

Dynamics of Dark Matter Misalignment Through the Higgs Portal

arXiv: 2211.09132 [hep-ph]

Mudit Rai¹

University of Pittsburgh

Collaborators : Brian Batell, Akshay Ghalsasi.

[1] mur4@pitt.edu

Motivation

- ▶ Ultra-light scalar dark matter (10^{-10} eV – 100 keV), generically produced via the misalignment mechanism, is a theoretically well-motivated and phenomenologically distinctive scenario.
- ▶ A minimal model realization consists of a scalar field coupled through the super-renormalizable Higgs portal [1].
- ▶ The cosmology of this scenario is rich and distinctive, involving the dynamical misalignment of the scalar field during the radiation era through two competing mechanisms: *thermal misalignment* and *VEV misalignment*.
- ▶ Under certain conditions, the DM relic abundance is insensitive to initial conditions and thus controlled by the DM mass and Higgs portal coupling. This leads to a relic density target that can be compared with experimental tests.

Higgs portal model

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

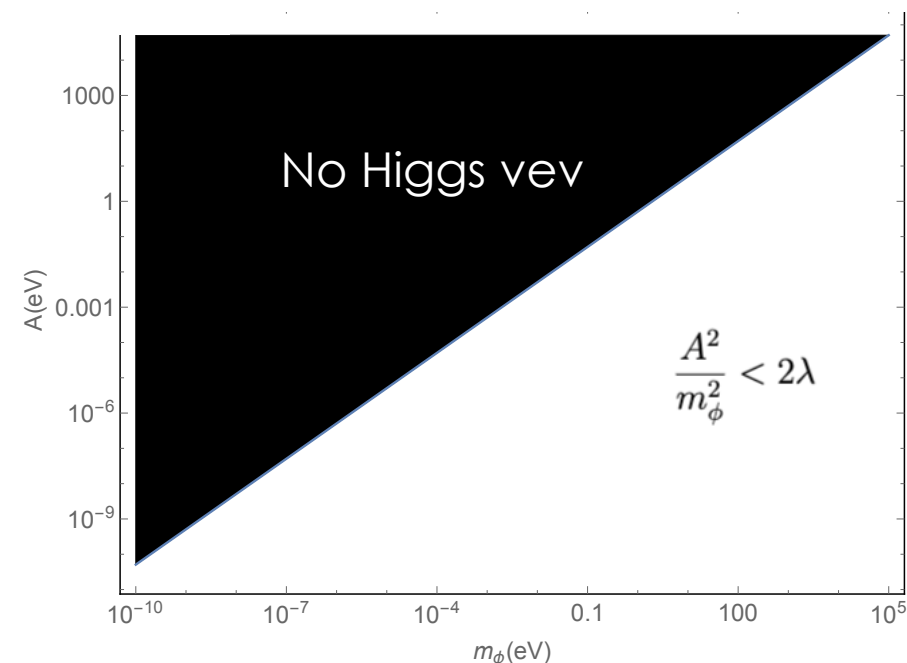
$$V = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}m_\phi^2 \phi^2 + \frac{1}{2}A \phi h^2$$

- Since we are always in regime where $A^2 \lesssim m_\phi^2 \ll \lambda v^2$,

$$\theta \sim \frac{A}{2\lambda v} \simeq \frac{Av}{M_h^2}, \quad M_h^2 \simeq 2\lambda v^2 + \frac{A^2}{2\lambda}, \quad M_\phi^2 \simeq m_\phi^2 - \frac{A^2}{2\lambda}.$$

- Scalar fields vev's :

$$v^2 = \frac{\mu^2}{\lambda - A^2/2m_\phi^2}, \quad \phi_0 = -\frac{Av^2}{2m_\phi^2}$$



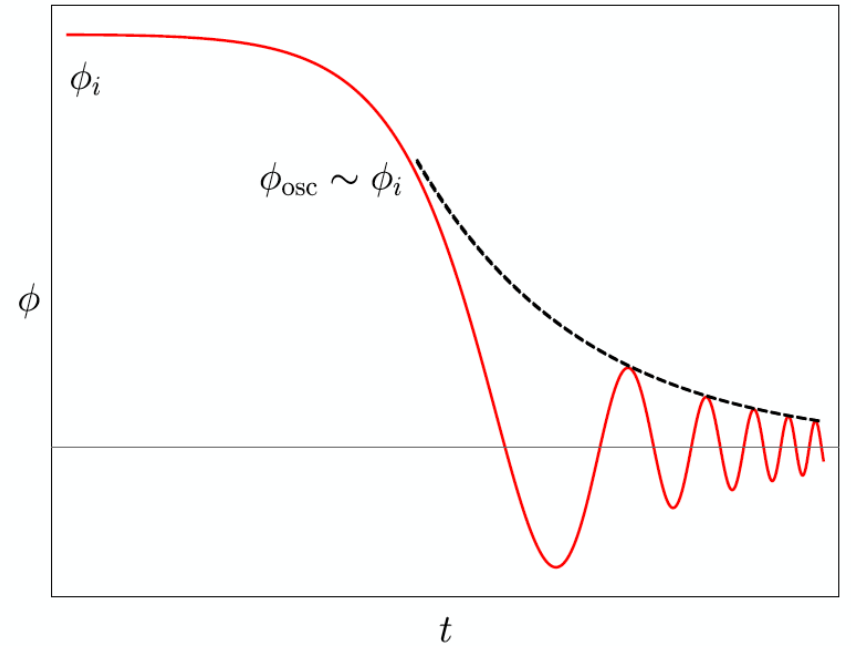
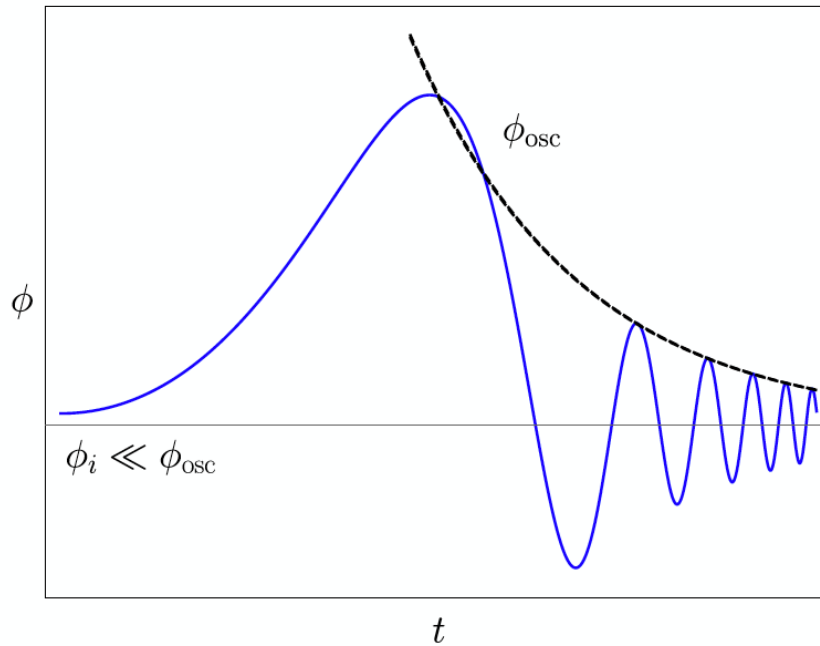
Overview of cosmological setup

