Supercool Dark Matter

Joachim Kopp

(University of Mainz / PRISMA Cluster of Excellence)

Brda 2016 Workshop, Medana, Slovenia

Based on work done in collaboration with
Michael J. Baker
arXiv:1608.07578

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

erc

PRISMA

Dark Matter with an Afterburner

Joachim Kopp

(University of Mainz / PRISMA Cluster of Excellence)

Brda 2016 Workshop, Medana, Slovenia

Based on work done in collaboration with
Michael J. Baker
arXiv:1608.07578

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

erc

PRISMA

The Vev Flip-Flop

Dark Matter Decay between Weak Scale Phase Transitions

Joachim Kopp

(University of Mainz / PRISMA Cluster of Excellence)

Brda 2016 Workshop, Medana, Slovenia

Based on work done in collaboration with
Michael J. Baker
arXiv:1608.07578

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

Setting the Dark Matter Relic Density

- Thermal freeze-out
  - $\chi\chi \leftrightarrow$ SM SM in equilibrium
  - At $m_\chi/T \gtrsim 25$, DM density too low to maintain equilibrium
  - DM abundance fixed henceforth

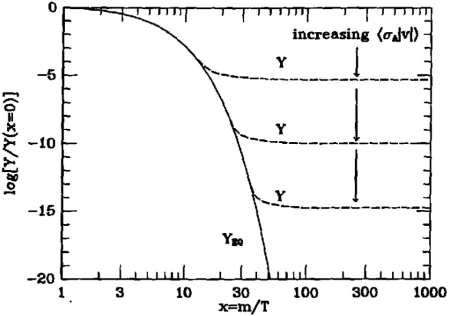


Image credit: Kolb Turner

Setting the Dark Matter Relic Density

- Thermal freeze-out
- Asymmetric DM
  - Particle–antiparticle asymmetry similar to the baryon asymmetry

Setting the Dark Matter Relic Density

- Thermal freeze-out
- Asymmetric DM
- Misalignment mechanism for axion DM
  - Scalar field oscillates about shallow potential minimum

Setting the Dark Matter Relic Density

- Thermal freeze-out
- Asymmetric DM
- Misalignment mechanism for axion DM
- Dodelson–Widrow mechanism for sterile neutrino DM
  - Oscillations between active and sterile neutrinos
  - Hard interactions collapse wave function into pure ν_s ($\sim \sin^2 2\theta$) or pure ν_a ($\sim 1 - \sin^2 2\theta$)
  - After many interactions, significant ν_s abundance can be produced.

This talk: Temporarily unstable DM

- Initial overabundance reduced by DM decay
- Electroweak phase transition stabilizes DM
    - Relic density frozen

The Vev Flip-Flop

The Vev Flip-Flop

Consider SM + complex scalar S

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$
$$- \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

- S charged under dark sector $\mathbb{Z}_2$
- S carries hypercharge -1

The Vev Flip-Flop

Consider SM + complex scalar S

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$
$$- \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

- S charged under dark sector $\mathbb{Z}_2$
- S carries hypercharge -1

Add DM fermion χ

$$\mathcal{L} \supset y_\tau \overline{L_\tau} H \tau_R^- + y_\chi S^\dagger \bar{\chi} \tau_R^- + h.c.$$

- χ stabilized by $\mathbb{Z}_2$
- χ unstable when $\langle S \rangle \neq 0$

The Vev Flip-Flop

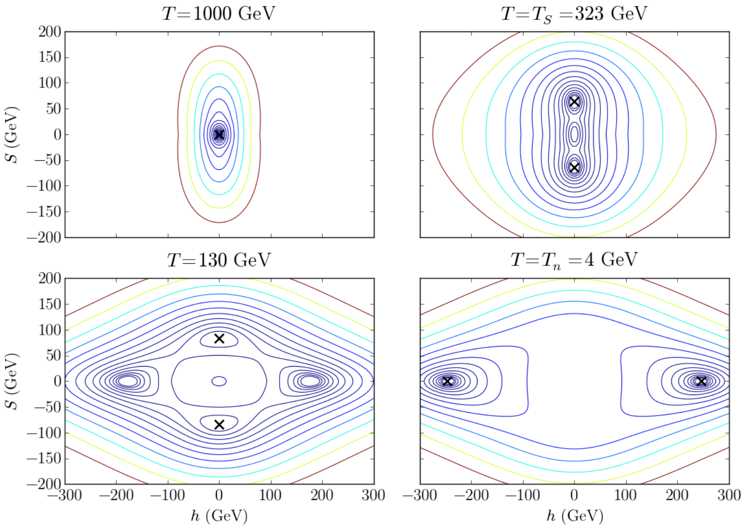
Consider SM + complex scalar S

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$
$$- \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

