Thermal misalignment of Scalar Dark Matter

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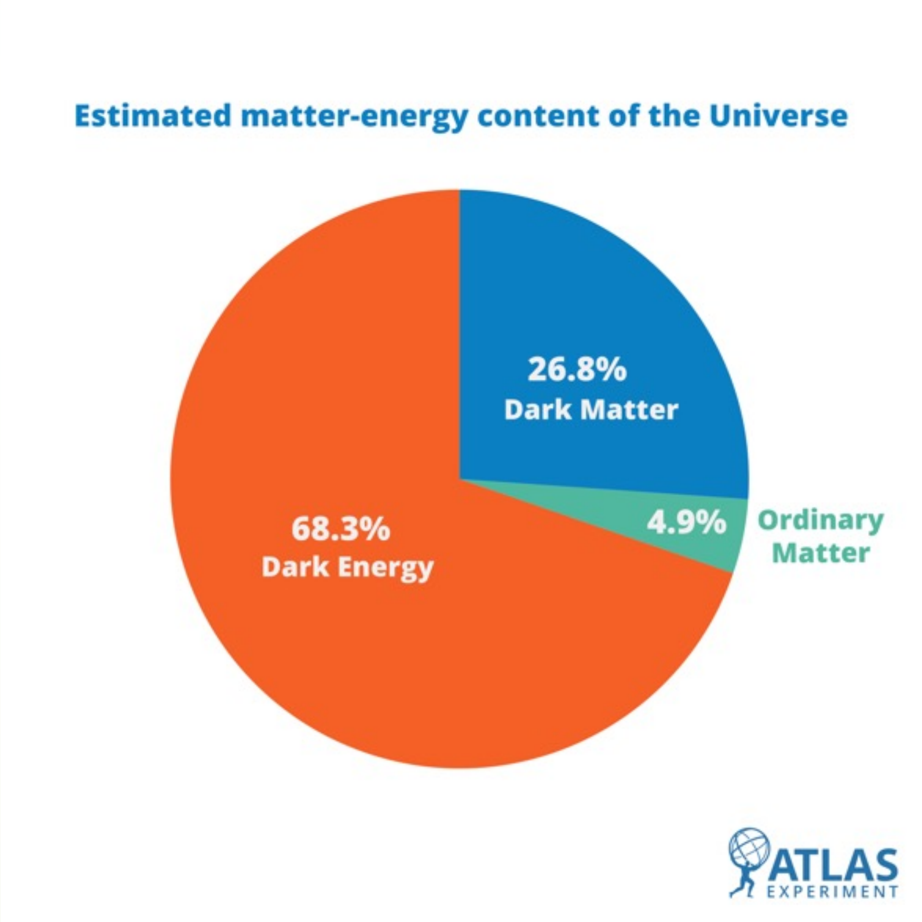
(Work in Progress)

Motivation

- Dark Matter makes up about a quarter of energy content in this universe.



Motivation

- Dark Matter candidates have a large window of possibility, with masses ranging from as light as $10^{-22} eV$ to as heavy as 10 Solar masses.
- In this study, we focus on the Ultra Light Dark Matter scenario, with masses 10^{-22} eV – keV.
- These are generically produced in the early universe through the misalignment mechanism.
- An important question of the Sensitivity to initial conditions is always relevant in misalignment mechanisms.
- We focus on "thermal misalignment" mechanism for our study.

Brian Batell and Akshay Ghalsasi, 2109.04476 [hep-ph]

Thermal Misalignment mechanism

- In a conventional misalignment mechanism, the late time oscillation amplitude and resulting abundance depends on the initial field value.
- We will describe a simple mechanism to dynamically generate large scalar DM misalignment starting from fairly generic initial conditions.
- The mechanism relies on a coupling of the scalar dark matter to a Higgs(scalar d.o.f) field in thermal equilibrium and the resulting finite temperature potential.

Model

- Light scalar ϕ with small coupling to Higgs(S) in thermal bath:

$$V(\phi, S) = \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_S^2(1 - \frac{\beta\phi}{M_{pl}})S^2 + \frac{\lambda}{4}S^4$$

- The mass eigenvalues are :

$$m_\pm^2(\phi, S) = \frac{-m_S^2\left(1 - \frac{\beta\phi}{M_{pl}}\right) + 3\lambda S^2 + m_\phi^2 \pm \sqrt{\left(-m_S^2\left(1 - \frac{\beta\phi}{M_{pl}}\right) + 3\lambda S^2 - m_\phi^2\right)^2 + 4S^2\beta^2\frac{m_S^4}{M_{pl}^2}}}{2}$$

- Since $\frac{m_S}{M_{pl}} < 1$, one can get an approx. form:

$$m_+^2(\phi, S) \sim m_S^2\left(-1 + \frac{\beta\phi}{M_{pl}} + \frac{3\lambda S^2}{m_S^2}\right)$$

Effective potential

- One needs to consider the effective potential:

$$V_{\text{eff}}(\phi, T) = V_0(\phi) + V_1^0(\phi) + V_1^T(\phi)$$

- The first term is the usual zero temperature potential.
- The second term is the Coleman-Weinberg potential, which is neglected in this study.
- In principle this CW potential can overwhelm the tree level potential for small ULDM masses m and large couplings. We simply restrict to values where the tree-level potential dominates.