- Our study starts in the radiation era at high temperatures, $T \gg v$.
- The feeble coupling of the scalar ϕ to the Higgs [1] leads to non-trivial dynamical evolution of during the radiation era through two effects:
 - Thermal misalignment ϕ_T : The scalar experiences a finite temperature potential and is driven towards its high temperature minimum at large field values.
 - VEV misalignment ϕ_V : During the electroweak phase transition the Higgs VEV turns on and induces a shift in the VEV [2].

[1] Pospelov et al, Phys.Rev.D82:043533,2010

[2] Arkani-Hamed et al, Phys. Rev. D 104, 095014

Thermal Misalignment vs Standard Misalignment



Effective potential

- There are three contributions to the effective potential:

$$V_{\text{eff}}(\phi, h, T) = V_0(\phi, h) + V_{\text{CW}}(\phi, h) + V_T(\phi, h, T)$$

Tree-level Coleman-Weinberg Finite-Temperature

- The first term is the usual zero temperature potential.
- In our study, the CW potential only effects the Higgs transition slightly and does not have a major impact on our final results, thus ignored.
- ϕ is not in thermal equilibrium, but experiences a thermal potential due to its coupling to SM via Higgs, all of which is in thermal equilibrium.

1-loop finite temperature effective potential

- For our model, the thermal potential is given as:

$$V_T(\phi, h, T) \supset \frac{1}{2\pi^2} T^4 J_B \left[\frac{m_h^2(\phi, h, T)}{T^2} \right] + \frac{3}{2\pi^2} T^4 J_B \left[\frac{m_\chi^2(\phi, h, T)}{T^2} \right] + \dots$$

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

- The ϕ -dependent masses of the Higgs and Nambu-Goldstone bosons are

$$m_{0,h}^2(\phi, h) = -\mu^2 + 3\lambda h^2 + A\phi,$$

$$m_{0,\chi}^2(\phi, h) = -\mu^2 + \lambda h^2 + A\phi,$$

Higgs field

- Dimensionless variables:

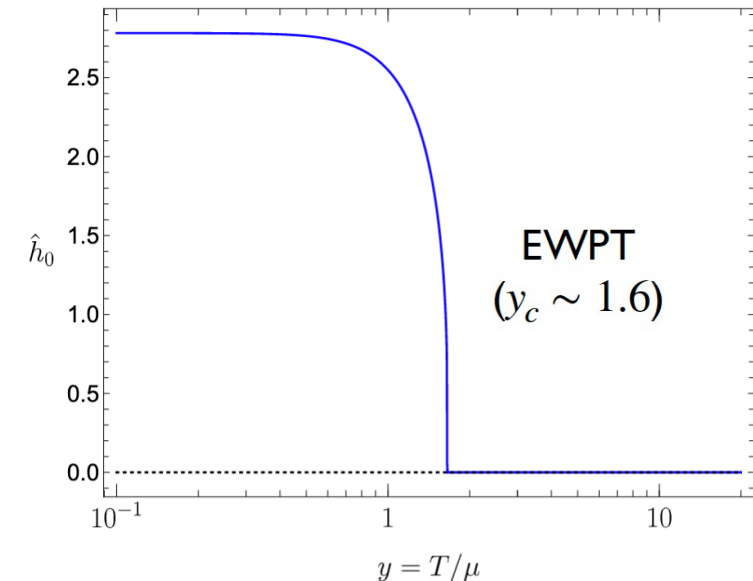
$$y = \frac{T}{\mu}, \quad \hat{\phi} = \frac{\phi}{M_{\text{pl}}}, \quad \hat{h} = \frac{h}{\mu}, \quad \kappa = \frac{m_\phi M_{\text{pl}}}{\mu^2}, \quad \beta = \frac{A M_{\text{pl}}}{\mu^2}$$

