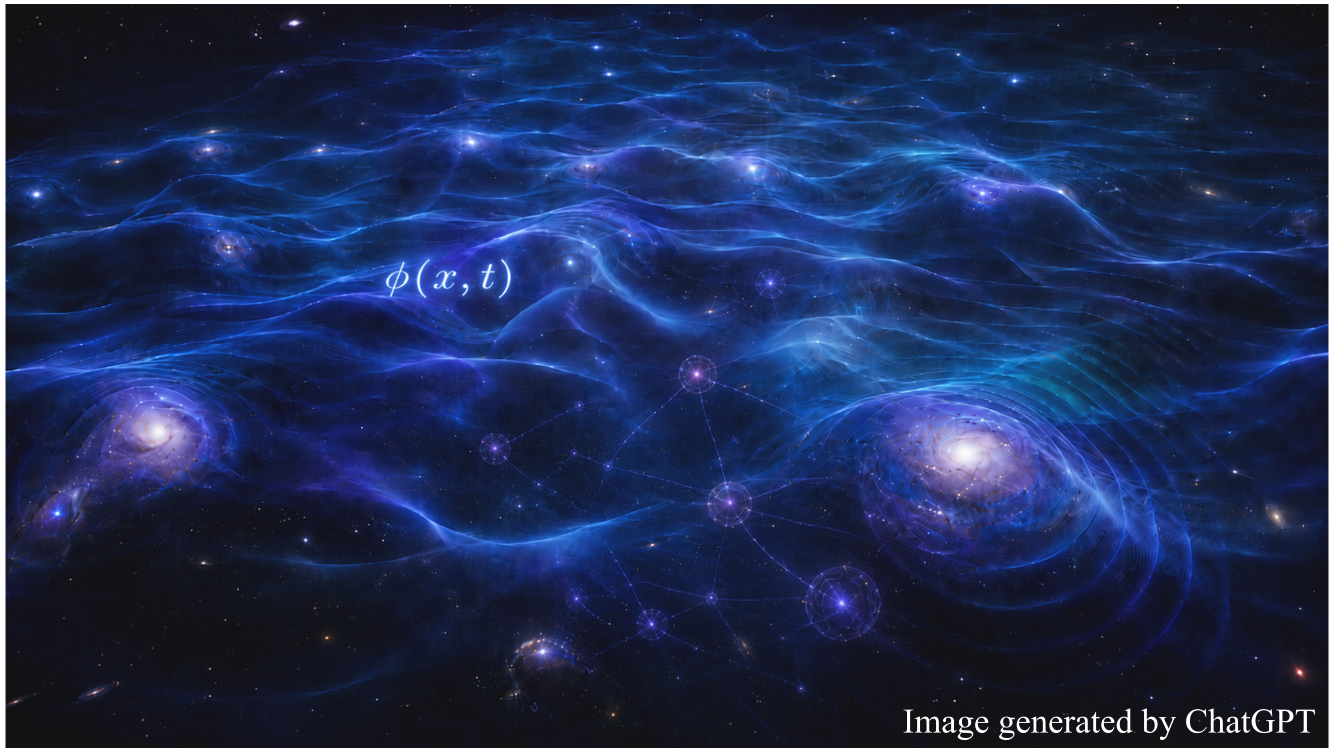
# Non-equilibrium Dynamics of light scalars coupled to dark sectors

**Gopolang (Gopi) Mohlabeng**

Simon Fraser University



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28 July 2026

LIGHT DARK
WORLD 2026
July 28th - July 31st
Carleton University
Ottawa, Canada

SFU

# Outline

1. Brief intro to scalar fields and how they control effective theory parameters

2. I will discuss three examples of scalar controlled masses and couplings

- Dark matter sources neutrino mass through long-range interaction

Davoudiasl, Mohlabeng & Sullivan, PRD 98, 021301(R) (2018)

- Thermal relic dark matter promoted to ultra heavy status

Davoudiasl & Mohlabeng, JHEP 04 (2020) 177

- Non-equilibrated scalar leading to strongly first order phase transition

Knapp-Perez, Mohlabeng, Ratz & Tait, JCAP 03 (2026) 002

3. Summary and outlook

# Scalars are hard to avoid

- Generic features in many theories of fundamental physics

**Moduli** - scalars parametrizing flat directions in string compactifications

- obtain VEV which determine parameters of low-energy theory, i.e. masses, couplings etc.

Coughlan, Fischler, Kolb, Raby, Ross, PLB 131 (1983) 59

de Carlos, Casas, Quevedo, Roulet, PLB 318 (1993) 447

Buchmüller, Hamaguchi, Ratz, PLB 574 (2003) 156

+ many others

**Dark Higgses** - radial modes of dark symmetry breaking carries a VEV that sets masses of mediators/dark matter

e.g. Batell et al arXiv: 2207.06905 for current constraints

**Axions/ALPs** - angular mode of broken global symmetry.

- radial partner carries VEV that sets decay constant.

Preskill, Wise, Wilczek / Abbott, Sikivie / Dine, Fischler, PLB 120 (1983) 127, 133, 137

Svrcek, Witten, JHEP 06 (2006) 051

Arvanitaki et al, PRD 81 (2010) 123530

+ many others

**Dark matter**

- Can also drive the dynamics of the universe

- **Inflaton -** scalar field whose energy density drives rapid accelerated expansion in early universe

Guth, PRD 23, 347 (1981).