Effective Potential : Thermal piece

- The 1-loop finite temperature potential is given by :

$$V_{finite}(\phi, S, T) = \frac{T^4}{2\pi^2} J_B\left[\frac{m_+^2(\phi,\mathrm{S})}{T^2} + \frac{\lambda}{2}\right]$$

- The extra factor of $\lambda/2$ comes from resuming the Hard thermal loops, where the leading contribution involves mass correction at tree level(Full Dressing) $m^2 \rightarrow m^2 + \Pi(\mathrm{T})$, where $\Pi(\mathrm{T}) \sim cT^2 + \cdots$

David Curtin et al, https://arxiv.org/pdf/1612.00466.pdf

Evolution of fields

- The EoM of the two fields are coupled due to the coupling and Temperature dependent potential correction.

- We will do a change of variables:

$$y = \frac{T}{m_s}; \quad \kappa = \frac{m_\phi M_{pl}}{m_S^2}$$

- Also we define dimensionless fields : $S_d = \frac{S}{m_s}, \phi_d = \frac{\phi}{M_{pl}}$

Evolution of Scalar Dark Matter

- EoM for φ :

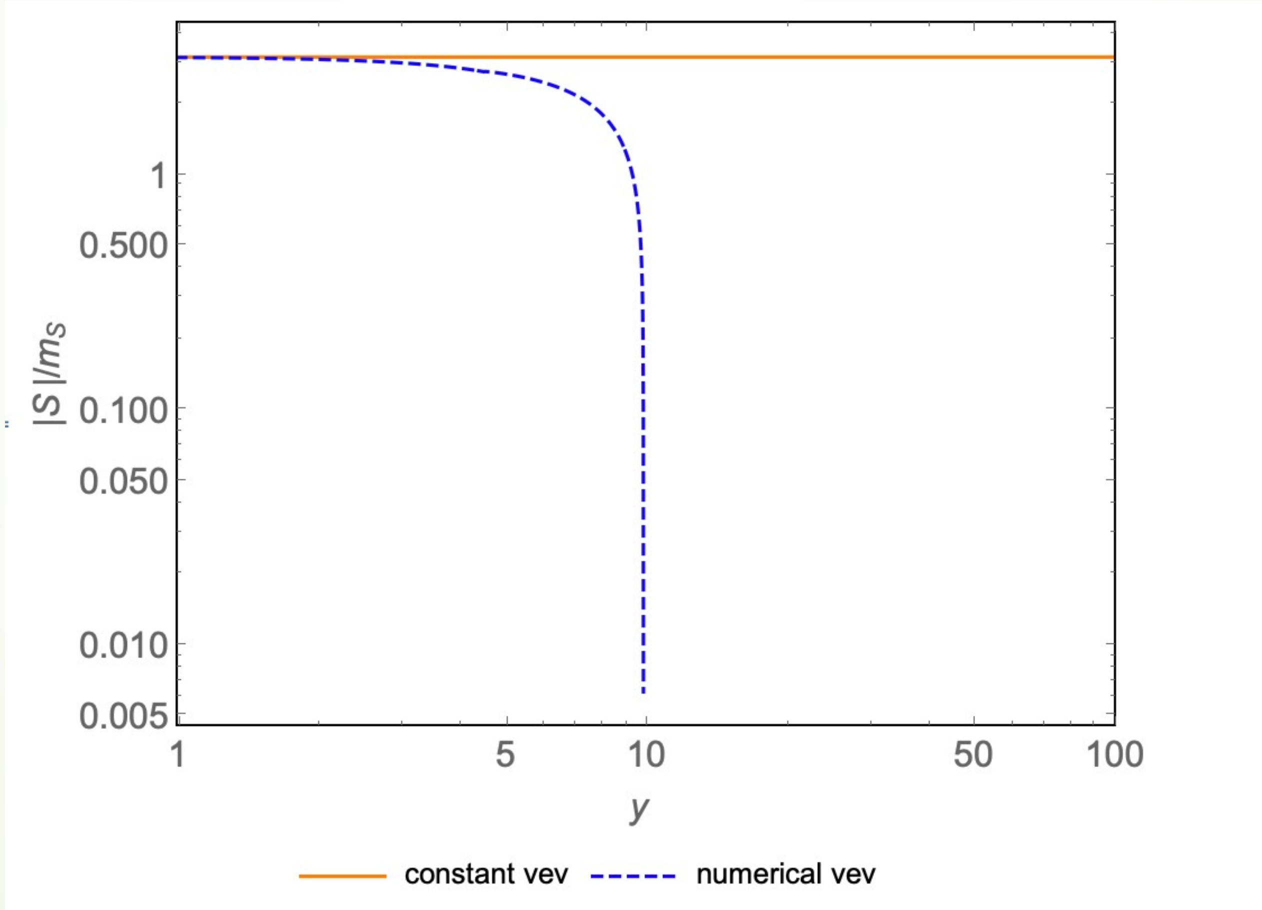
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_{eff}}{\partial \phi} = 0$$

