

Dynamic Freeze-In: Impact of Thermal Masses and Cosmological Phase Transitions on Dark Matter Production

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Overview

M.Baker, M.Breitbach, J.Kopp, LM - arXiv:1712.039625

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Three Models:

- Kinematically Induced Freeze-In
- Vev-Induced Production with a Vev-Flipflop
- Vev-Induced Mixing with a Vev-Flipflop

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This Talk:

- Vev-Induced Mixing with a Vev-Flipflop

The Vev-Flipflop (2-step PT)

The Vev-Flipflop

Introduction

- Add a scalar field S to the SM Lagrangian.
- Coupled via a Higgs Portal coupling

Effective Potential

$$V \supset -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_P (H^\dagger H)(S^\dagger S)$$

The Vev-Flipflop

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- Include thermal effects and 1-loop contributions into effective Potential

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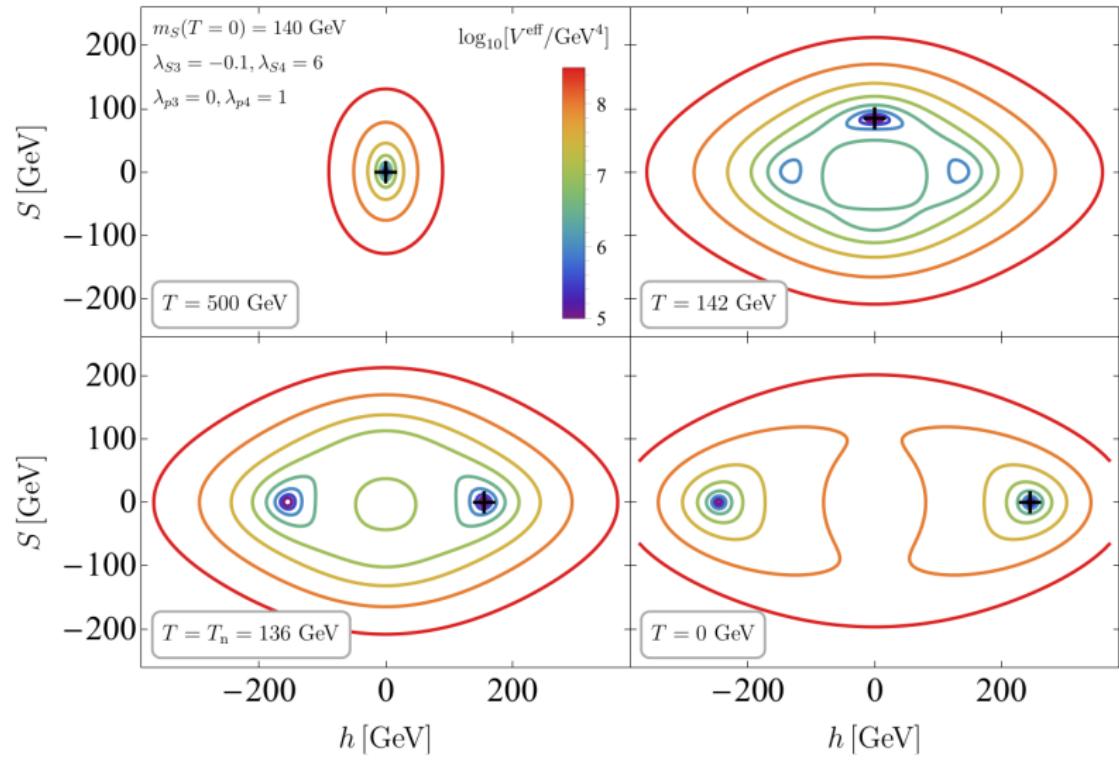
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Goal

Choose coefficients such that S undergoes two phase-transitions as thermal corrections become subdominant.

The Vev-Flipflop

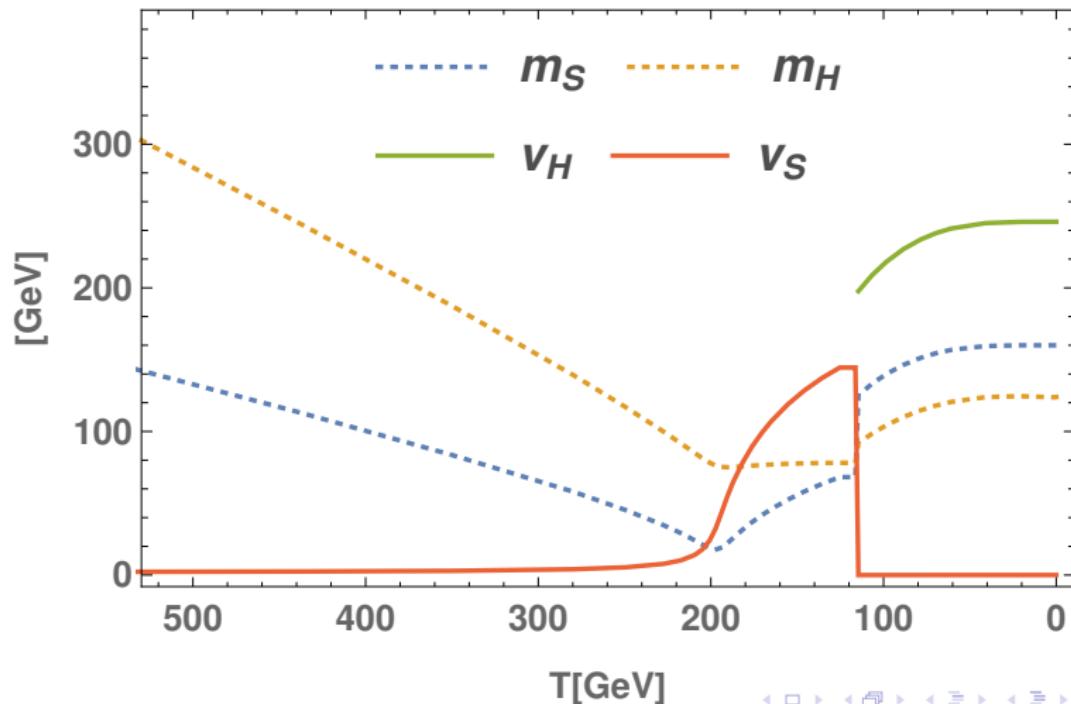
The Effective Potential



The Vev-Flipflop

Evolution of Temperature Dependent Quantities

- Thermal Evolution tracked with *CosmoTransitions*



Vev-Induced Mixing

Vev-Induced Mixing

Model Overview

Field	Mass	$SU(3)_c \times SU(2)_L \times U(1)_Y$	\mathbb{Z}_2	\mathbb{Z}'_2
χ	$\mathcal{O}(100 \text{ GeV})$	(1, 1, 0)	+1	-1
ψ	$\mathcal{O}(10 \text{ TeV})$	(1, 1, 0)	-1	-1
S	$\mathcal{O}(100 \text{ GeV})$	(1, 1, 0)	-1	+1

$$L_{int} \supset y_\chi S \bar{\chi} \psi + h.c.$$

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- Freeze-In Scenario
- S vev leads to mixing between χ and ψ with small mixing angle $\theta = \frac{v_S y_\chi}{m_\psi} \approx 10^{-8}$