- Higgs field tracks its minima, which can be derived by minimizing the potential, $\frac{\partial V}{\partial h} = 0$:

$$0 = \lambda \hat{h}^2 - (1 - \beta \hat{\phi}) + \frac{y^2}{2\pi^2} (6\lambda(J'_B[\eta_h] + J'_B[\eta_\chi]) + g^2(J'_B[\eta_{W_T}] + J'_B[\eta_{W_L}]) + (g^2 + g'^2)J'_B[\eta_{Z_T}])$$

$$+ \frac{y^2}{2\pi^2} \left(\frac{\partial \eta_{Z_L}}{\partial z} J'_B[\eta_{Z_L}] + \frac{\partial \eta_{A_L}}{\partial z} J'_B[\eta_{A_L}] \right) - \frac{y^2}{2\pi^2} (12y_t^2 J'_F[\eta_t])$$

where, $\eta_i = m_i^2(\phi, h, T)/T^2$



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 and temperature:

$$\hat{\phi}'' + \frac{1}{\gamma^2 y^6} \left[\kappa^2 \hat{\phi} + \frac{\beta \hat{h}^2}{2} + \frac{\beta y^2}{2\pi^2} (J'_B[\eta_h] + 3J'_B[\eta_\chi]) \right] = 0.$$

- We solve it numerically by inserting the Higgs solution.

Initial Conditions

- We consider two sets of initial conditions as our benchmark models :
- For a long enough period of inflation and a low enough Hubble, $H_I < v$, the effective temperature experienced by the scalar field is $T \sim H_I$.
- Since $H_I \ll v$, the Higgs is close to its vev and the true minima of ϕ is approximately given by it's 0 T value :

$$\phi[y_i] = \phi_0 = \frac{\beta M_{pl}}{\beta^2 - 2\lambda\kappa^2}$$

- $\phi_i = 0$, serves as a representative example of the general situation where ϕ_i is vastly different than ϕ_0 , and Higgs VEV misalignment controls the final relic density for low masses.

Onset of oscillations

- As the universe expands, the Hubble parameter decreases until it eventually falls below the effective mass, marking the onset of scalar oscillations ϕ ,

$$[3H(y_{\text{osc}})]^2 = m_\phi^2(y_{\text{osc}}) \simeq m_\phi^2 \quad \longrightarrow \quad y_{\text{osc}} = \frac{T_{\text{osc}}}{\mu} = \sqrt{\frac{\kappa}{3\gamma}}$$

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

$$\kappa > 3\gamma, y_{\text{osc}} \gg 1$$

- Region 2 (small κ , low T):

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

Approximate DM density : Region I

- Region I :

$$(\kappa \gtrsim 10^3, \quad m_\phi \gtrsim 3 \times 10^{-3} \text{eV})$$

- In this region, the thermal misalignment dominates over the kick due to Higgs transition, hence we drop the Higgs dependent term to get an approximate form of the equation:

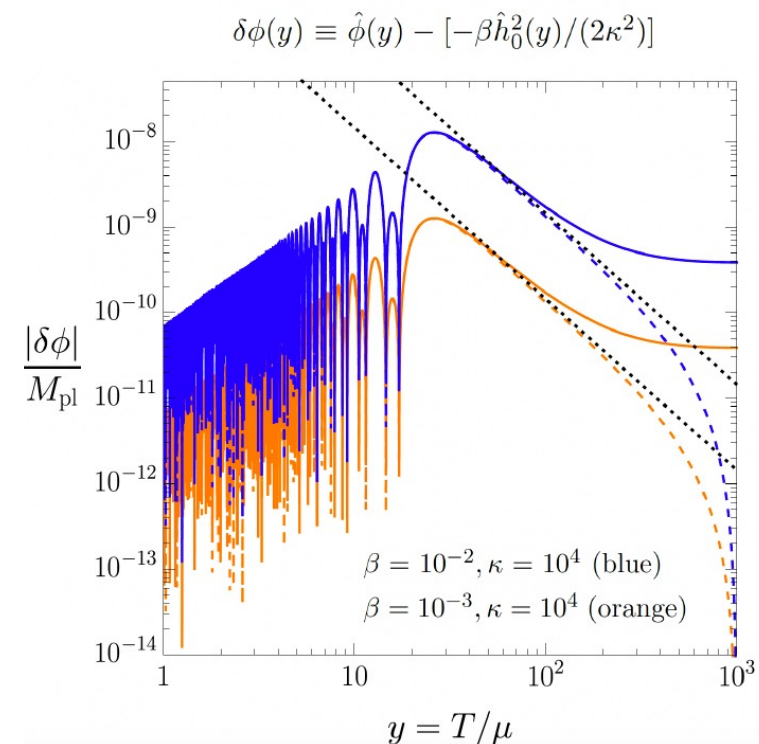
$$\hat{\phi}''(y) + \frac{\beta}{2\pi^2\gamma^2 y^4} (J'_B[\eta_h] + 3(J'_B[\eta_\chi])) = 0.$$

- This yields :

$$\hat{\phi}(y) = -\frac{\beta}{6\pi^2\gamma^2 y^2} + \phi_i \quad \Rightarrow \quad \hat{\phi}(y_{osc}) = -\frac{\beta}{2\pi^2\gamma\kappa} + \phi_i$$