- **Quintessence -** slowly evolving scalar field whose energy density drives late-time accelerated expansion of universe - **Dark Energy**

Amendola, PRD 62, 043511 (2000)

- **Relaxions -** dynamically sets electroweak scale

Graham, Kaplan & Rajendran, PRL 115 (2015) 221801

+ many others…

In many of these scenarios there is a common theme - **VEV controls masses and couplings of interacting fields**

**central organizing principle of this talk**

- Scalar coupling to both dark sector and/or SM is often allowed leading to opportunities for detection

- Interacting & evolving scalar often leads to **dynamically changing couplings and masses**

$$g_i(\phi),\ m_j(\phi),\ y_f(\phi),\ \lambda_l(\phi)$$

e.g. 1. Dynamical QCD coupling, leading to early confinement

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{1}{g_s^2} + \frac{\phi}{M_*}\right) G_{\mu\nu}G^{\mu\nu}$$

Ipek & Tait, PRL 122 (2019) 112001

Heurtier, Huang and Tait, JHEP 12 (2021) 216

Berger, Ipek, Tait & Waterbury, JHEP 07 (2020) 192

+ many others

2. Scalar coupled to EM field strength $\mathcal{L} \supset \boxed{\frac{\phi^2 d_\alpha}{M_{pl}^2 4e^2}} F_{\mu\nu}F^{\mu\nu}$

Leads to variations in fine structure constant $\frac{\Delta\alpha}{\alpha} \sim d_\alpha^{(2)} \frac{\phi^2}{M_{pl}^2}$

Brzeminski, Chacko, Dev & Hook, PRD 104 (2021) 075019

Ghosh, Boddy & Yu PRD 114 (2026) 2, 023525

+ many others

## 3. Scalar controlled Yukawa couplings lead to novel cosmological dynamics

$$\mathcal{L} \supset \sum_{i,j} \frac{g_{i,j}}{\Lambda} \phi \bar{Q}_i \tilde{\Phi} u_j$$

Froggatt & Nielsen, Nucl. Phys. B 147 (1979) 277

Lillard, Ratz, Tait & Trojanowski, JCAP 07 (2018) 056

Cheek, Osinski, Roszowski & Trojanowski, JHEP 03 (2023) 149

## 4. Scalar controlled masses

- mass varying neutrinos

Fardon, Nelson & Weiner, JCAP 10 (2004) 005

Davoudiasl, Mohlabeng & Sullivan, PRD 98, 021301(R) (2018)

+ many others

- mass varying dark matter

Anderson & Carrol, astro-ph/9711288 **(VaMPs - varying mass particles)**

Davoudiasl & Mohlabeng, JHEP 04 (2020) 177 **(THUMPs - Thermal Ultra Massive Particles)**

Ferrante, Perelstein & Yu, PRL 136 (2026) 201004

+ many others

- dark matter coupled to dark energy - possible explanation for dynamical equation of state

C. Wetterich, Astron. Astrophys. 301 (1995) 321

Khoury, Lin & Trodden, PRL. 135, 181001 (2025)

Burrage & Sevillano Munoz, arXiv: 2603.28881

+ many others

## I will discuss three examples that share common thread of modulus controlled masses and couplings

**Result in novel dark sector dynamics**

1. Dark matter sources neutrino mass through long-range interaction

Davoudiasl, Mohlabeng & Sullivan, PRD 98, 021301(R) (2018)

2. Thermal relic dark matter promoted to ultra heavy status

Davoudiasl & Mohlabeng, JHEP 04 (2020) 177

3. Non-equilibrated scalar leading to strongly first order phase transition

Knapp-Perez, Mohlabeng, Ratz & Tait, JCAP 03 (2026) 002

**Scalar/modulus is not thermalized with plasma**

# Galactic dark matter population as the source of neutrino masses

- Neutrino mass can be zero in vacuo and generated by local dark matter distribution through long-range scalar interaction

$$\mathcal{L} \supset -g_\chi \phi \bar{\chi}\chi - m_\chi \bar{\chi}\chi - g_\nu \phi \bar{\nu}\nu - \frac{1}{2} m_\phi^2 \phi^2$$

- Classical background scalar field gives neutrinos apparent mass

$$m_\nu \equiv g_\nu \phi$$

- dark matter also gets an apparent mass

$$m_\chi \equiv g_\chi \phi + m_\chi$$

- Assume long range force is described by Yuwaka potential

- Positive mass and number density means long-range force between DM and neutrinos is repulsive