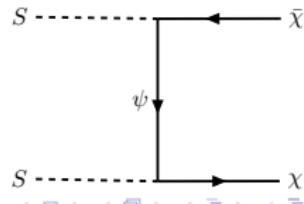
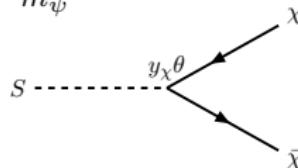
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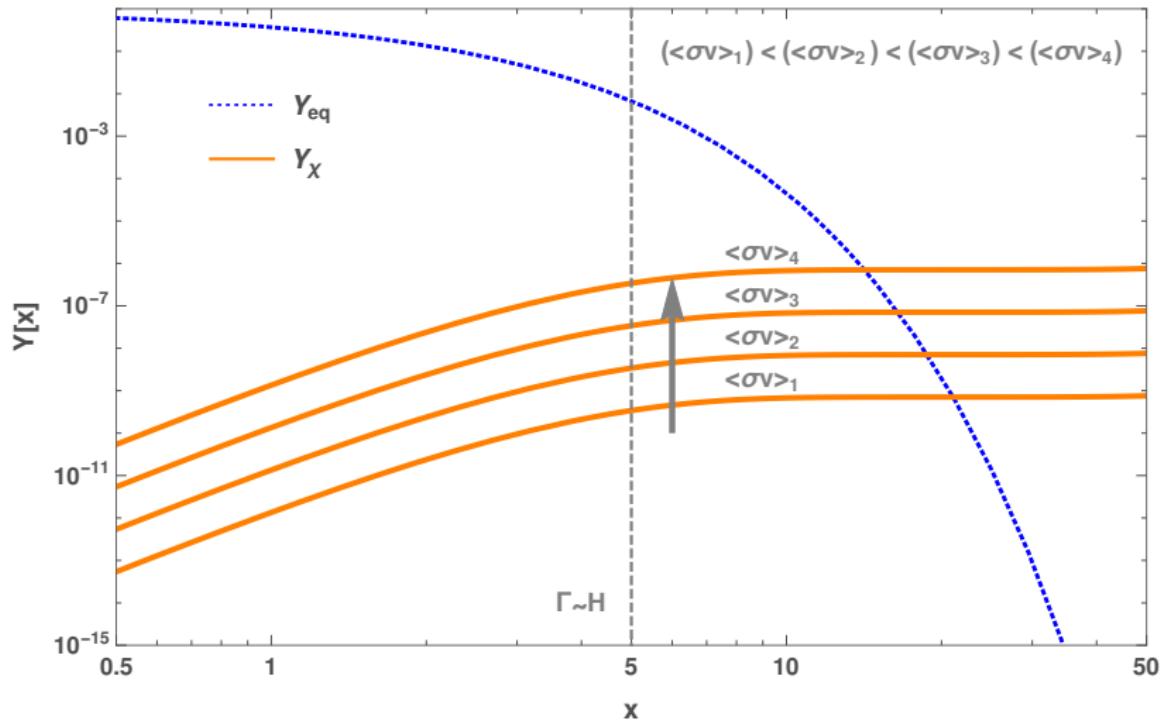
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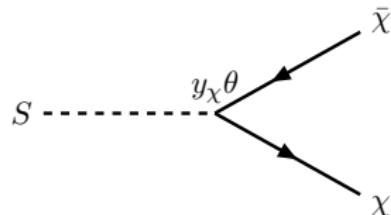
Freeze-In

A Lightning Fast Reminder

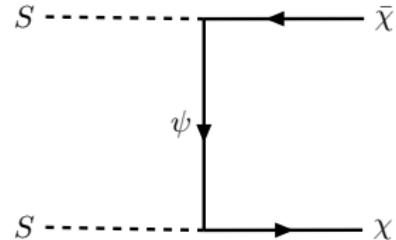


Vev-Induced Mixing

Producing χ from the thermal bath



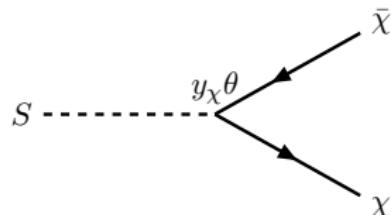
$$\Gamma_{S\chi\chi} = y_\chi^2 \theta^2 \frac{\sqrt{m_S^2 - 4m_\chi^2} (m_S^2 - 4m_\chi^2)}{8\pi m_S^2}$$



$$\sigma_{SS\bar{\chi}\chi} \approx y_\chi^4 \frac{(s - 4m_\chi^2)^{\frac{3}{2}}}{8\pi m_\psi^2 s \sqrt{s - 4m_S^2}}$$

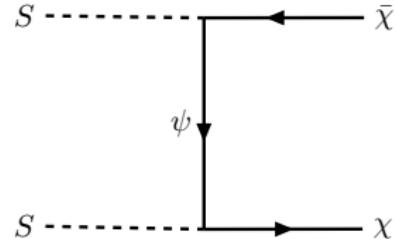
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- Vev-dependent
- Only while S has a vev