- In terms of dimensionless quantities, this leads to;

$$\frac{d^2\phi_d}{dy^2} + \frac{\kappa^2\phi_d}{\gamma^2 y^6} + \frac{\beta S_d^2}{2\gamma^2 y^6} + \frac{1}{4\pi^2\gamma^2 y^4}\frac{\partial \tilde{m}_+^2}{\partial \phi_d}\int_0^\infty dx\, \frac{x^2}{\xi(y)(e^{\xi(y)} - 1)} = 0$$

$$\xi(y) = \sqrt{x^2 + \frac{\tilde{m}_+^2}{y^2}}$$

Higgs field dynamics



Onset of oscillations

- For oscillations, we have,

$$(3H)^2 \sim m_\phi^2(T)$$

- We will focus on 2 regions, where in both cases:

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

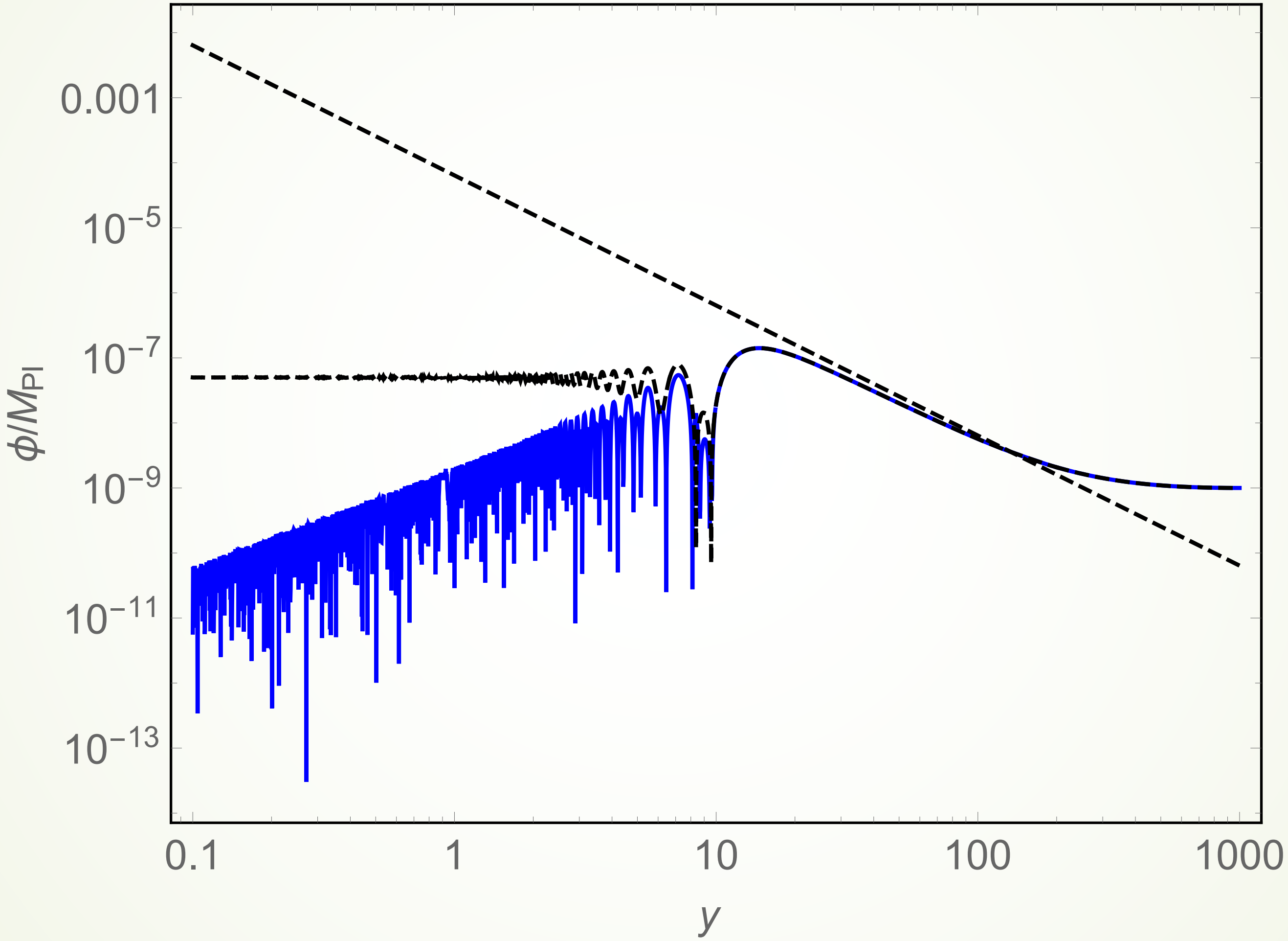
- Region 1 (small β, large κ, high T):

$$\kappa > 3\gamma, \beta < 4\sqrt{\lambda\pi/2}\kappa, y \gg 1$$

- Region 2 (small κ , low T):