- For our parameters scalar field equation of motion is described by

$$(\Box + m_\phi^2)\phi = -g_\chi \bar{\chi}\chi - g_\nu \bar{\nu}\nu$$

- We assume static and spatially uniform DM and neutrino populations

$$\phi \sim \frac{-g_\chi n_\chi}{m_\phi^2 + \omega_\nu^2}$$

Screening mass induced by neutrinos

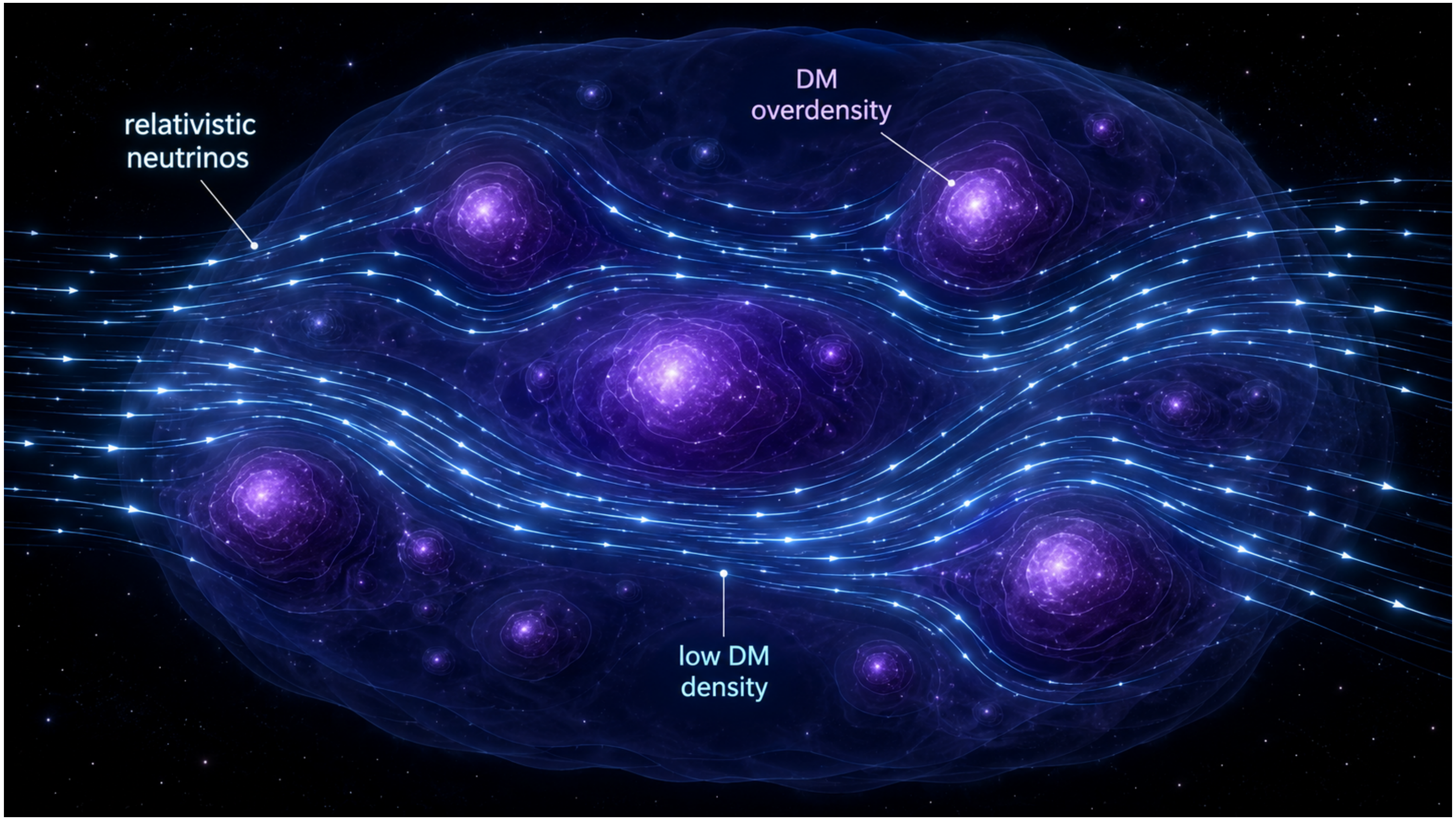
$$\omega_\nu^2 \equiv \frac{g_\nu^2 n_\nu}{\langle E_\nu \rangle}$$

- for dominant screening mass term and low DM density, neutrino number density drives $\phi \to 0$

➡ Neutrinos are massless and relativistic in DM underdense regions

- Once DM clumps enough $n_\chi$ drives $\phi$ to non-zero values

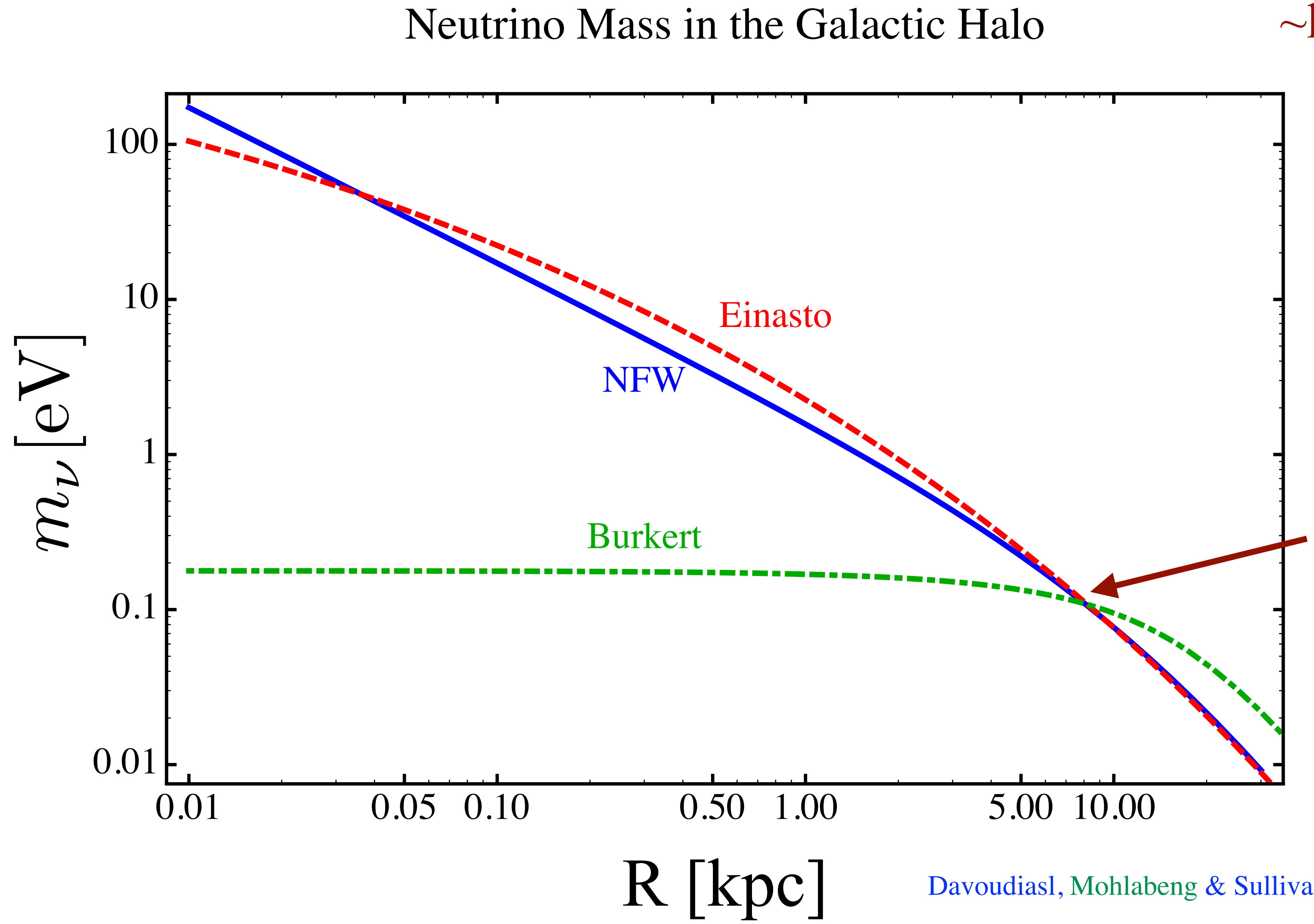
- Cosmic neutrinos are repelled from DM overdense regions