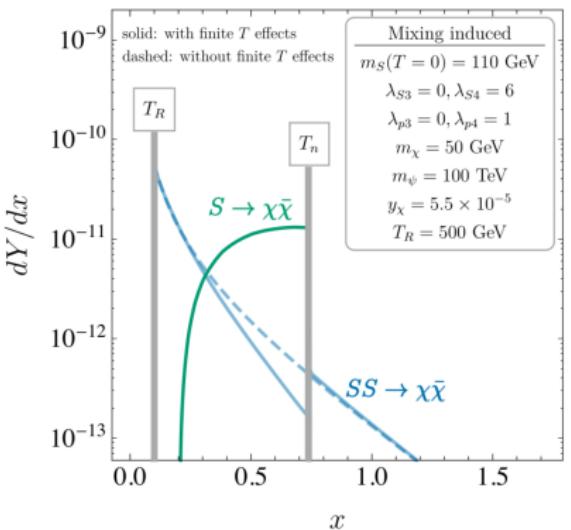
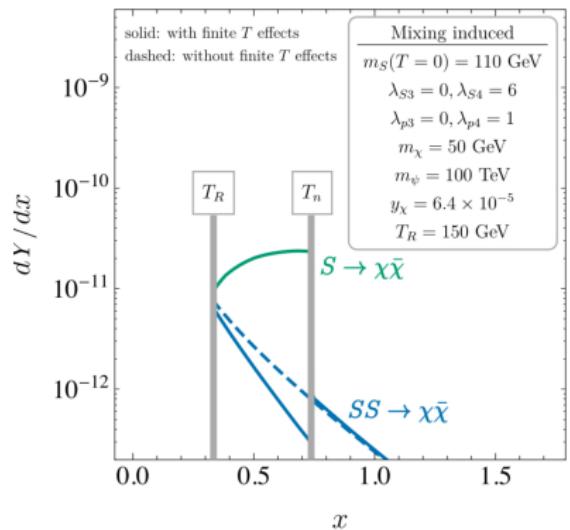
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- Vev-independent
- Immediately after reheating

- This suggests dependence on reheating temperature
- Different scaling of Boltzmann Equations (Decay vs. Annihilation)

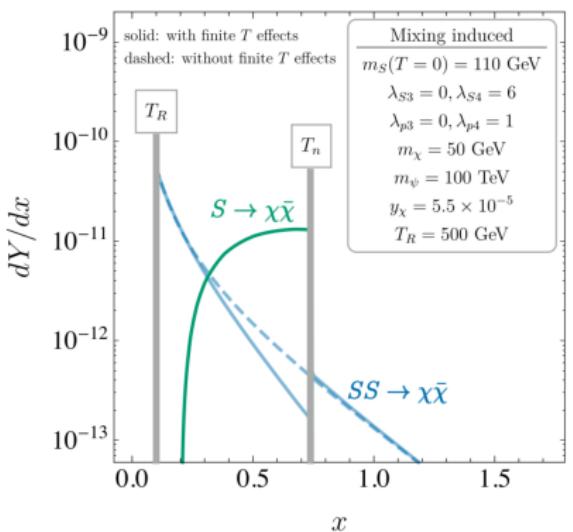
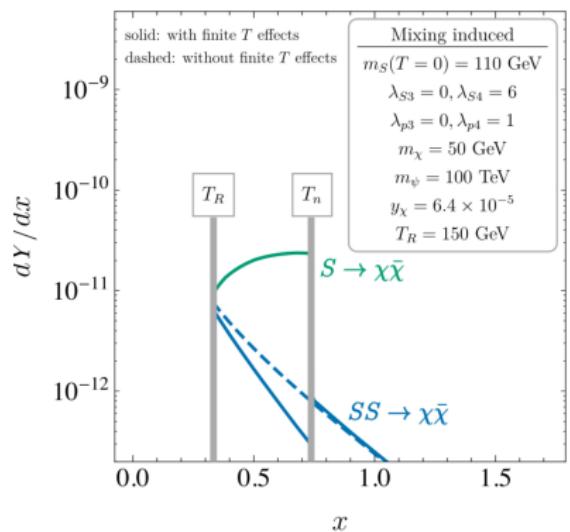
Vev-Induced Mixing

Instantaneous Yield



Vev-Induced Mixing

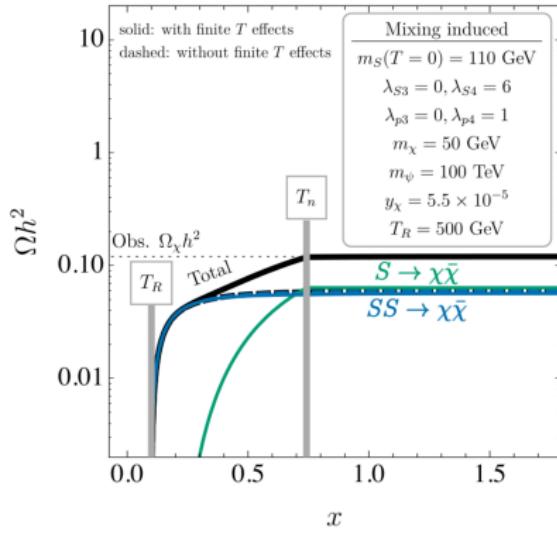
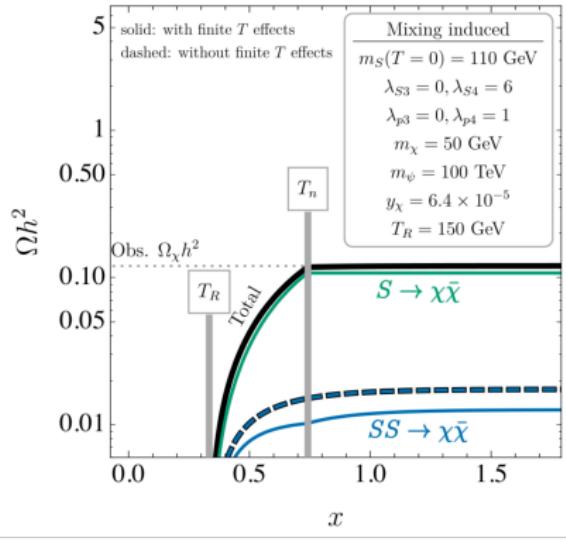
Instantaneous Yield



