initial value $\varphi_I \gg \varphi_0$ is too large thermal misalignment cannot erase the initial conditions.

$$\varphi_{\rm pre}(T) = -\frac{AM_{\rm Pl}^2}{6\pi^2\gamma^2T^2} + \varphi_I \quad \text{for} \quad T \gg T_{\rm osc}$$

$$P(\varphi_I) \sim \exp[-V(\varphi_I)/H_I^4] \implies \varphi_I \sim H_I/g$$

BENCHMARK :

$$\varphi_I \sim \delta \times M_{\rm Pl}$$

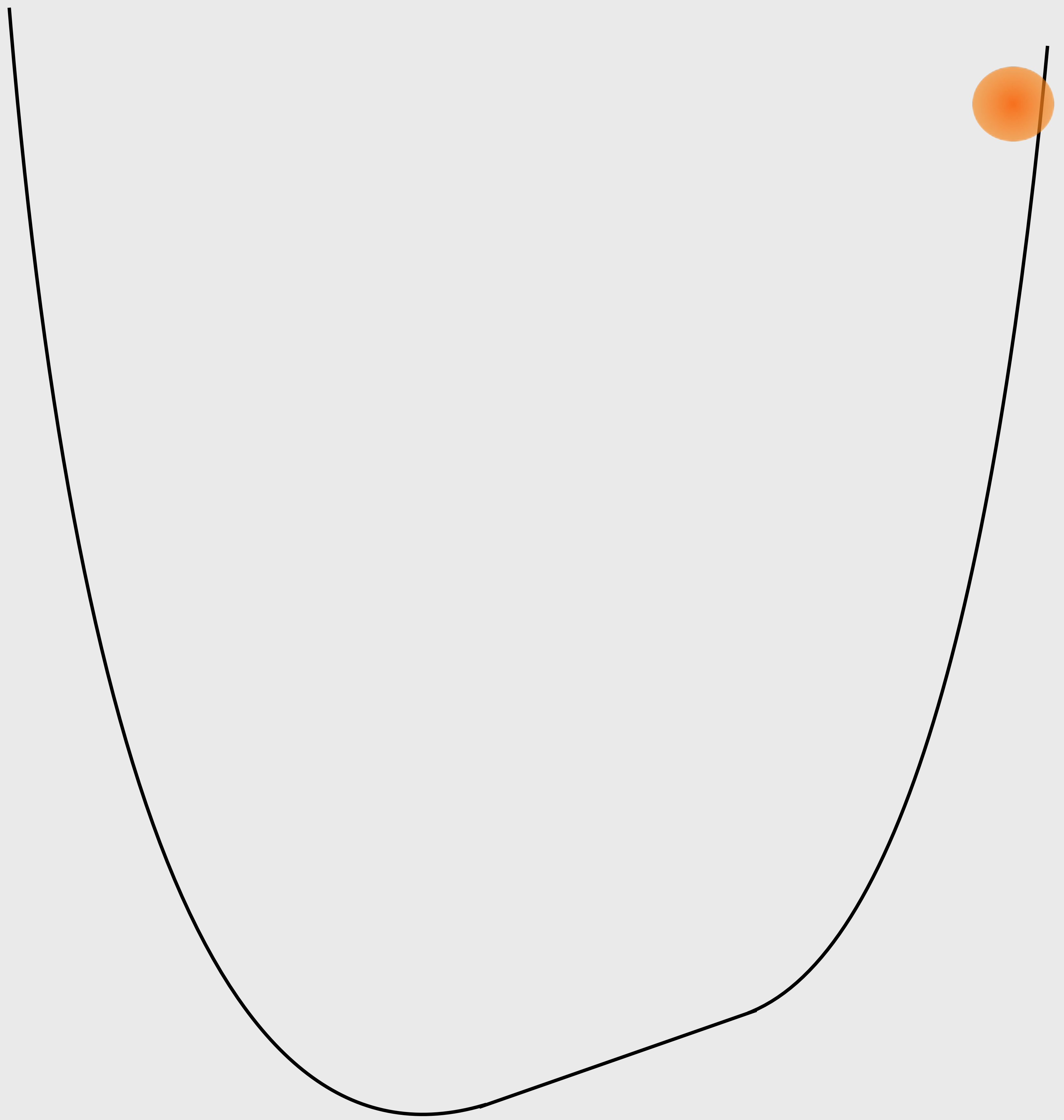
Slipping, Sliding, & Stopping

- What about after inflation ends?