- The DM density can be given by a simple approx. form:

$$\begin{aligned} \Omega_{DM} &= \frac{\rho(T_0)}{\rho_{tot}} = \frac{\rho(y_{osc})}{\rho_{tot}} \left(\frac{y_0}{y_{osc}} \right)^3 \left(\frac{g_{*,0}}{g_{*,osc}} \right) \\ &= 0.26 \left(\frac{\beta}{0.05} \right)^2 \left(\frac{1000}{\kappa} \right)^{3/2} \end{aligned}$$



Approximate DM density: Region 2

- Region 2 : $\kappa < 1, m_\phi < 10^{-5} eV$
- The thermal misalignment is negligible, thus we get :

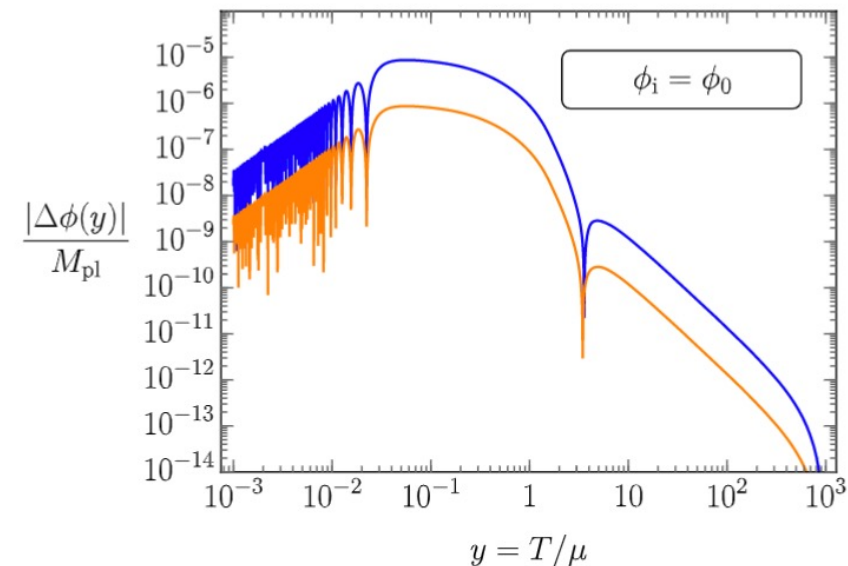
$$\phi''(y) + \frac{1}{\gamma^2 y^6} (\kappa^2 \hat{\phi}) = 0,$$

- Solution:

$$\phi(y) = \frac{1}{y^4} \frac{\beta}{24\gamma^2\lambda} + \phi_0$$

- The DM density is given by :

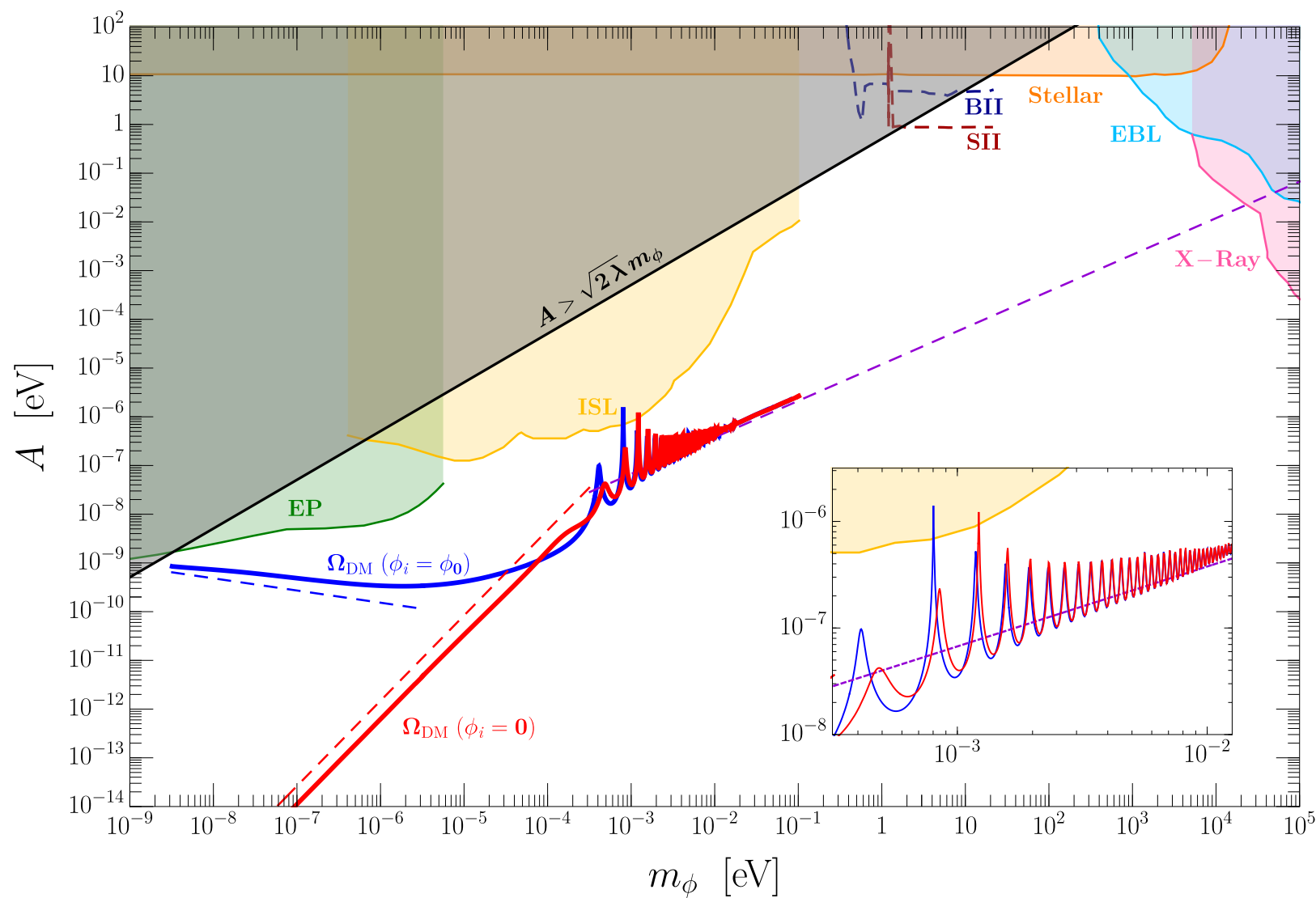
$$\begin{aligned} \Omega_{DM} &= \frac{\rho(T_0)}{\rho_{tot}} = \frac{\rho(y_{osc})}{\rho_{tot}} \left(\frac{y_0}{y_{osc}} \right)^3 \left(\frac{g_{*,0}}{g_{*,osc}} \right) \\ &= 0.26 \left(\frac{\beta}{2 \times 10^{-4}} \right)^2 \left(\frac{\kappa}{10^{-3}} \right)^{1/4} \end{aligned}$$