Reheating Temperature plays important role

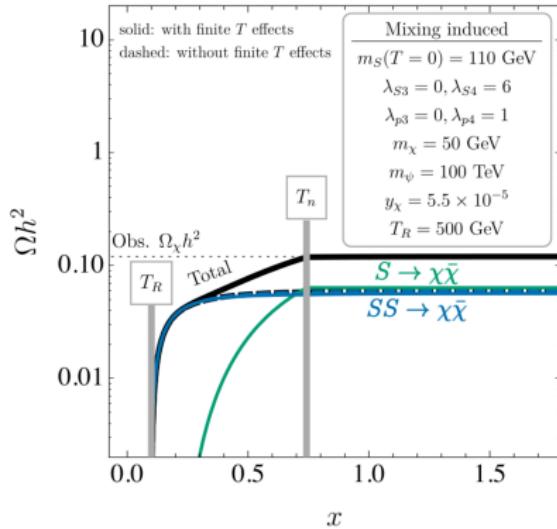
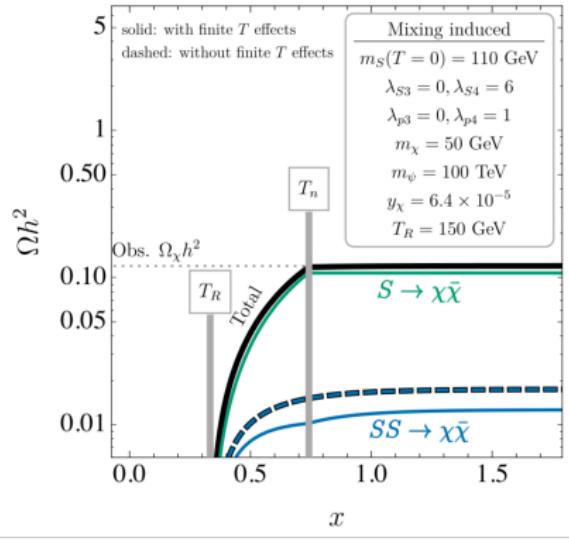
Vev-Induced Mixing

Relic Abundance



Vev-Induced Mixing

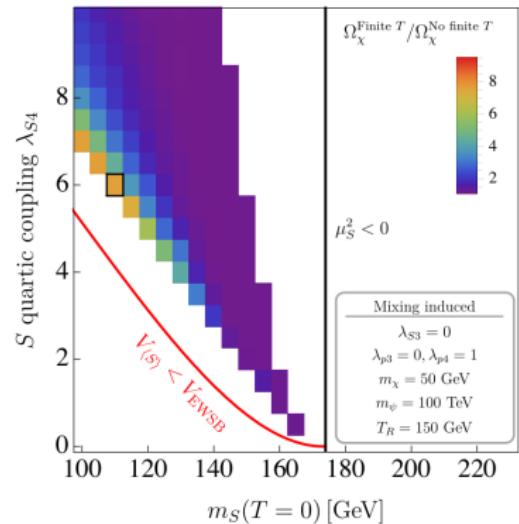
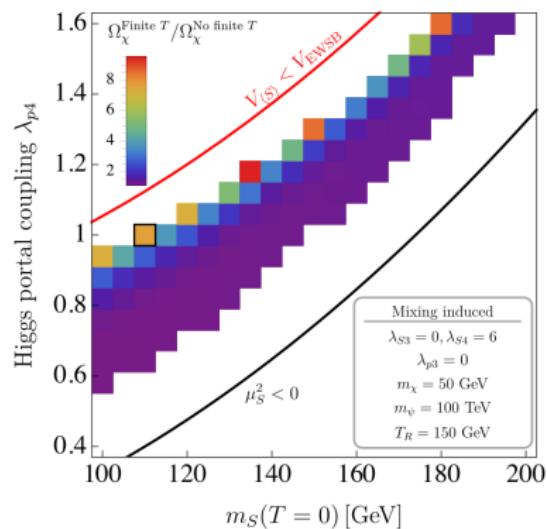
Relic Abundance



Get roughly an order of magnitude less DM when neglecting thermal effects

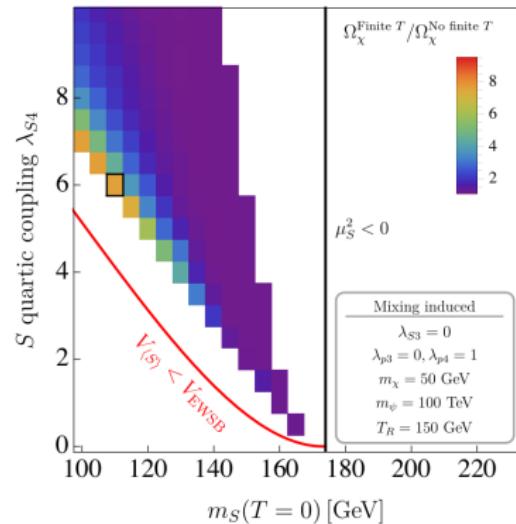
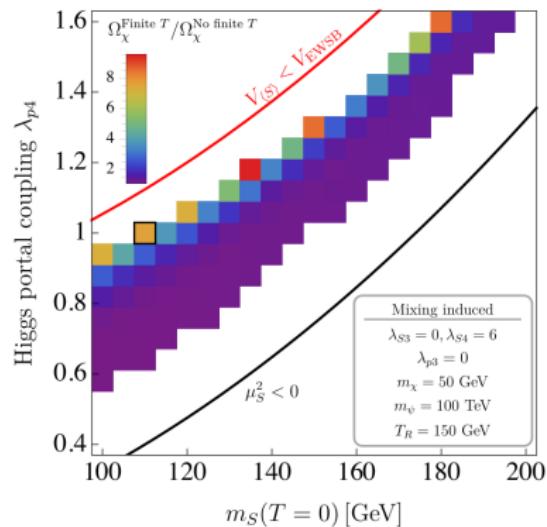
Vev-Induced Mixing

Parameter Space



Vev-Induced Mixing

Parameter Space

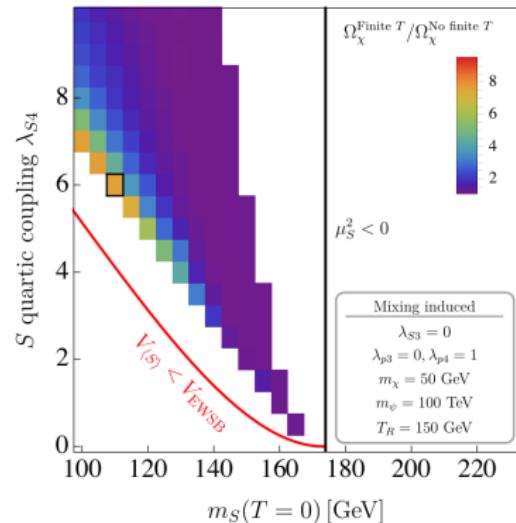
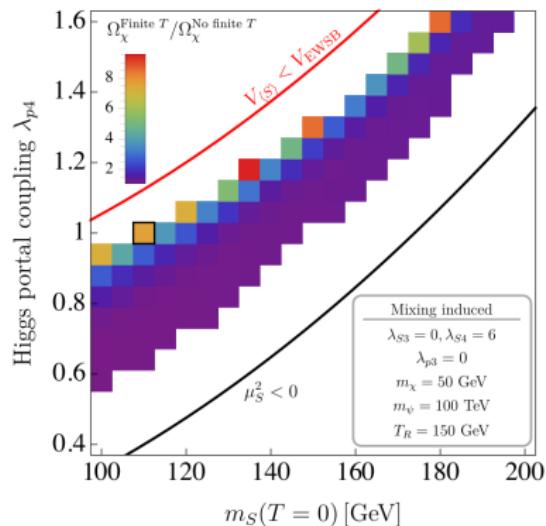