Evolution of $\langle S \rangle$ and $\langle H \rangle$:

1. Universe starts out with $\langle S \rangle = \langle H \rangle = 0$
   - Scalar potential dominated by thermal corrections
2. As T drops, $\langle S \rangle$ develops vev
   - DM unstable
3. At even lower T, H develops vev
4. Feedback of $\langle H \rangle$ through Higgs portal λ_p changes sign of $S^\dagger S$ term
   - $\langle S \rangle = 0$
   - DM stabilized again

The Vev Flip-Flop



Scalar Potential at finite T

Four types of contributions:

- Tree level

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

$$- \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

Scalar Potential at finite T

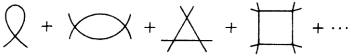
Four types of contributions:

- Tree level

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$
$$- \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

- Coleman–Weinberg Coleman Weinberg 1973, Dolan Jackiw 1974

$$V^{\text{CW}} = \sum_i \frac{n_i}{64\pi^2} m_i^4(h, S) \left[\log \frac{m_i^2(h, S)}{\Lambda^2} - \frac{3}{2} \right]$$



Scalar Potential at finite T

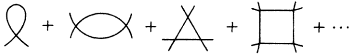
Four types of contributions:

- Tree level

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

- Coleman–Weinberg   Coleman Weinberg 1973, Dolan Jackiw 1974

$$V^{\text{CW}} = \sum_i \frac{n_i}{64\pi^2} m_i^4(h, S) \left[\log \frac{m_i^2(h, S)}{\Lambda^2} - \frac{3}{2}\right]$$



- One-loop finite T corrections   Dolan Jackiw 1974

$$V^T = \sum_i \frac{n_i T^4}{2\pi^2} \int_0^\infty dx\, x^2 \log \left[1 \pm \exp\left(-\sqrt{x^2 + m_i^2(h, S)/T^2}\right)\right]$$

Scalar Potential at finite T

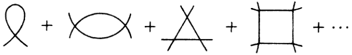
Four types of contributions:

- Tree level

$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$
$$- \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

- Coleman–Weinberg   Coleman Weinberg 1973, Dolan Jackiw 1974

$$V^{\text{CW}} = \sum_i \frac{n_i}{64\pi^2} m_i^4(h, S) \left[\log \frac{m_i^2(h, S)}{\Lambda^2} - \frac{3}{2}\right]$$

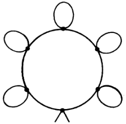


- One-loop finite T corrections   Dolan Jackiw 1974

$$V^T = \sum_i \frac{n_i T^4}{2\pi^2} \int_0^\infty dx\, x^2 \log\left[1 \pm \exp\left(-\sqrt{x^2 + m_i^2(h, S)/T^2}\right)\right]$$

- Resummed “daisy” contributions   Dolan Jackiw 1974, Carrington 1992

$$V^{\text{daisy}} = -\frac{T}{12\pi} \sum_i n_i \left(\left[m_i^2(h, S) + \Pi_i(T)\right]^{\frac{3}{2}} - \left[m_i^2(h, S)\right]^{\frac{3}{2}} \right)$$



Evolution of DM abudance

Boltzmann equations

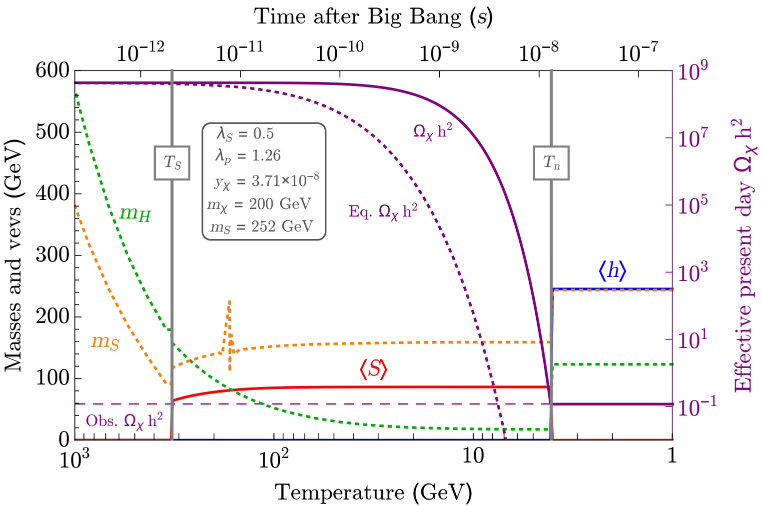
$$\dot{n}^j_\chi + 3Hn^j_\chi = -\frac{\Gamma}{\gamma^j}\left(n^j_\chi - n^{j,\text{eq}}_\chi\right)$$