$$y_{osc} < 1, \kappa < 3\gamma$$

Evolution of ULDM



For, $\kappa = 10^3, \beta = 10^{-2}$

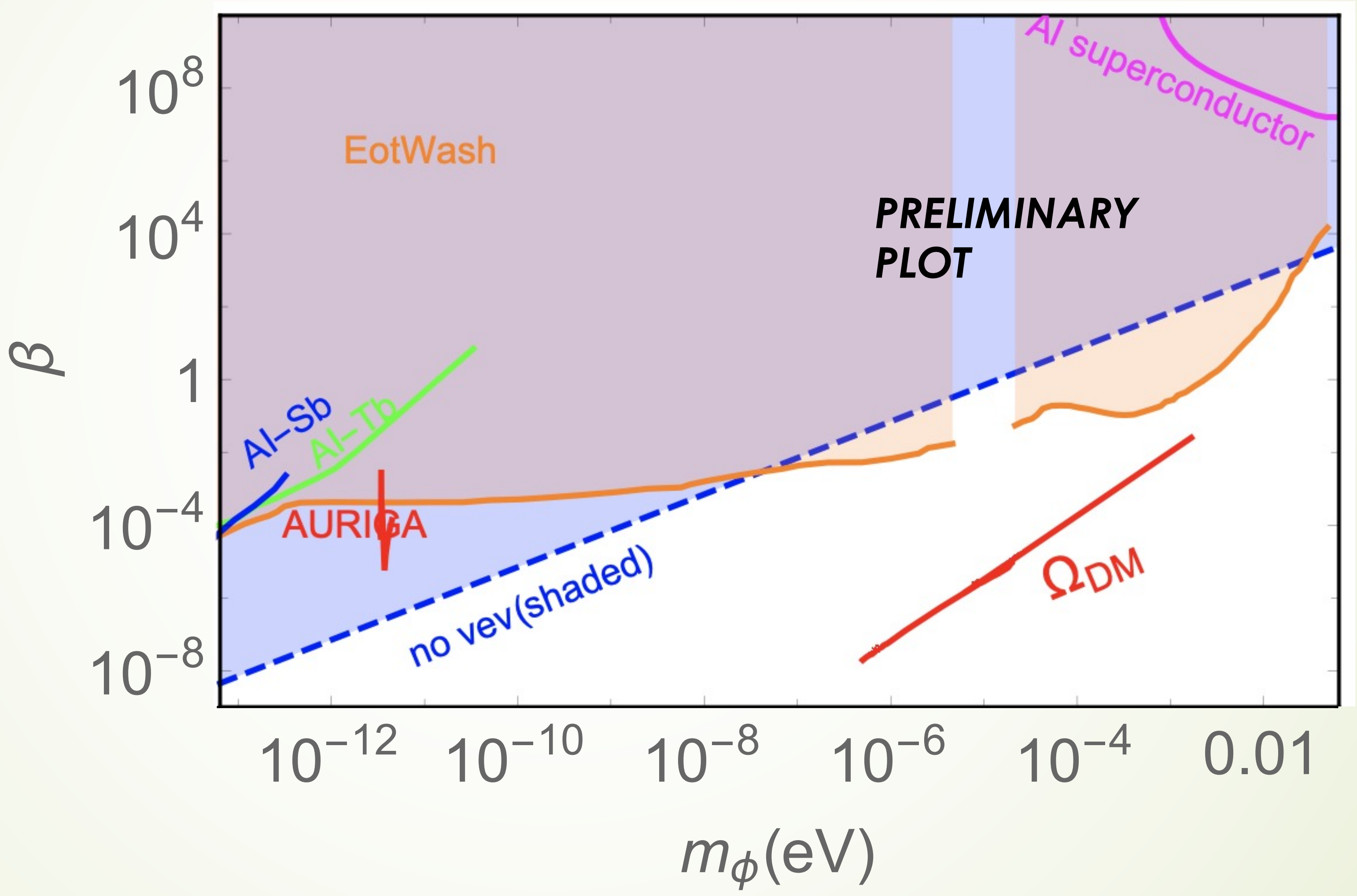
Blue : after subtracting vev
Black : without subtracting vev

Phenomenological Constraints

- Eotwash: In the limit of a very long-range force, bounds are derived from post-Newtonian tests of General Relativity
- AI-TB : a terrestrial experiment operated in broadband mode
- AI-SB : long baseline, broadband, space-based antenna.
- AI-SR : a shorter, resonant satellite antenna
- The potential reach for an analysis on existing AURIGA data, representative of the sensitivity of resonant-mass detectors.
- Al-Superconductor: sensitivity of an Aluminium superconductor target for absorption of scalar relic dark matter.

Arvanitaki et al [https://arxiv.org/pdf/1606.04541.pdf]

Relic Abundance Constraint Plot



Conclusions

- Ultralight scalars in DM models lead to a well-motivated and phenomenologically distinct viable scenarios.
- Focus has been on thermal misalignment — which entails dynamical generation of large misalignment needed to obtain the correct DM relic abundance.
- The mechanism relies on a finite temperature potential due to a coupling of DM to Scalar bath. It is insensitive to initial conditions and the abundance is dictated by the couplings and masses.
- Particularly, we have focused on the phenomenology of a realistic scenario where the DM couples to the Higgs. A variety of opportunities for probing this scenario in the future exist.
- Assuming standard cosmology, constraints from thermal misalignment puts stringent constraints on Higgs-scalar coupling over several order of magnitudes.

THANK YOU!

BACKUP SLIDES

Misalignment mechanism

- During early times (high temperature) the scalar is held up by Hubble friction and remains approximately at its initial field value.
- As the universe cools, the Hubble eventually drops below the scalar mass. This signals the onset of scalar oscillations.
- At late times, the scalar oscillates about its minimum and is also diluted due to Hubble expansion.