- Lower m_S and higher λ_{P4} lead to more DM from decay channel.

$$m_S^2 = -\mu_S^2 + \frac{\lambda_{P4}\mu_H^2}{2\lambda_H}$$

Vev-Induced Mixing

Parameter Space



- Lower m_S and higher λ_{P4} lead to more DM from decay channel.
- $$m_S^2 = -\mu_S^2 + \frac{\lambda_{P4}\mu_H^2}{2\lambda_H}$$
- Greater μ_S leads to deeper minima, and therefore a later PT

Summary

Cosmological Phasetransitions & Thermal Corrections

- Gravitational waves from 1st order PT
- Possibly opportunities for Baryogenesis in 1st oder PT's
- Can bring hidden sectors in contact with SM during thermal evolution of the universe
- Depending on the model thermal corrections can significantly alter the predicted relic density
- Can open and close kinematic thresholds
- ...

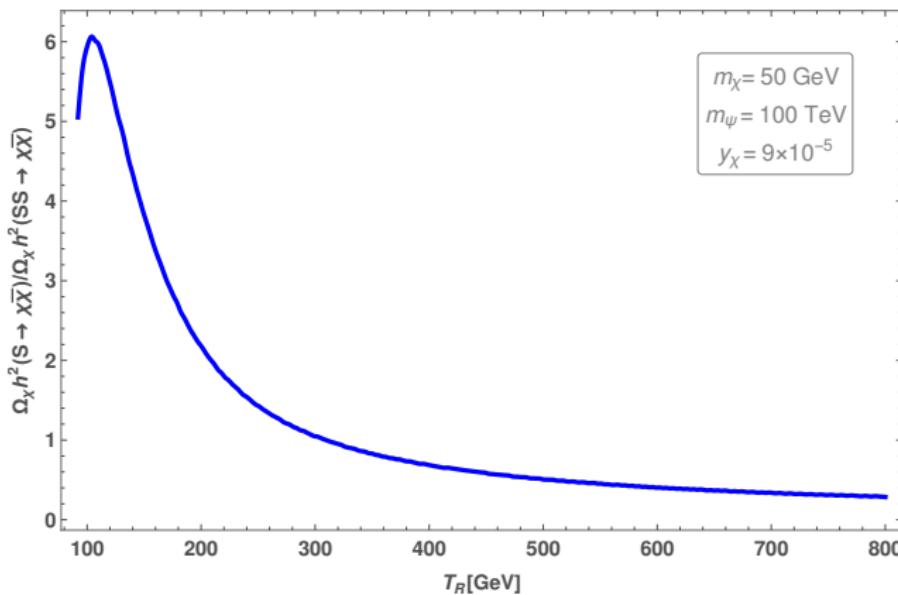
More fun models: arXiv:1712.039625

CAUTION: WATER IS HOTTER THAN AVERAGE

IN A PROFOUND SENSE WHICH WE WON'T
EXPLAIN HERE BECAUSE IT DOESN'T FIT
THE VIBE OF A CAUTIONARY SIGN.

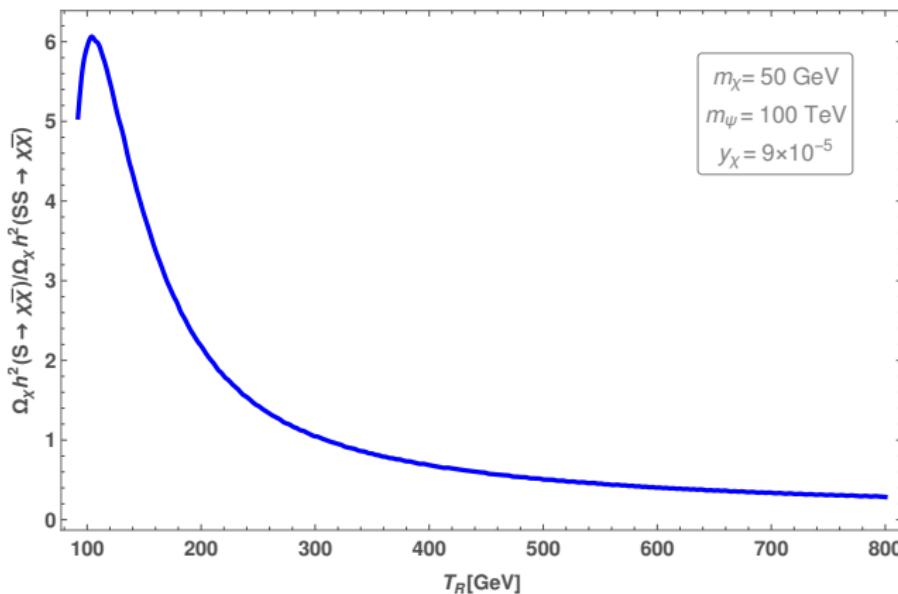
Vev-Induced Mixing

Dependence on reheating Temperature



Vev-Induced Mixing

Dependence on reheating Temperature



- For low T_R up to roughly an order of magnitude more dark matter production via decay channel