Experimental and observational probes

- Equivalence principle / inverse square law tests [*Piazza, Pospelov, 2010; Graham, Kaplan, Mardon, Rajendran, Terrano 2016*]
- Stellar cooling [*Hardy, Lasenby, 2016*]
- Extragalactic background light and X-rays [*Fradette, Pospelov, Pradler, Ritz, 2018; Cadamuro, Redondo, 2011; Flacke, Frugieuele, Fuchs, Gupta, Perez, 2017; Essig, Kuflik, McDermott, Volansky, Zurek, 2011*]
- Resonant absorption in molecules [*Arvanitaki, McDermott, Van Tilburg 2017*]

Relic Density Plot



Conclusions

- Ultralight bosons represent a well-motivated and phenomenologically distinctive class of DM models.
- We have studied the cosmology of a light scalar coupled through the super-renormalizable Higgs portal.
- The cosmology of this scenario is rich and distinctive, involving the dynamical misalignment of the scalar field during the radiation era through two competing mechanisms: *thermal misalignment* and *VEV misalignment*.
- Under certain conditions, a relic density target can be defined which is not insensitive to initial conditions.
- New ideas are needed to probe much of the cosmologically interesting regions of parameter space.

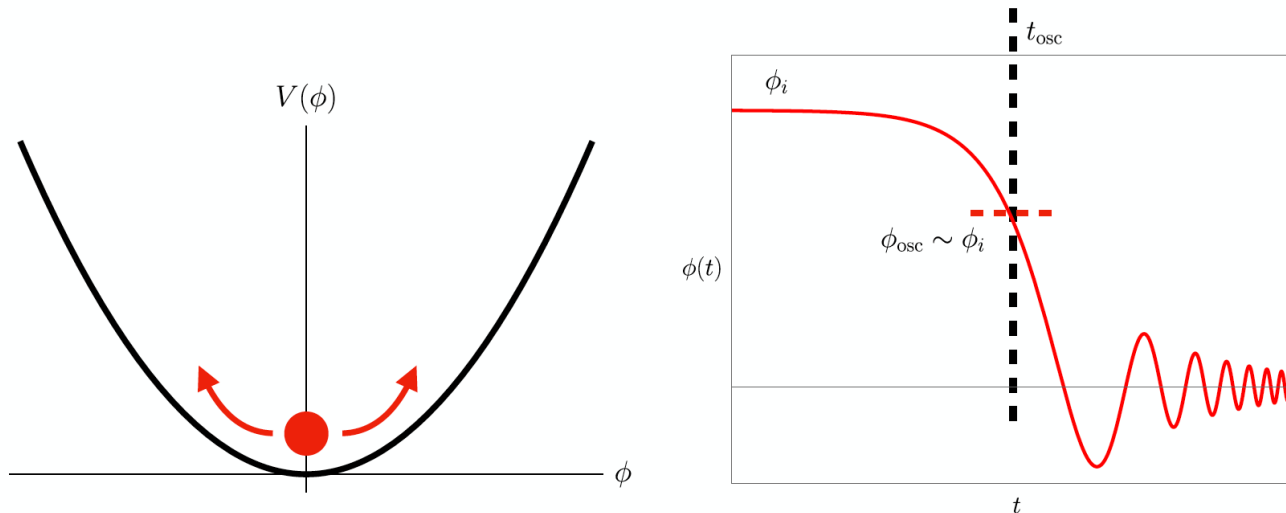
THANK YOU!

BACKUP Slides

Standard Misalignment mechanism

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

- During early times (high T) the scalar is held up by Hubble friction and remains fixed at its initial value.
- As the universe cools, $H < m$. This signals the onset of scalar oscillations.
- At late times, the scalar oscillates about its minimum and is diluted due to Hubble expansion.