- Inside the Milky Way galaxy we calculate the neutrino mass to be

$$m_\nu \sim 0.1\,\mathrm{eV}\left(\frac{g_\nu}{10^{-19}}\right)\left(\frac{g_\chi/m_\chi}{10^{-19}\mathrm{GeV}^{-1}}\right)\left(\frac{\rho_\chi}{0.3\mathrm{GeV.cm}^{-3}}\right)\left(\frac{10^{-26}\,\mathrm{eV}}{\underset{\uparrow}{m_\phi}}\right)^2$$

~kpc scale interaction



**0.1 eV at 8 kpc**

Davoudiasl, Mohlabeng & Sullivan, PRD 98, 021301(R) (2018)

- Focus of this study was on scalar controlled neutrino masses

- DM mass is also scalar dependent

- Dynamically changing DM mass separates physics of production from physics of detection, opening up new phenomenological possibilities

E.g. DM can freeze-out while light and become much heavier at late times, evading bounds on thermal relics like the unitarity limit

**Thermal Ultra Massive Particles (THUMPs)**

# THermal Ultra Massive Particles (THUMPs)

- Dark matter is light before freeze-out, i.e. WIMP

- Require it to over-annihilate so that number density of DM particles after freeze-out is very small

- DM obtains large mass after freeze-out which sets the right relic density

- Over-annihilation sets small number density for heavy DM, expected at present times

## Concrete example

$$\mathcal{L} \supset (\lambda\phi + m_\chi^i)\bar{\chi}\chi + i g_D Q_D A'_\mu \bar{\chi}\gamma^\mu\chi + \varepsilon . e A'_\mu \bar{f}\gamma^\mu f - \frac{1}{2}m_\phi^2(\phi - \phi_0)^2$$

$m_\chi^f$

dark photon

SM fermions

light scalar

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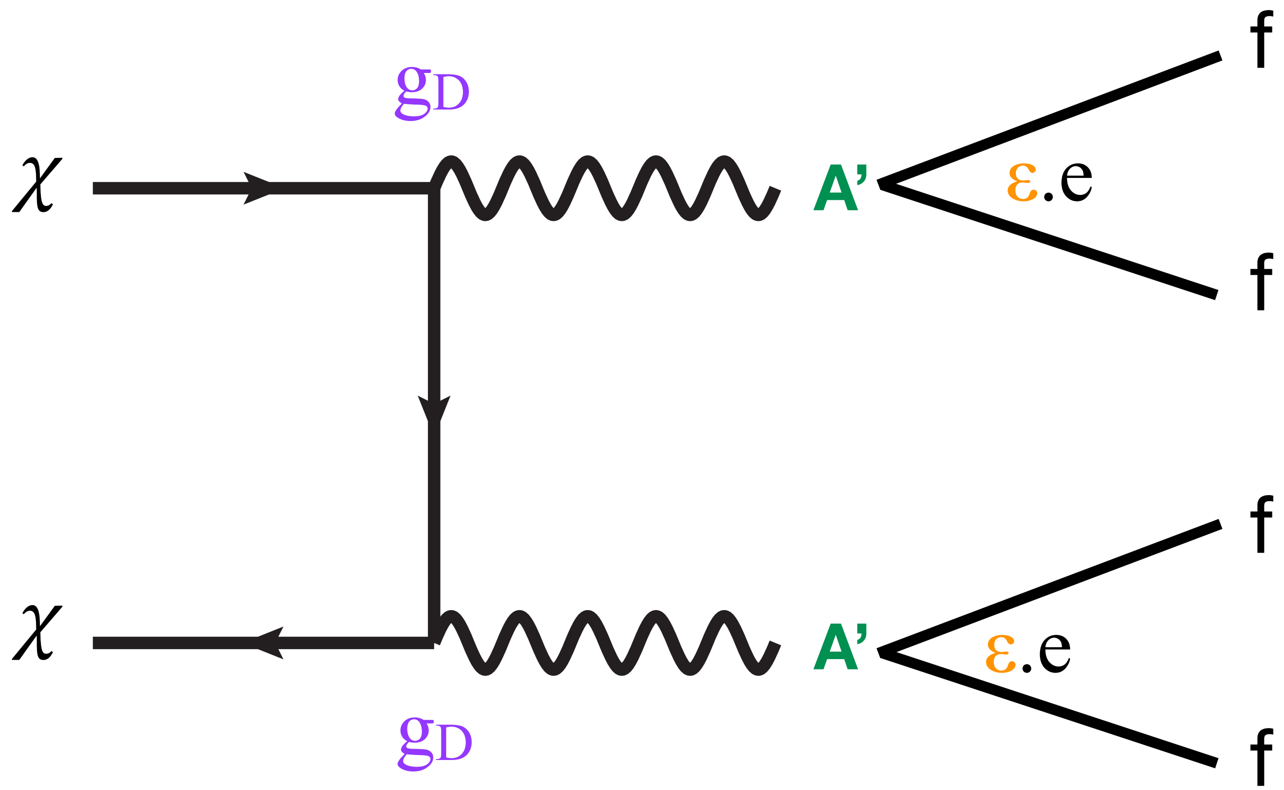
# Before freeze-out DM over-annihilates