Dark Matter Relic Density

Definition

$$\Omega_\chi h^2 = \frac{\rho_{\chi,0}}{\rho_{\text{crit},0}}$$

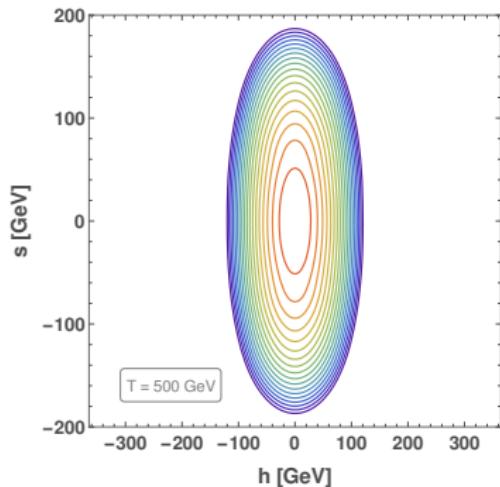
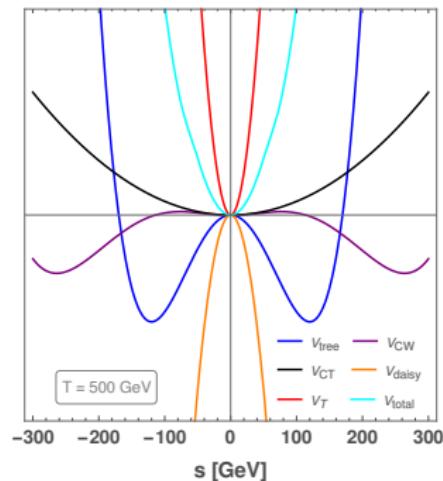
$$\rho_{\chi,0} = m_\chi Y_\chi(T) s(T) \left(\frac{a(T)}{a(T_0)} \right)^3$$

Equation used in this work

$$\Omega_\chi h^2 = \frac{\rho_{\chi,0}}{\rho_{\text{crit},0}} h^2 = m_\chi n_\chi(T) \left(\frac{a(T)}{a(T_0)} \right)^3 \frac{1}{\rho_{\text{crit},0}} h^2$$

The Vev-Flipflop

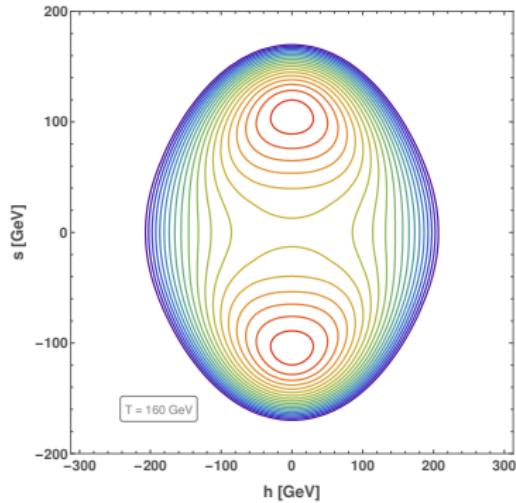
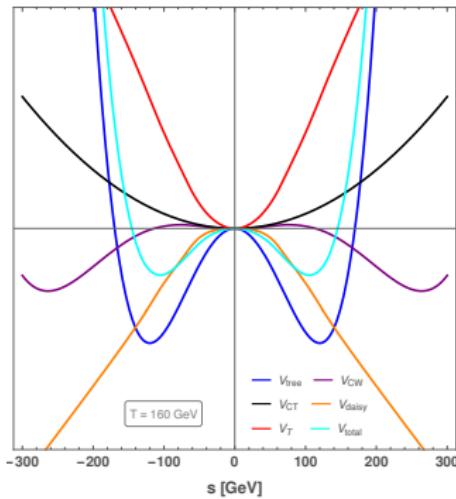
The Effective Potential



- $V_T \propto T^4$ dominates effective potential
- Potential symmetric at high temperatures

The Vev-Flipflop

The Effective Potential

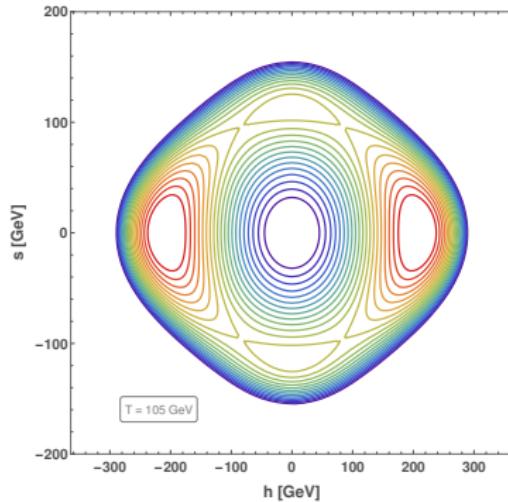
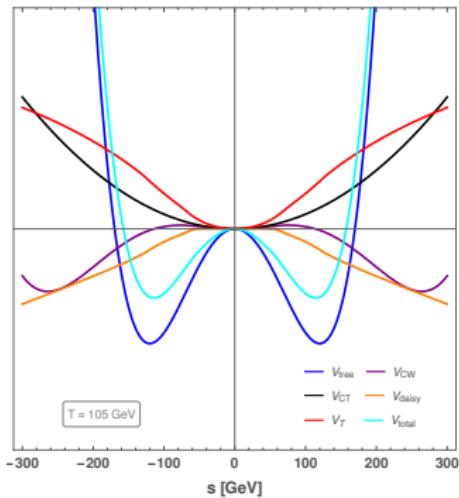


- Temperature falls and pot. get's closer to tree-level pot.

- Minima in s direction have formed
- PT to s minimum

The Vev-Flipflop

The Effective Potential

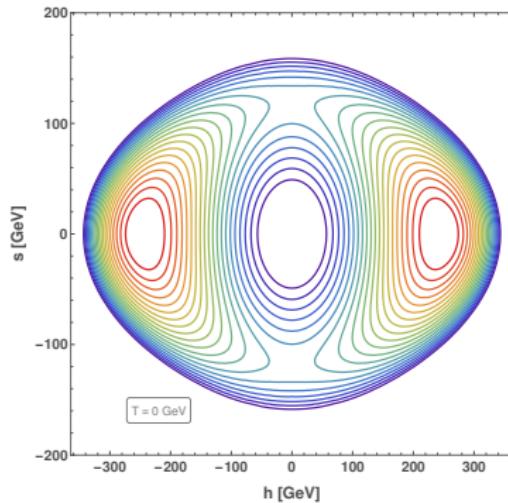
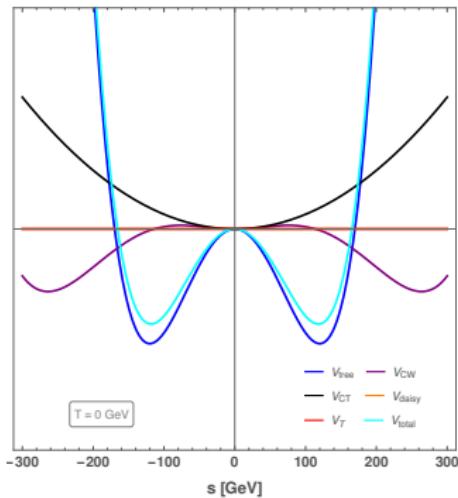