Standard Misalignment mechanism

- The energy density redshifts as matter

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

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

$$\begin{aligned} \Omega_\phi|_0 &= \frac{\rho_{\phi,0}}{\rho_{c,0}} \simeq \frac{\frac{1}{2} m_\phi^2 \phi_{\text{osc}}^2 (T_0/T_{\text{osc}})^3 (g_{*S}^0/g_{*S}^{\text{osc}})}{\rho_{c,0}} \\ &\approx 0.2 \left(\frac{m_\phi}{10^{-11} \text{ eV}} \right)^{1/2} \left(\frac{\phi_i/M_{\text{pl}}}{10^{-4}} \right)^2 \end{aligned}$$

Mass eigenstates

➤ Mass eigenvalues :

$$M_{h,\phi}^2 = \frac{1}{2} \left[2\lambda v^2 + m_\phi^2 \pm \sqrt{(2\lambda v^2 - m_\phi^2)^2 + 4A^2 v^2} \right]$$

Thermal potential : Basics

- Thermal potentials can be understood from the phase space distributions.
- Consider a field ψ with mass m_ψ in thermal bath, then it's free energy density ($\mu = 0$) gives the thermodynamic effective potential (- : bosons, + : fermion)

$$V_{th}(\chi) = \mathcal{F} = -P$$

$$\begin{aligned} V_{th}(\chi) &= \frac{(-1)^n g}{6\pi^2} T^4 \int_0^\infty dx \frac{x^4}{\sqrt{x^2 + m_\psi^2(\chi)/T^2}} \{ \exp[(\sqrt{x^2 + m_\psi^2(\chi)/T^2}] \pm 1 \}^{-1} \\ &= \frac{(-1)^n g}{2\pi^2} T^4 \int_0^\infty dx x^2 \log[1 \pm e^{-\sqrt{x^2 + m_\psi^2(\chi)/T^2}}] \end{aligned} \quad x = p/T$$

- Where the Phase space and pressure is given as :

$$f(p) = \{ \exp[(\sqrt{p^2 + m_\psi^2(\chi)} - \mu)/T] \pm 1 \}^{-1} \quad P = \frac{g_\psi}{2\pi^2} \int_0^\infty dp \frac{p^4}{3E(p)} f(p)$$

Finite temperature J functions

- At high temperature, one can expand them as :

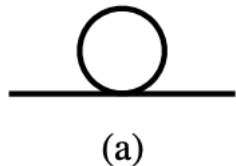
$$J_B(y^2) \approx J_B^{\text{high-}T}(y^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}y^2 - \frac{\pi}{6}y^3 - \frac{1}{32}y^4 \log\left(\frac{y^2}{a_b}\right)$$

$$J_F(y^2) \approx J_F^{\text{high-}T}(y^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}y^2 - \frac{1}{32}y^4 \log\left(\frac{y^2}{a_f}\right) \quad \text{for } |y^2| \ll 1$$

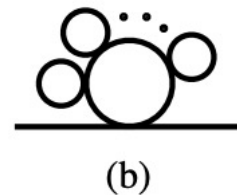
- At low temperature, they are Boltzmann suppressed, thus the analysis reverts to the Tree level potential.
- We account for the hard thermal loops by using the Truncated dressing, where the masses are replaced by

$$m^2 = m_{\text{tree}}^2 + \Pi(T), \quad \Pi(T) \propto T^2$$

Hard Thermal loops basics



1-loop mass correction
 λT^2



higher-loop daisy correction
 $\frac{\lambda^n T^{2n-1}}{\mu^{2n-3}}$

$$V = \frac{-\mu^2 \phi^2}{2} + \frac{\lambda \phi^4}{4}$$

- Large ratios of T/μ have to be resummed ($\mu^2 \sim \lambda T^2$), which can be done by replacing the tree mass by

$$m^2(\phi) = m_{\text{tree}}^2(\phi) + \Pi(\phi, T),$$

- For scalars, Π gives the leading contribution in T to the one-loop thermal mass, and is obtained by differentiating V_{th} with respect to field:

$$\Pi \sim \lambda T^2 + \dots$$

- This includes the hard thermal loops and daisy contributions to all orders.

Potential including thermal effects

- Thus, by resumming the thermal mass in the arguments of the thermal potential, ("Truncated Full Dressing"), we get:

$$\hat{V} = -\frac{1}{2}\hat{h}^2(1 - \beta\hat{\phi}) + \frac{1}{4}\lambda\hat{h}^4 + \frac{1}{2}\kappa^2\hat{\phi}^2 + \frac{y^4}{2\pi^2} (J_B[\eta_h] + 3J_B[\eta_\chi] + 4J_B[\eta_{W_T}] + 2J_B[\eta_{Z_T}] + 2J_B[\eta_{W_L}] + J_B[\eta_{Z_L}] + J_B[\eta_{A_L}] - 12J_F[\eta_t])$$

- For Higgs and the Goldstones, the correction is given by

$$\eta_h = \frac{1}{y^2} \left(3\lambda\hat{h}^2 - (1 - \beta\hat{\phi}) + \frac{y^2}{4} \left(2\lambda + y_t^2 + \frac{3}{4}g^2 + \frac{1}{4}g'^2 \right) \right) \quad y = \frac{T}{\mu}, \quad \hat{\phi} = \frac{\phi}{M_{\text{pl}}}, \quad \hat{h} = \frac{h}{\mu}, \quad \kappa = \frac{m_\phi M_{\text{pl}}}{\mu^2}, \quad \beta = \frac{AM_{\text{pl}}}{\mu^2}$$

$$\eta_\chi = \frac{1}{y^2} \left(\lambda\hat{h}^2 - (1 - \beta\hat{\phi}) + \frac{y^2}{4} \left(2\lambda + y_t^2 + \frac{3}{4}g^2 + \frac{1}{4}g'^2 \right) \right),$$