if $m_\chi^i \gtrsim m_{A'}$ then dominant annihilation process is



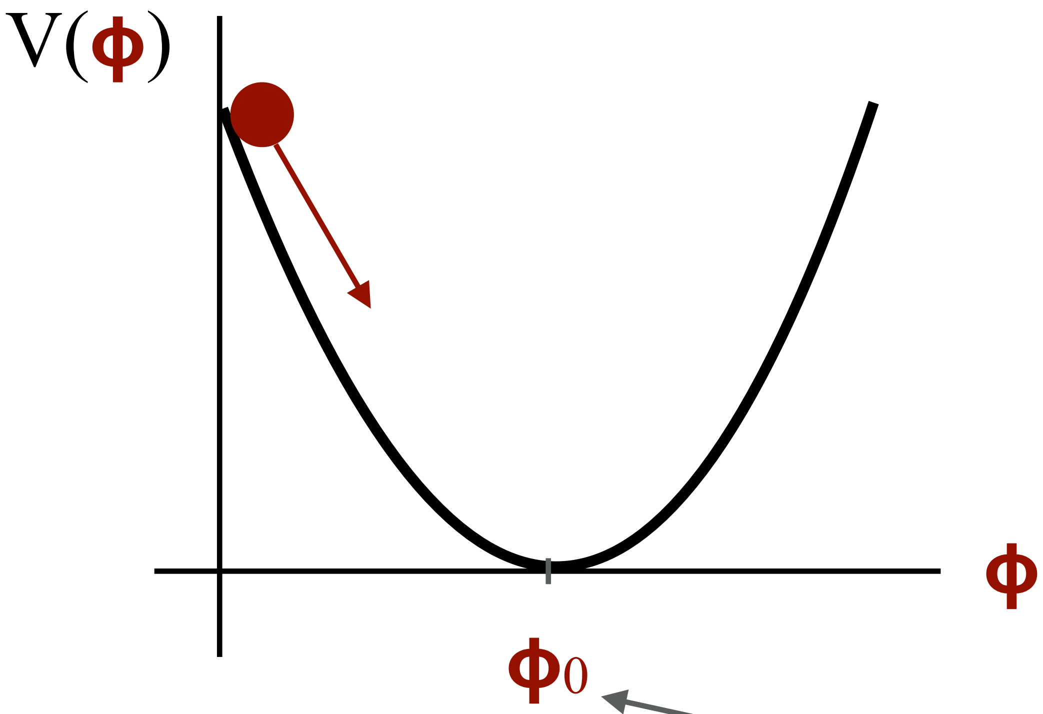
Thermal annihilation process

Large number ~ 1, ensures DM annihilates efficiently

$$\langle \sigma v \rangle \approx \frac{g_D^4}{16\pi {m_\chi^i}^2} \sqrt{1 - \left( \frac{m_{A'}}{m_\chi^i} \right)^2}$$

Davoudiasl & Mohlabeng, JHEP 04 (2020) 177

- After freeze-out, ultra-light scalar rolls in its potential



$$V(\phi) = \frac{1}{2} m_\phi^2 (\phi - \phi_0)^2$$

Vacuum expectation value

- When scalar reaches minimum, gives large mass to dark matter after freeze-out

$$\mathcal{L}_m \supset (m_\chi^i + \lambda\phi)\bar{\chi}\chi \qquad m_\chi^f \to m_\chi^i + \lambda\phi_0$$