Misalignment mechanism

- The energy density redshifts as matter

$$\rho_\phi = \frac{1}{2} m_\phi \left\langle \phi^2(t) \right\rangle \sim a(t)^{-3} \sim t^{-3/2} \sim T^3$$

- The relic abundance at late times will depend on the initial value of field via the oscillation field value:

$$\Omega_\phi\big|_0 = \frac{\rho_{\phi,0}}{\rho_{c,0}} \simeq \frac{\frac{1}{2} m_\phi^2 \phi_{\rm osc}^2 (T_0/T_{\rm osc})^3 (g_{*S}^0/g_{*S}^{\rm osc})}{\rho_{c,0}}$$

Finite temperature potential

- The 1-loop Finite temperature potential involves :

$$J_{\mathrm{B/F}}(y^2) = \int_0^\infty dx\, x^2 \,\log\left[1 \mp \exp(-\sqrt{x^2+y^2})\right]$$

- At high temperature, one can expand it :

$$J_B(y^2) \approx J_B^{\mathrm{high}-T}(y^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}y^2 - \frac{\pi}{6}y^3 - \frac{1}{32}y^4 \log\left(\frac{y^2}{a_b}\right)$$

- At low temperature, one notices that the Finite temperature part is Boltzmann suppressed, thus the analysis reverts to the Tree level potential.

Potential Minimization(late times) : T=0

- Potential minimization at T=0 yields,

$$\phi_{min} = \frac{\beta M_{\rm pl}}{\beta^2 - 2\lambda\kappa^2};\ S_{min} = \pm\sqrt{\frac{-2\kappa^2 m_s^2}{\beta^2 - 2\lambda\kappa^2}};\quad \frac{\beta}{\kappa} < \sqrt{2\lambda};\ V_{min} = \frac{1}{2}\frac{\kappa^2 m_s^4}{\beta^2 - 2\lambda\kappa^2} < 0$$

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

- For $\beta > \sqrt{2\lambda}\kappa$, we do not have a vev(only a saddle point at {0,0}), and this will constraint our parameter space.

Evolution of Higgs field

- EoM for field S :

$$\ddot{S} + 3H\dot{S} + \Gamma\dot{S} + \frac{\partial V_{eff}}{\partial S} = 0$$

- The EoM then becomes, in terms of dimension-less fields

$$\frac{\partial^2 S_d}{\partial y^2} - \frac{\Gamma M_{pl}}{\gamma m_S^2 y^3}\frac{\partial S_d}{\partial y} + \frac{M_{pl}^2}{\gamma^2 y^6 m_s^2}\left(-\left(1-\beta\phi_d\right)S_d + \lambda S_d^3 + \frac{y^2}{4\pi^2}\frac{\partial \tilde{m}_+^2}{\partial S_d}\int_0^\infty dx\,\frac{x^2}{\xi(y)(e^{\xi(y)}-1)}\right) = 0$$

where,

$$\xi(y) = \sqrt{x^2 + \frac{\tilde{m}_+^2}{y^2}}$$

Γ=decay width of Higgs in plasma

High Temperature trajectory

- The scalar field "slow rolls" toward its minimum at large field values.

$$|\ddot{\phi}| \ll |H\dot{\phi}|$$

- This leads to

$$\phi(y) \approx \frac{\beta M_{pl}}{144\gamma^2 y^2}$$

- For $\phi_i \ll \frac{M_{pl}}{\beta}$, the trajectory is not sensitive to the initial conditions.