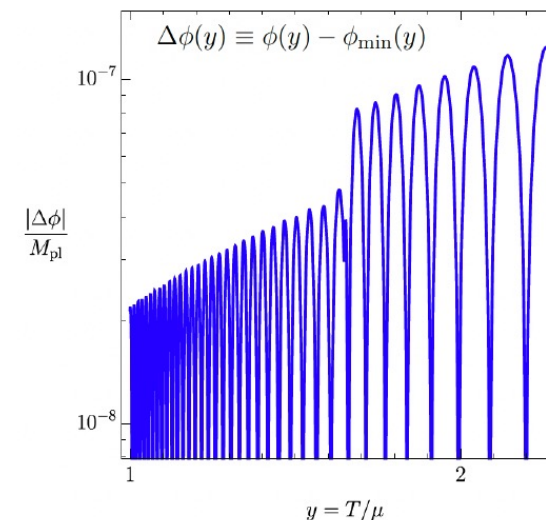
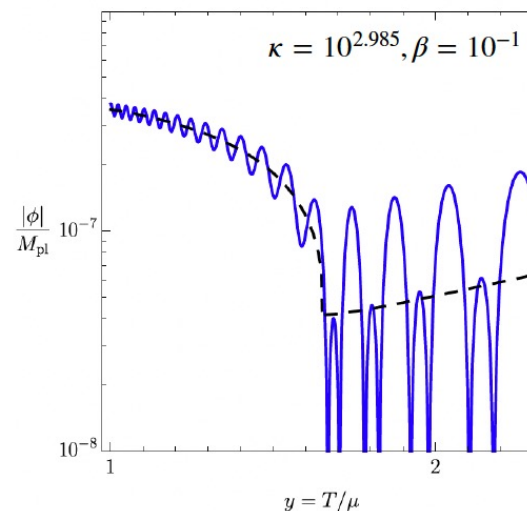
- For Longitudinal vector boson modes, it is given as(gauge basis):

$$\Pi_{GB}^L(0) = \frac{11}{6}T^2 \text{diag}(g^2, g^2, g^2, g'^2)$$

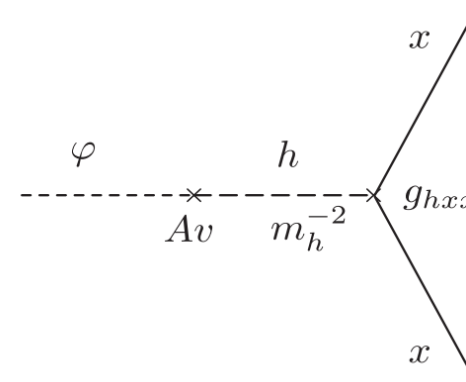
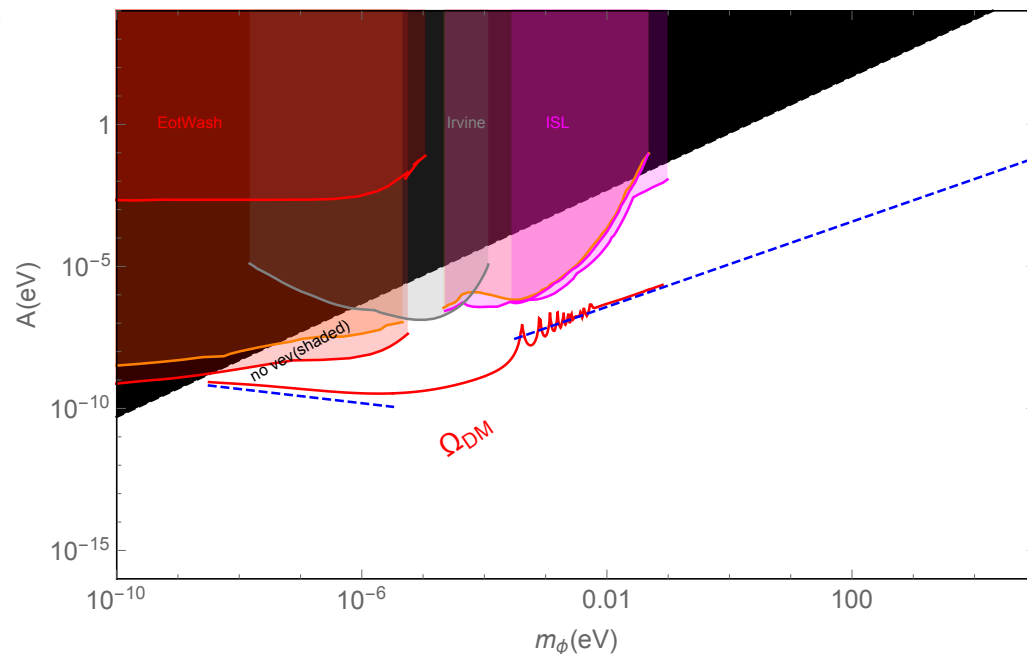
- Contributions to Fermions(no zero modes, thus no IR divergence in propagators) and transverse vector boson modes(gauge symmetry) are suppressed.

Intermediate Region

- In Region the scalar evolution is the result of a competition between thermal misalignment and VEV misalignment.
- Initially, thermal misalignment occurs at high temperatures and oscillations begin before the EWPT
- At the EWPT, the Higgs field rapidly moves from the origin towards $h \rightarrow v$, simultaneously inducing a shift in the ϕ VEV towards its zero-temperature value.
- This acts as a step-like forcing term in the scalar equation of motion, causing a suppression or enhancement in the oscillation amplitude
- In the example at right, the scalar field is near its oscillation maximum as the shift in the ϕ VEV occurs.