- Minima in s direction persist, but universe will tunnel to global minimum eventually
- 1st order PT to h minimum

- Global minimum in h direction has formed
- Potential Barrier between h and s minima, *Supercooling*

The Vev Flip-Flop

The effective Potential



- At 0 GeV, temperature-dependent corrections have vanished
- Higgs minimum assumes SM value of 246 GeV

Computing the Dark Matter Abundance

The Boltzmann Equation

Outline

Goal

Track number density through thermal evolution of universe

The Boltzmann Equation

Outline

Goal

Track number density through thermal evolution of universe

- Describe non-equilibrium dynamics \Rightarrow Boltzmann Equation
- Take temperature dependent masses and vevs into account
- Depending on the process, different RHS (Collisionterm)

Boltzmann Equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = - \int d\Pi_{\bar{\chi}} d\Pi_\chi d\Pi_{\bar{f}} d\Pi_f (2\pi)^4 \delta(p_{\bar{\chi}} + p_\chi - p_{\bar{f}} - p_f) [|M_{\bar{\chi}\chi \rightarrow \bar{f}f}|^2 f_{\bar{\chi}} f_\chi (1 \pm f_{\bar{f}})(1 \pm f_f) - |M_{\bar{f}f \rightarrow \bar{\chi}\chi}|^2 f_{\bar{f}} f_f (1 \pm f_{\bar{\chi}})(1 \pm f_\chi)]$$

The Boltzmann Equation

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$$\frac{dn_\chi}{dt} + 3Hn_\chi = - \int d\Pi_{\bar{\chi}} d\Pi_\chi d\Pi_{\bar{f}} d\Pi_f \quad f_i = (\exp(E_i/T) \pm 1)^{-1}$$
$$(2\pi)^4 \delta(p_{\bar{\chi}} + p_\chi - p_{\bar{f}} - p_f)$$
$$[|M_{\bar{\chi}\chi \rightarrow \bar{f}f}|^2 f_{\bar{\chi}} f_\chi (1 \pm f_{\bar{f}})(1 \pm f_f) - |M_{\bar{f}f \rightarrow \bar{\chi}\chi}|^2 f_{\bar{f}} f_f (1 \pm f_{\bar{\chi}})(1 \pm f_\chi)]$$

The Boltzmann Equation

Derivation

Often approximations and simplifications can be made

- $f_{\bar{f}} = f_f \& f_{\bar{\chi}} = f_\chi$
- $|M_{\bar{f}f \rightarrow \bar{\chi}\chi}|^2 = |M_{\bar{\chi}\chi \rightarrow \bar{f}f}|^2$
- Neglect Pauli-Blocking/Bose-Condensation $(1 \pm f_i) \approx 1$
- Depending on mass of particles and temperature $f_i \approx e^{-E_i/T}$
- Changing variables from t to $x = m/T$ and from n to $Y = n/s$ often convenient

The Boltzmann Equation

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Simplified Form

$$\Rightarrow \frac{dY_\chi}{dx} = -\frac{s \langle \sigma v \rangle}{Hx^2} [Y_\chi^2 - (Y_\chi^{eq})^2]$$

The Boltzmann Equation

Derivation

Often approximations and simplifications can be made

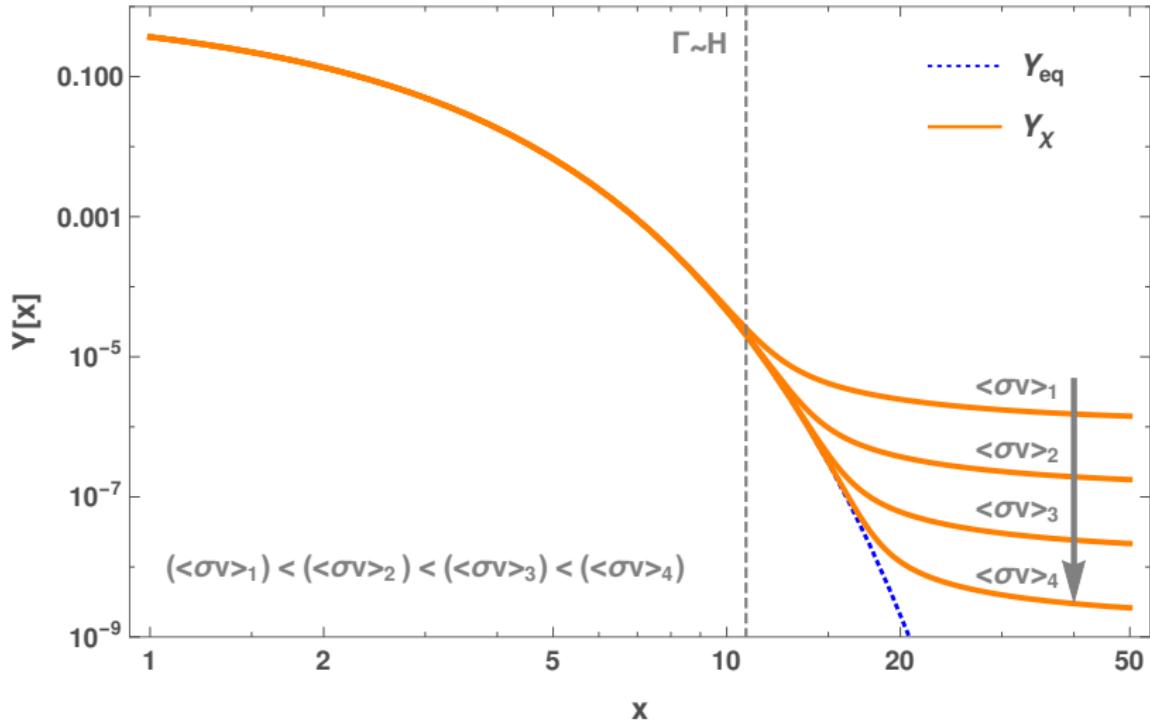
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Simplified Form

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- Numerically solve ODE in C or if possible integrate in *Mathematica*