Onset of scalar oscillations

- For oscillations, we have,

$$(3H)^2 \sim m_\phi^2(T)$$

- We have

$$H \sim \frac{\gamma m_\phi y^2}{\kappa}$$

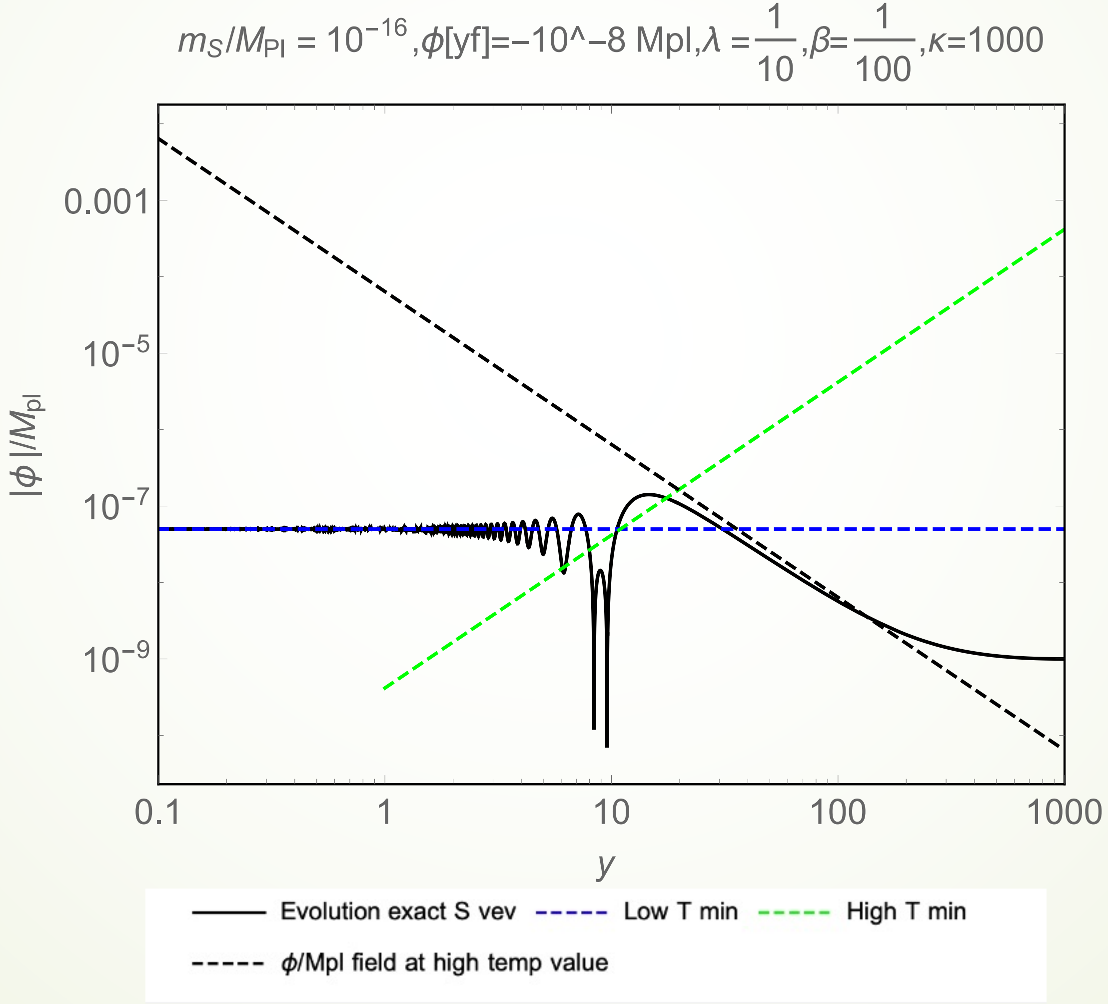
$$m_\phi^2(T) = \frac{\partial^2 V_{eff}}{\partial \phi^2}$$
$$\sim m_\phi^2 + \frac{y^2 m_s^2}{24}\frac{\partial^2 m_+^2(\phi,S)}{\partial \phi^2} - \frac{y\, m_s}{12\pi}\frac{\partial^2 m_+^3(\phi,S)}{\partial \phi^2} + \ldots$$

- This results in:

$$\Rightarrow y^4 + \frac{y}{144\pi\gamma^2}\frac{\beta^2}{\sqrt{\left(-1+\frac{\beta\phi}{M_{\rm pl}}+\frac{3\lambda S^2}{m_S^2}+\frac{\lambda y^2}{2}\right)}} - \frac{\kappa^2}{9\gamma^2} \sim 0$$

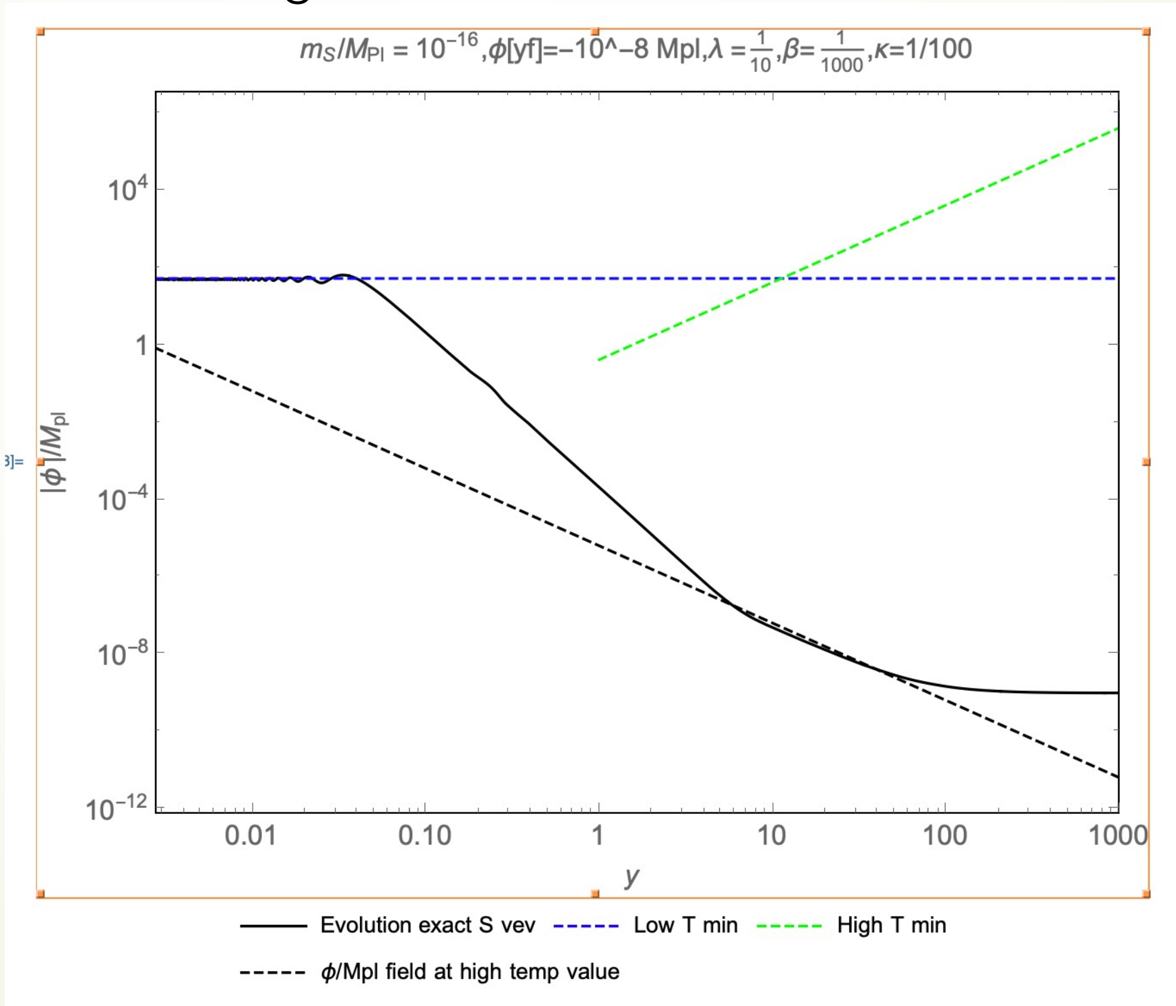
Region 1 (small β, large κ, high T)