Fifth force experiments Constraints



- In the limit of a very long-range force of range $\sim m_\phi^{-1}$, bounds are derived from post-Newtonian tests of relativity.
- The universal coupling turns out to be :

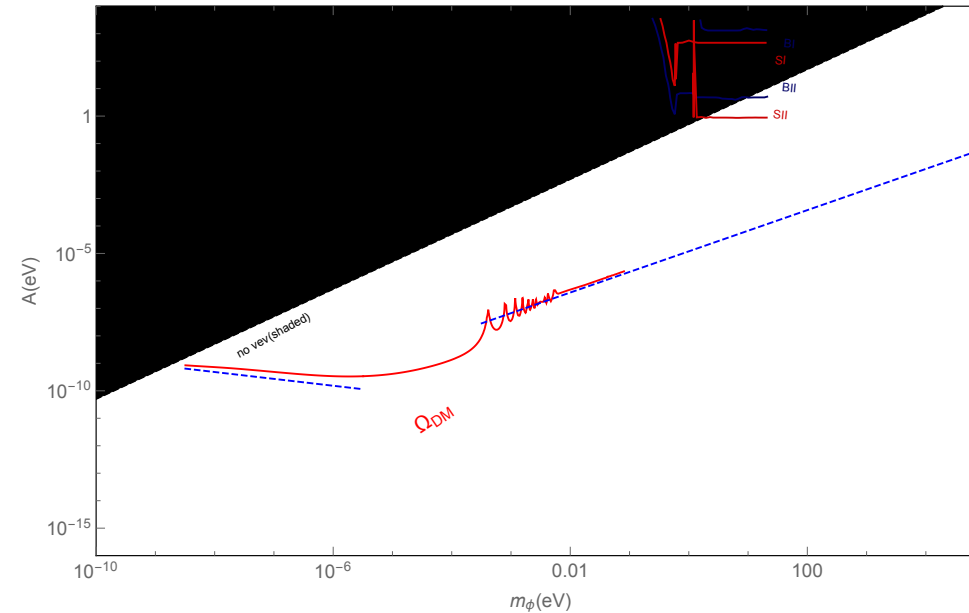
$$\alpha = g_{hNN} \frac{\sqrt{2} M_P}{m_{\text{nuc}}} \frac{A v}{m_h^2}$$

$$\simeq 10^{-3} \left(\frac{m_h}{115 \text{ GeV}} \right)^{-2} \frac{A}{10^{-8} \text{ eV}}.$$

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

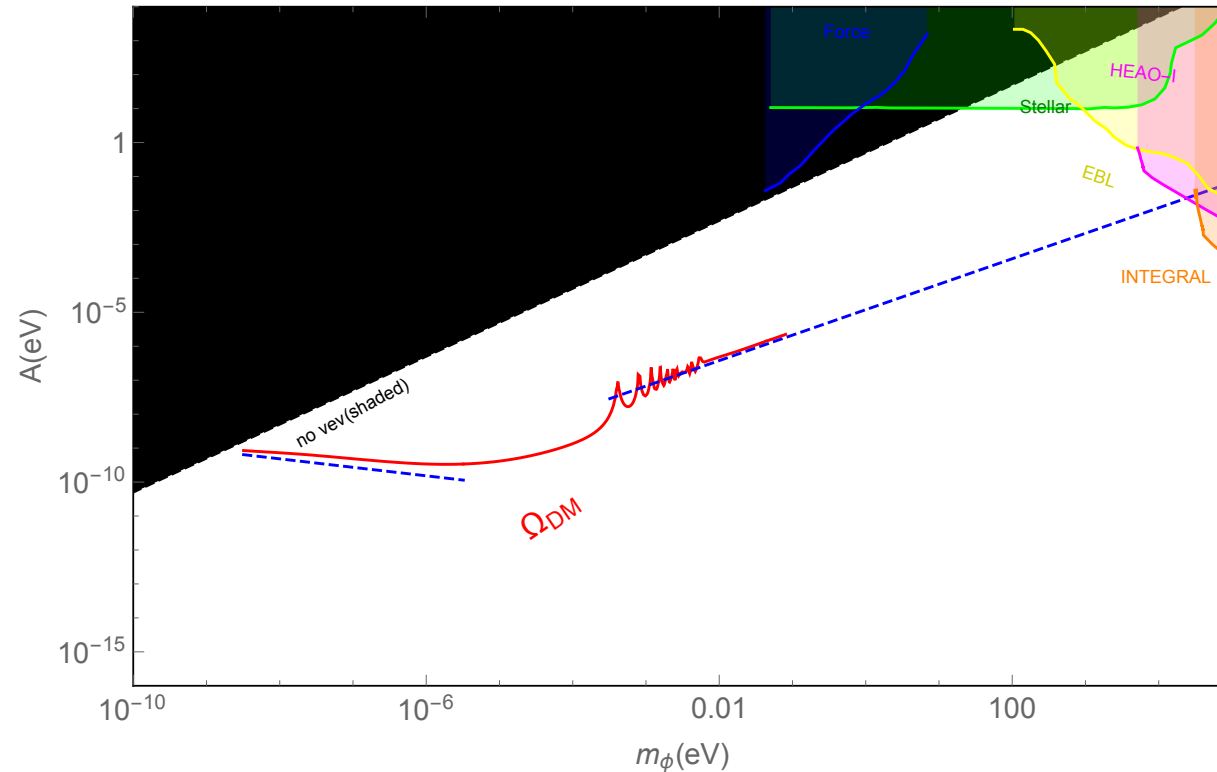
$$V(r) = -\frac{Gm^2}{r} (1 + \alpha^2 e^{-m_\phi r})$$

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.

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.

2 body photon decay

- Extragalactic bounds
 - 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.
- Two body photon decays($\phi \rightarrow \gamma\gamma$)
 - 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.