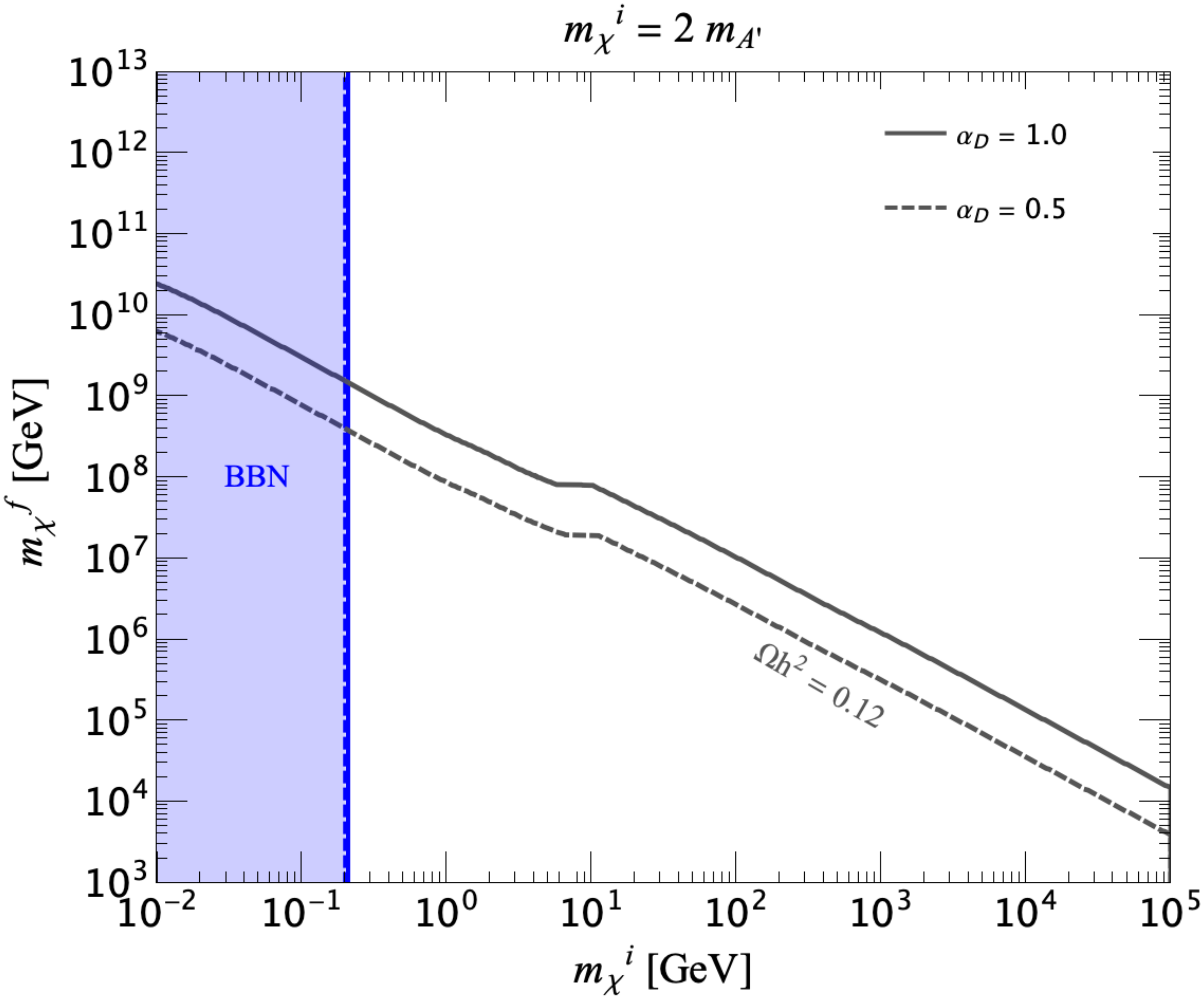
Some benchmark numbers

| $\lambda$ | $m_\phi$ | $\phi_0$ |
|---|---|---|
| $10^{-6}$ | $10^{-14}$ eV | $10^{15}$ GeV |