We find that above $\kappa > O(100)$, we have thermal mislignment dominate over vev



Region 2 : (small κ , low T)

Here the vev misalignment dominates over the thermal misalignment.



Region 1 (small β, large κ, high T)

- In this region, we try to calculate the relic abundance and energy density.

$$\rho_\phi = \frac{1}{2} m_\phi^2 \phi_{osc}^2 = \frac{\beta^2 m_S^4}{2 \times 48^2 \gamma^2}$$

$$\frac{\rho_\phi}{\rho_R} = \frac{\frac{1}{2} m_\phi^2 \phi_{osc}^2 \frac{y_{eq}}{y_{osc}} \frac{g_*^{eq}}{g_*^{osc}}}{\frac{\pi^2}{30} g_*^{eq} y_{eq}^4 m_S^4} \sim 4.02 \times 10^5 \frac{\beta^2 m_s}{\kappa^{3/2}}$$

$$\sim 1 \times (\frac{\beta}{0.004})^2 (\frac{m_s}{243.5\mathrm{GeV}})(\frac{140}{\kappa})^{3/2}$$

$$\Omega \sim \frac{T_0^3}{\rho_{oC}} \frac{\sqrt{3}}{128\sqrt{\gamma_{osc}}} \frac{g_*^0}{g_{*osc}} \frac{\beta^2 m_s}{\kappa^{3/2}}$$

$$\Omega \sim 0.3 \times \left(1.4 \times 10^5 \frac{\beta^2 m_s}{\kappa^{3/2}}\right)$$

$$\Omega \sim 0.3 \times (\frac{\beta}{0.004})^2 (\frac{m_s}{243.5\mathrm{GeV}})(\frac{140}{\kappa})^{3/2}$$

Region 2 (small κ , low T)

- Since the thermal part of the potential is not relevant, we get :