$$m_{\rm eff}^2(\varphi) = \partial_\varphi V_{\rm CW} \big/ \varphi \sim g^2 H_I^2$$

$$H \sim T^2 / M_{\rm Pl}$$

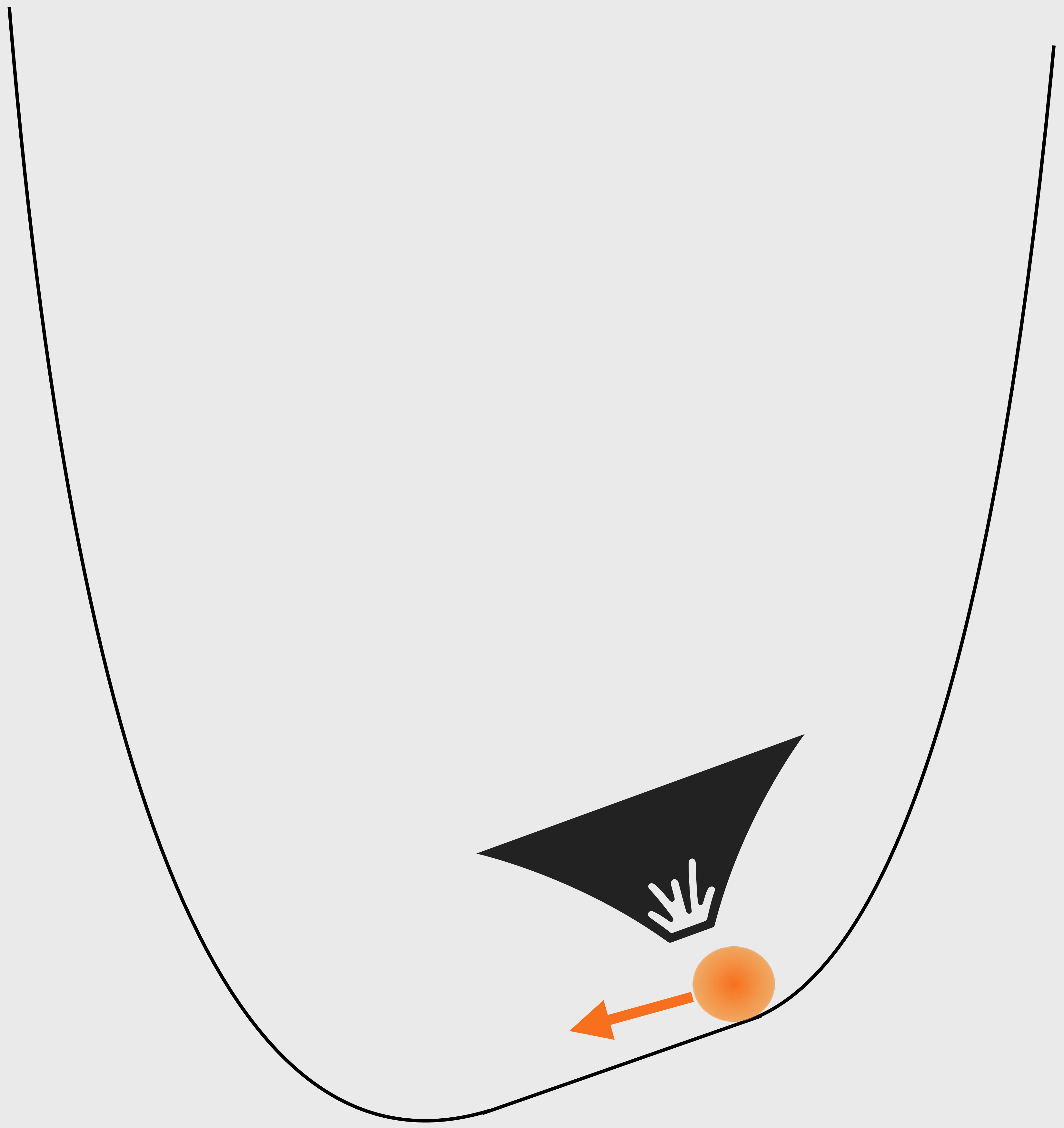
$$T_{\rm slide}^2 \sim g^2 \varphi_I M_{\rm Pl} \sim H_I^2 \times \delta$$



$T_{\rm slide} \ll H_I$

Slipping, Sliding, & Stopping

- Now our field is **flying** past the origin in field space.
- Fermions are very nearly massless here.
- Burst of fermions produced. Effective source of friction/damping.



KOFFMANN, GREENE ARXIV:HEP-PH/0003018

FELDMAN, KOFFMANN, LINDE ARXIV:HEP-PH/9812289

Slipping, Sliding, & Stopping

- The field eventually comes to rest.

- Linear portion of the potential is "special" because it is the most flat.

- Turning points provide the condition

INITIAL CONDITIONS

$$\varphi_I(t_0) = \varphi_i \quad \dot{\varphi}(t_0) = 0$$