Freeze-Out



Freeze-In

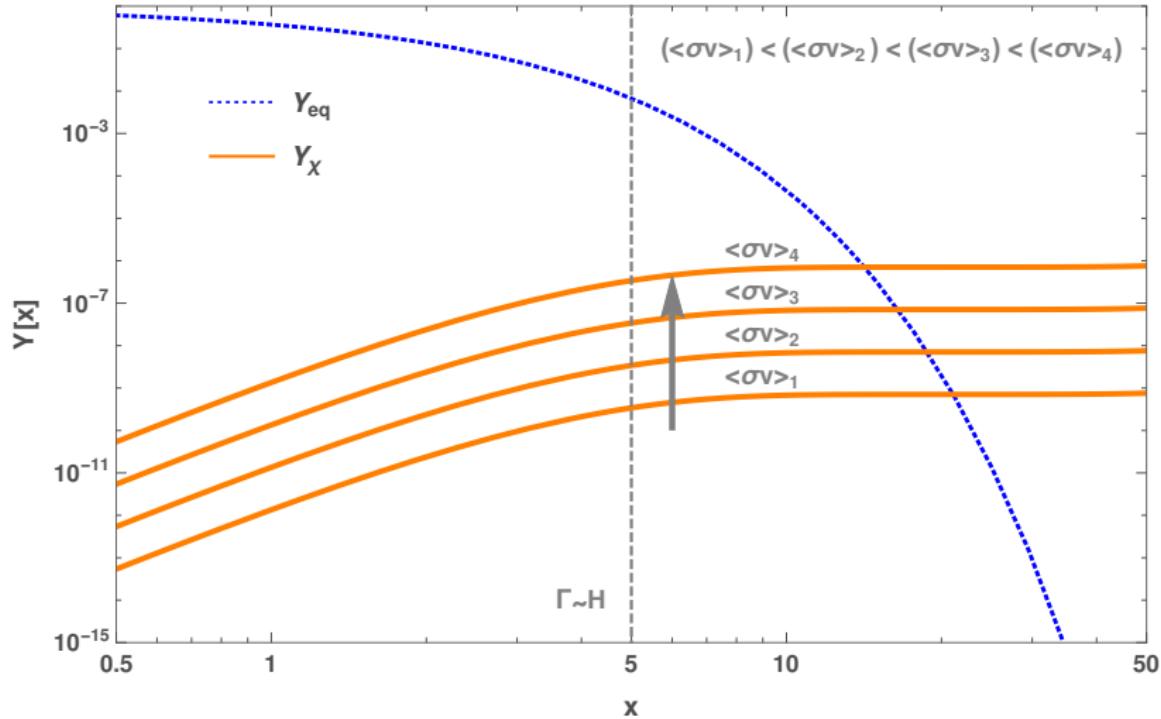
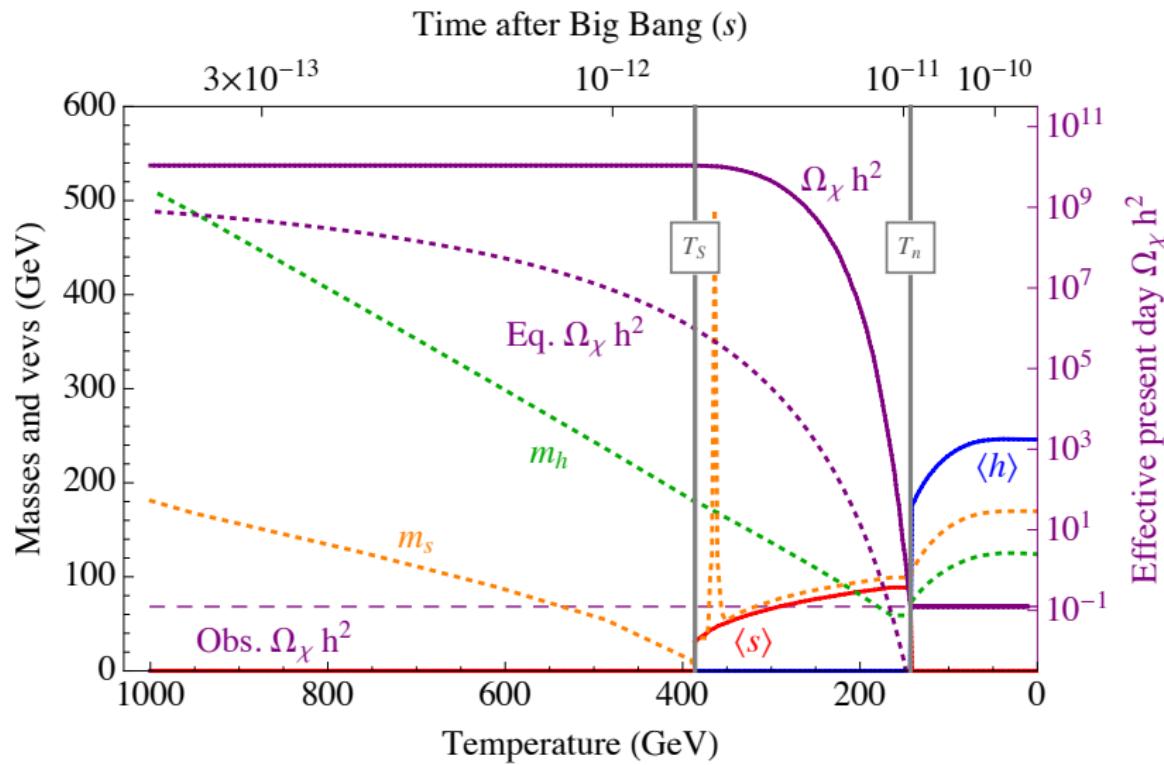


Illustration of the three Phases



J.Kopp & M.Baker arXiv:1608.07578

Vev-Induced Mixing

Boltzmann Equations

- The Boltzmann Equation for the decay channel is given by:

$$\frac{dY_\chi}{dT} = \frac{1}{2\pi^2 H(T) s(T)} K_1 \left(\frac{m_S(T)}{T} \right) \Gamma_{S\chi\chi}(T) m_S(T)^2$$

Vev-Induced Mixing

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- For the Annihilation Process:

$$\frac{dY_\chi}{dT} = \frac{1}{32\pi^4 H(T)s(T)} \int_{4m_S(T)^2}^{\infty} ds (s - 4m_S(T)^2) \sigma(s, T) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right)$$