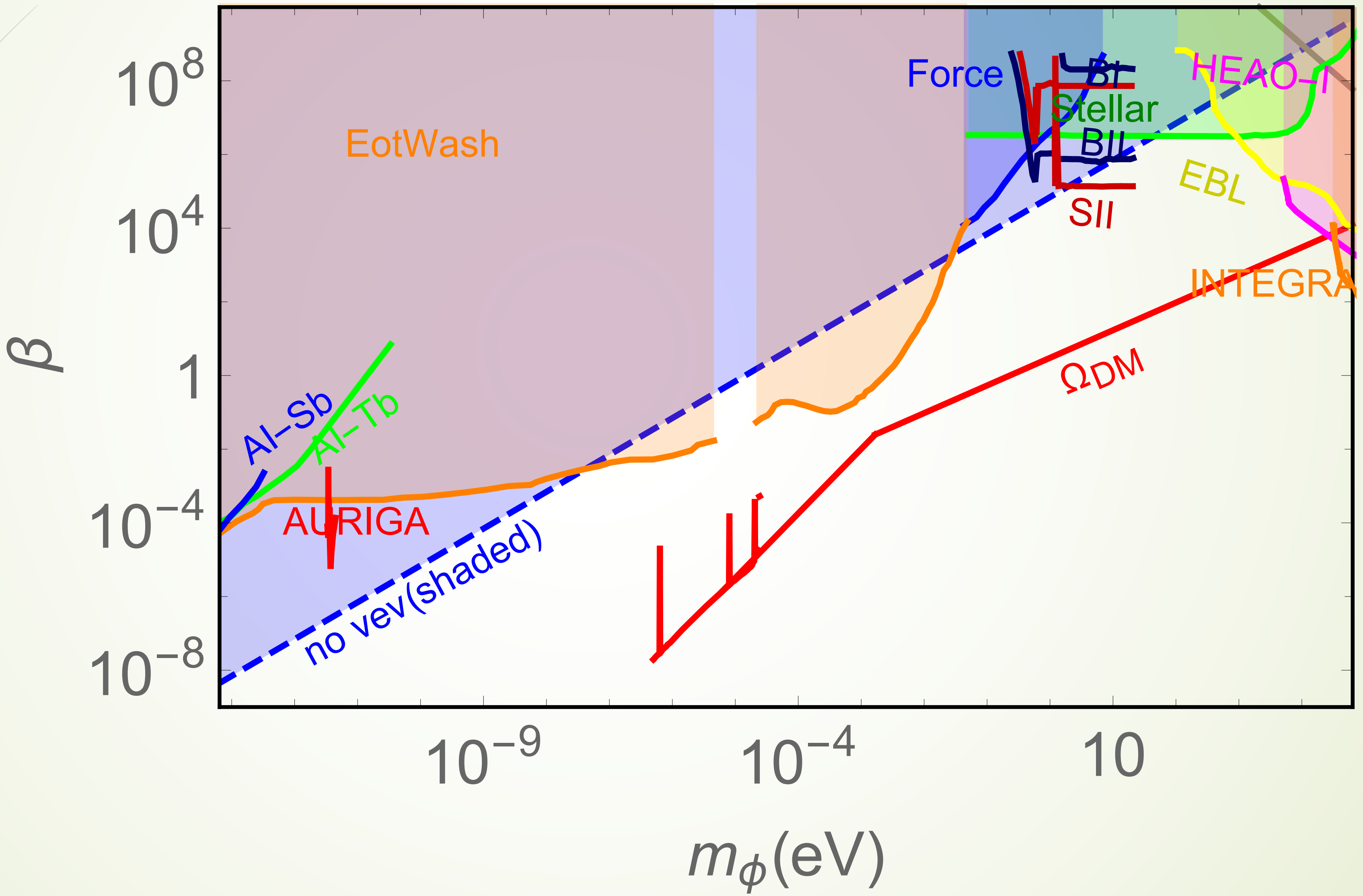
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi + \frac{m_s^2\beta}{2M_{pl}}S^2 = 0$$

- Using the boundary conditions at high temperature approx. form, we can solve this Differential equation to get the oscillation value of the field at $y = y_{osc} \sim \sqrt{\frac{\kappa}{3\gamma}}$:

$$\frac{\phi_{osc}}{M_{pl}} \sim \frac{\phi(0)}{M_{pl}} + (\frac{2}{3})^{1/4}\left(AJ_{-1/4}(\frac{3}{2}) + BJ_{1/4}(\frac{3}{2})\right)$$

$$\frac{\phi(0)}{M_{pl}} \sim \frac{-\beta}{2\lambda\kappa^2}$$

Phenomenological Constraints



Eotwash Constraints

- Field ϕ mediates a fifth force of range ~ m_ϕ^{-1}.
- The the universal coupling turns out to be :

$$\alpha = g_{hNN} \frac{\sqrt{2} M_P}{m_{\rm nuc}} \frac{Av}{m_h^2}$$
$$\simeq 10^{-3} \left(\frac{m_h}{115\,{\rm GeV}}\right)^{-2} \frac{A}{10^{-8}{\rm eV}}.$$

$$A = \frac{\beta m_s^2}{M_{pl}}$$

- In the limit of a very long range force, the Post Newtonian GR tests constraints it to be:

$$\alpha^2 \lesssim 10^{-5}$$

Pospelov et al, https://arxiv.org/pdf/1003.2313.pdf

Stellar Cooling bounds

- Stellar cooling constraints relies upon the draining and cooldown of stars due to production of ultralight particles (like ϕ) in stars.
- We consider the bounds coming from red giants (RG) and horizontal branch (HB) stars cooling.

Edward Hardy et al[arXiv:1611.05852 **[hep-ph]**]

EBL(Extragalactic Background Light)

- Photons emitted from very late decays that do not lie in ultraviolet range, can be observed today as a distortion of the diffuse extragalactic background light (EBL).

- Together these bounds cover the wavelength range between 0.1 and 1000 μm, that is roughly the mass range between 0.1 eV and 1 keV.

Thomas Flacke et al(https://arxiv.org/pdf/1610.02025.pdf)

BI, BII, SI, SII: Resonant absorption in gas chamber

- Bosonic dark matter (DM) detectors based on resonant absorption onto a gas of small polyatomic molecules.
- The excited molecules emit the absorbed energy into fluorescence photons that are picked up by sensitive photodetectors with low dark count rates.
- DM masses between 0.2 eV and 20 eV are targeted, with Bulk and Stack configurations being focused on.

Arvanitaki et al [https://arxiv.org/pdf/1709.05354.pdf]

Two-Body Decays Involving a Photon

- These bounds are on the lifetime of a ULDM, $\phi \rightarrow \gamma\gamma$.
- HEAO-1 : Data is from observations of 3-50 keV photons made with the A2 High-Energy Detector on HEAO-1 . Other datasets from the experiment are significantly weaker than those from the INTEGRAL experiment.
- INTEGRAL : Data is from observations of 20 keV to 2 MeV photons.

Rouven Essig et al(https://arxiv.org/pdf/1309.4091.pdf)