Davoudiasl & Mohlabeng, JHEP 04 (2020) 177

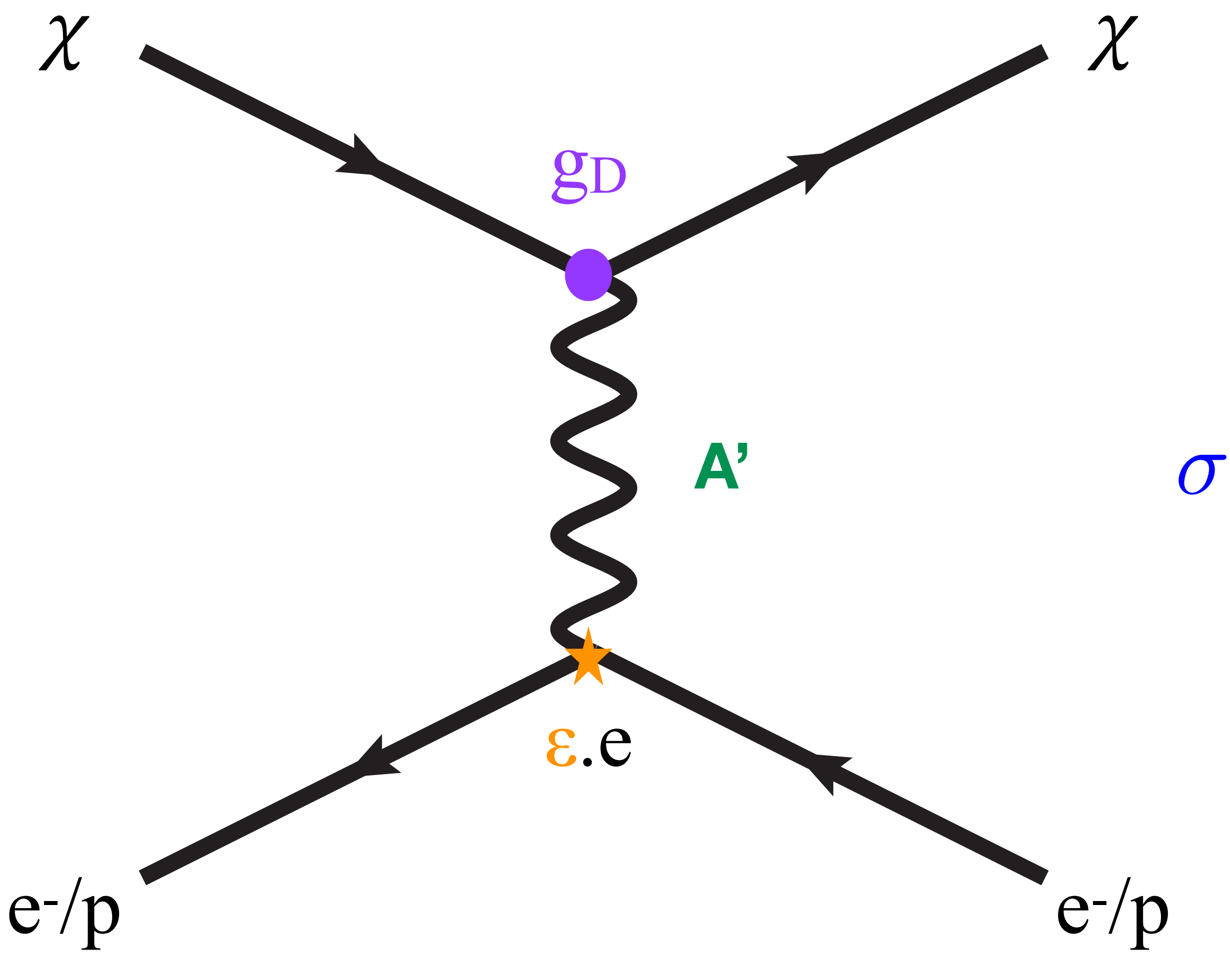
# Relic density

$$\Omega_\chi h^2 \sim n_\chi(m^i_\chi)\ m^f_\chi$$



Davoudiasl & Mohlabeng, JHEP 04 (2020) 177

# Direct Detection of THUMP Dark Matter

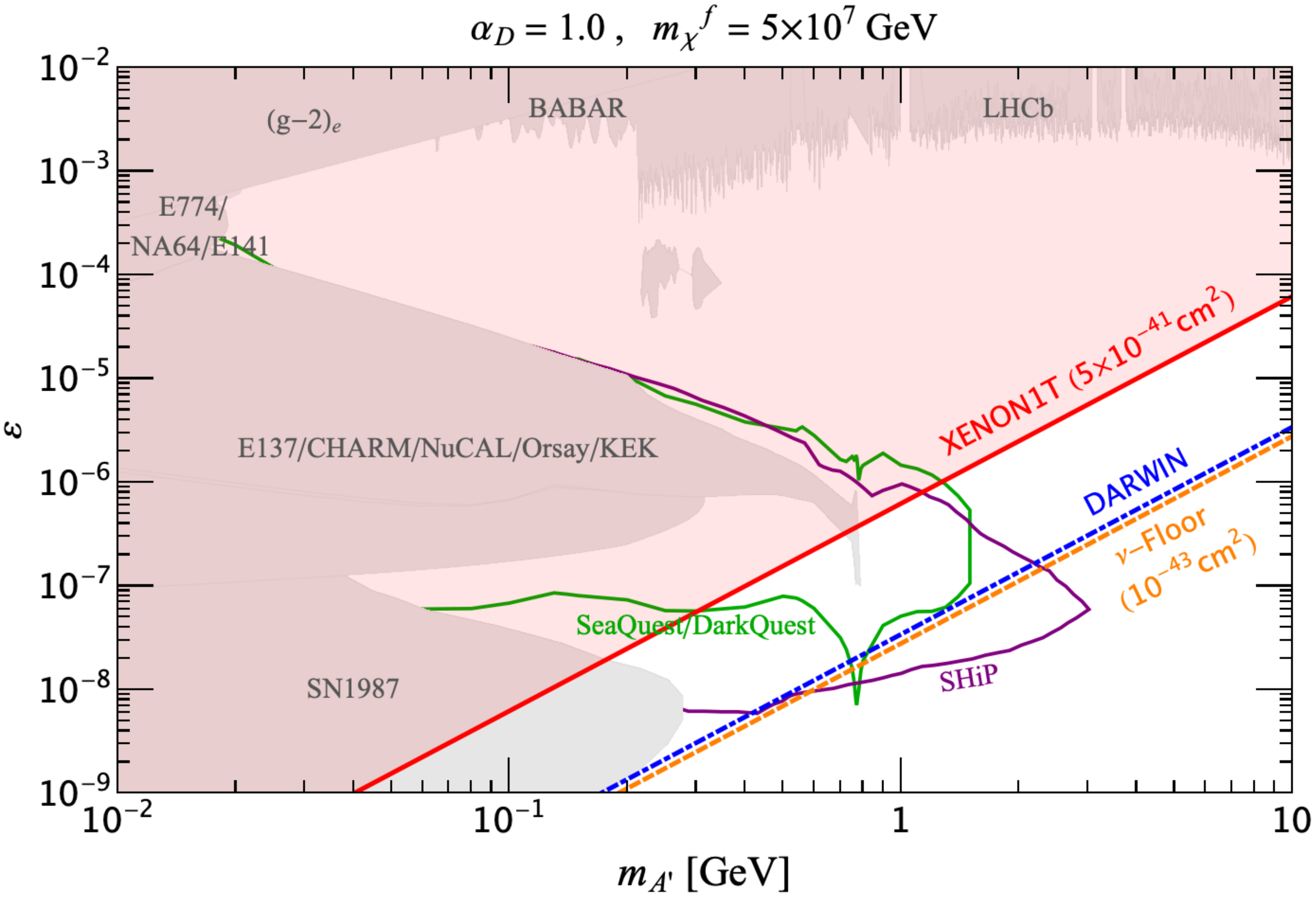


$$\sigma_{\chi n} \sim \frac{16\pi\mu_{n\chi}^2\epsilon^2\alpha\alpha_D}{m_{A'}^4}$$

- Light mediator, large direct detection cross-section

- Different modeling can produce cross-sections relevant for multi scattering in direct detection experiments

# Complementarity of direct detection and low energy accelerators



- Low energy experiments search for mediator
- Direct Detection experiments search for THUMP

Davoudiasl & Mohlabeng, JHEP 04 (2020) 177

- Previous two scenarios focussed on scalar controlled masses

**We will pivot to a scalar controlled quartic Higgs coupling**

$$g_i(\phi),\ m_j(\phi),\ y_f(\phi), \boxed{\lambda_l(\phi)}$$

- Focus on scalar field sufficiently weakly coupled to thermal bath that it is out of equilibrium

- While out of equilibrium, scalar potential still received thermal corrections

- Important consequences for symmetry breaking & phase transitions

- Potential of weakly coupled scalar receives thermal corrections from fact that masses and couplings of thermal bath depend on its VEV

- Generally contributions to the thermal effective potential of the scalar come from the Free energy

$$\mathcal{F}(T,\phi) \sim T^2 \left( \sum_i c_i^{(g)} g_i^2(\phi) + \sum_f c_f^{(y)} y_f^2(\phi) + \sum_j c_j^{(m)} m_j^2(\phi) + \sum_l c_l^{(\lambda)} \lambda_l(\phi) \right)$$

$$c_l^{(\lambda)} = \frac{3}{576} T^2$$

Laine & Vuorinen, arXiv: 1701.01554

- Free energy wants couplings to be as small as possible at high T

**Concrete example:** consider dark Higgs whose VEV spontaneously breaks U(1)’ gauge symmetry

$$\mathcal{L} \supset \mu^2 h^* h - \lambda(\phi)(h^* h)^2 + \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \mathcal{V}^{\phi}_{eff}(\phi, T, \Lambda, m_\phi, \phi_0)$$