n^j_χ … number density in j-th momentum mode
$n^{j,\text{eq}}_\chi$ … equilibrium number density in j-th momentum mode
H … Hubble parameter
Γ … decay rate
γ^j … relativistic gamma factor

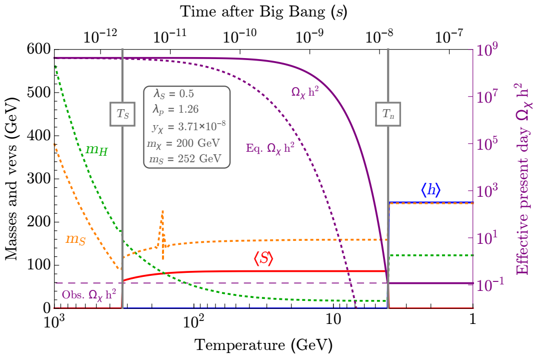
Friedmann equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\left(\rho_{\text{SM}} + \rho_\chi\right).$$

Evolution of DM abudance

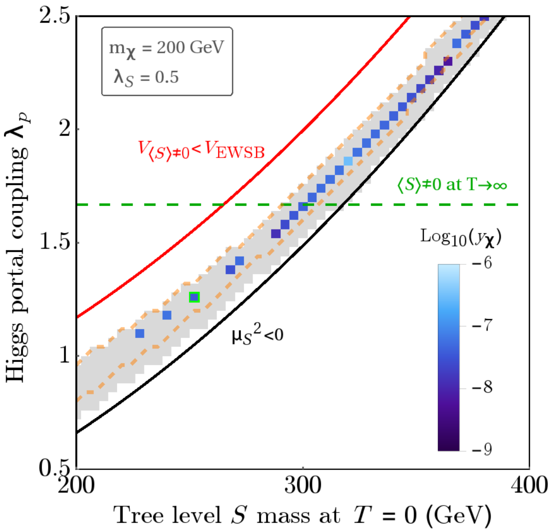


Evolution of DM abundance

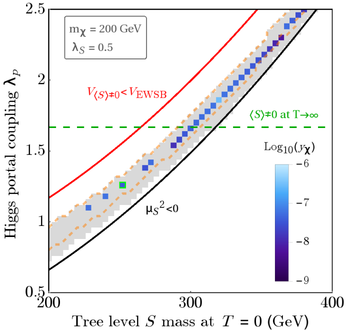


- Decays out of thermal equilibrium
- EWSB must be postponed to $T \sim$ few GeV to give DM time to decay
  - Universe goes through supercooled state
  - Electroweak phase transition is strongly first order
    $\rightarrow$ electroweak baryogenesis?

Parameter space



Parameter space



- Sucessful phenomenology in narrow sliver of parameter space
  - But this is the sliver preferred by electroweak baryogenesis
- At other points:
  - Phase transition to early
  - Why not increase y_χ?
    $\rightarrow$ Does not help, DM abundance will never drop below $n_\chi^{\rm eq}$

Summary

Summary

The Vev Flip-Flop

- is a new mechanism to set the DM relic density
  - Basic idea: DM temporarily unstable while $\mathbb{Z}_2$ symmetry is broken
- Works in limited parameter region
  - But this is the region favored by electroweak baryogenesis (strongly first order phase transition)

Summary

The Vev Flip-Flop

- is a new mechanism to set the DM relic density
  - Basic idea: DM temporarily unstable while $\mathbb{Z}_2$ symmetry is broken
- Works in limited parameter region
  - But this is the region favored by electroweak baryogenesis (strongly first order phase transition)

Future directions:

- More detailed collider pheno
- Switching annihilation on and off with a vev flip-flop
- Extended models (e.g. vev flip-flop in 2HDM)
- Building a model that incorporates electroweak baryogenesis
- ...

Thank you!