Equilibrated scalar

Non-equilibrated scalar

With $h = \frac{1}{\sqrt{2}}(h_1 + ih_2 + v)$

Quartic coupling $\lambda(\phi) = \left(\frac{\phi}{\Lambda}\right)^2$

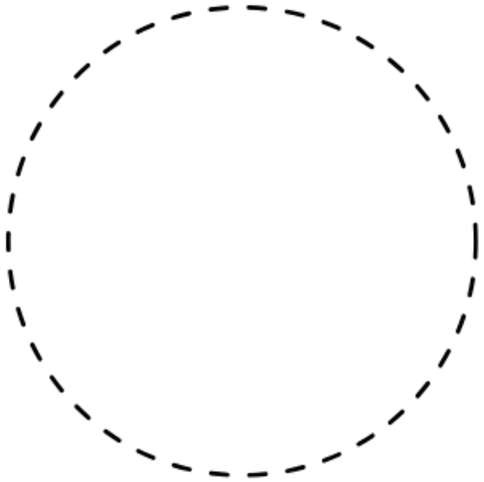
$\phi$ evolution in universe quantified by equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \mathcal{V}^{\phi}_{\rm eff}(\phi, T, \Lambda, m_\phi, \phi_0) = 0$$

$\phi$ value determines $\lambda(\phi)$

Quartic coupling determines symmetry breaking pattern of equilibrated scalar *h*

Thermal effective potential of *h* gets contributions up to two loops

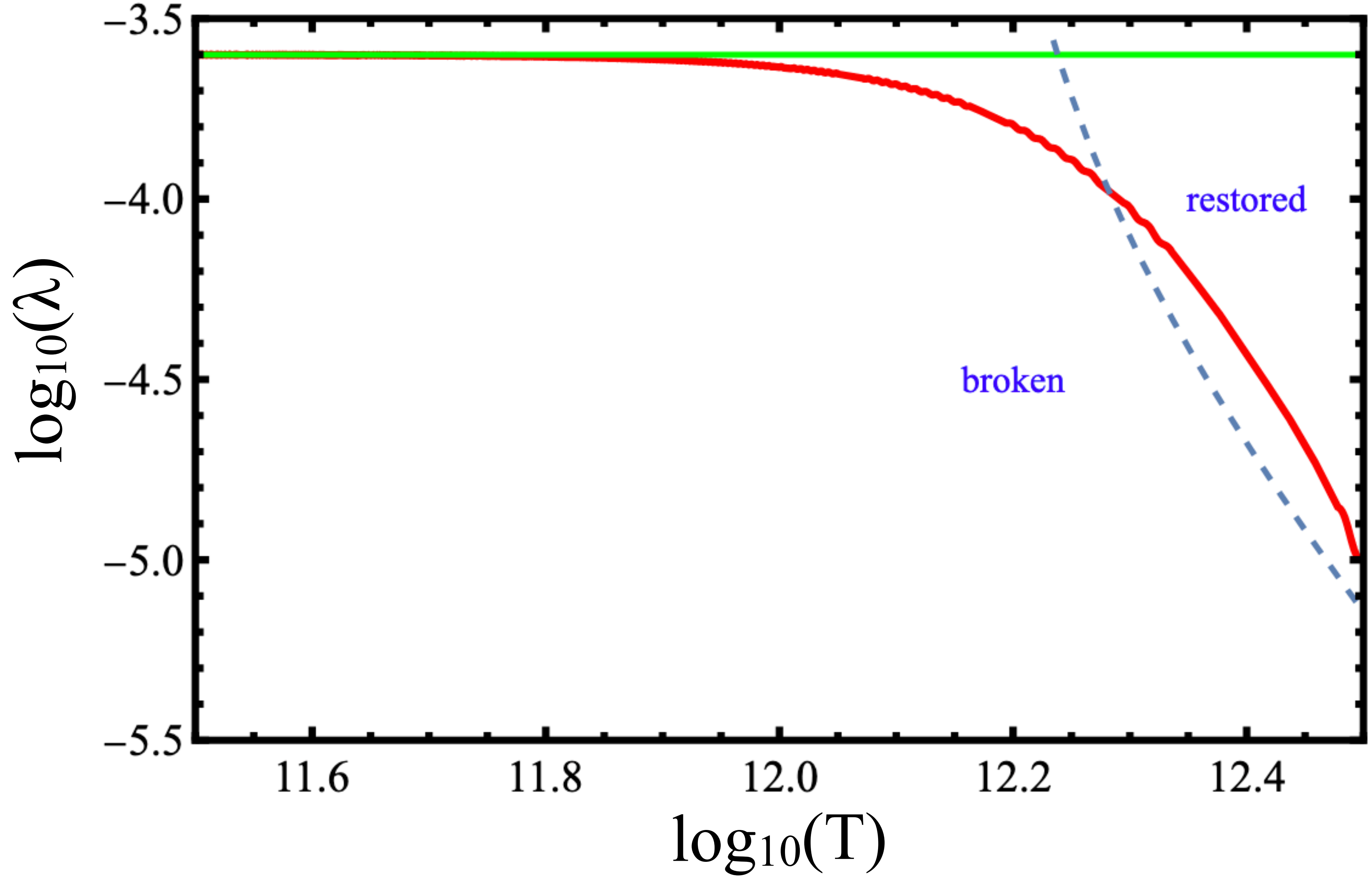


(a) 1-loop contribution to the effective potential.

(b) 2-loop contribution to the effective potential due to quartic.

$\mathcal{V}_{\text{eff}}^{(h)}(v, T, \mu, \lambda(\phi), g)$

# Strongly first order phase transition from field dependent quartic



Knapp-Perez, Mohlabeng, Ratz & Tait, JCAP 03 (2026) 002

# Summary

Scalar controlled couplings and masses can lead to interesting and rich phenomenology

Considered three seemingly different scenarios that share a common thread

**Modulus controlled effective masses and couplings**

1. Scalar controlled neutrino mass to address neutrino mass origin
2. Scalar controlled DM mass to address Ultraheavy DM
3. Scalar controlled quartic leading to strongly first order phase transition

All studies have important consequences for dark sector searches particularly DM

Modulus can itself also be dark matter

# Thank you