University of Zurich[UZH]

Thermal-Dynamic Dark Matter
Finite Temperature Effects in the Early Universe

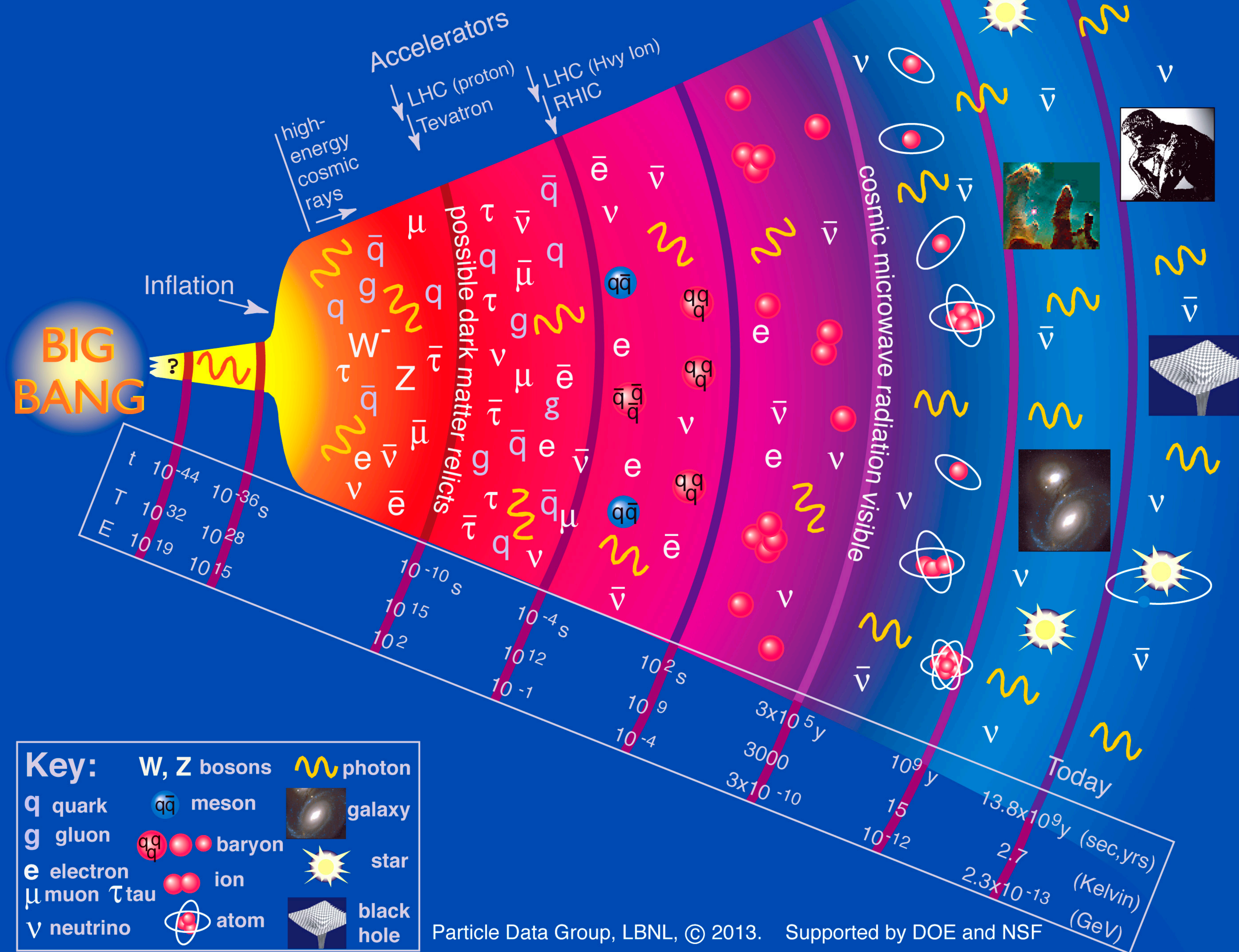
Michael J. Baker

Next Frontiers in the Search for Dark Matter, GGI
23 Sep 2019

Based on 1608.07578 (PRL), 1712.03962 (JHEP), and 1811.03101 (JHEP)

MJB, M. Breitbach, L. Mittnacht, J. Kopp

History of the Universe



The Main Message

Finite temperature effects, while often ignored, can have a dramatic consequence on the relic abundance of particles

Show this in several production mechanisms of dark matter

Approach

One BSM model with several new scenarios for producing DM:

- Instantaneous freeze-out
- Kinematically induced freeze-in
- Decaying dark matter

Main tools:

- One-loop effective potential at finite temperature
- Boltzmann equations

- Outline

- Model
- Particle physics and the effective potential at finite temperature
  - Instantaneous freeze-out
  - Kinematically induced freeze-in
- Two step phase transition (vev flip-flop)
  - Decaying dark matter

Model

- BSM Model

Field	Spin	$\mathbb{Z}_2$	mass scale
S	0	$+1$	0.1 GeV – 500 GeV
χ	$\frac{1}{2}$	-1	5 GeV – 5 TeV
ψ	$\frac{1}{2}$	-1	5 GeV – 5 TeV

$$\mathcal{L} \supset y_\chi \bar{\chi}\chi S + y_\psi \bar{\psi}\psi S + [y_{\chi\psi}\bar{\psi}\chi S + h.c.] + m_\chi \bar{\chi}\chi + \tilde{m}_\psi \bar{\psi}\psi$$
$$+ \mu_H^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 + \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_{S4}}{4!} S^4$$
$$- \frac{\lambda_{S3}}{3!}\,\mu_S S^3 - \lambda_{p3}\mu_S\, S(H^\dagger H) - \frac{\lambda_{p4}}{2}\, S^2(H^\dagger H)$$

Particle Physics and the Effective Potential at Finite T

- Particle Physics at Finite Temperature

Can we apply our usual zero-T techniques?
What happens to vertices and propagators?

Imaginary-time formalism: field operators quantized on

$$0 \leq it \leq 1/T$$

`The great advantage of this formalism is that perturbation theory may still be organised into a diagrammatic expansion with the same vertices as at T = 0.' [Weldon, 1983]

- What happens to propagators?

The scalar two-point Green's function is

$$D(\omega_n, \vec{p}) = \frac{1}{\omega_n^2 - \vec{p}^{\,2} - m^2 - \pi(\omega_n, \vec{p})}$$

$$\pi(\omega_n, \vec{p}) \underset{\text{I.R.}}{\overset{\text{1-loop}}{\approx}} \pi^{(1)}(\omega_n = 0, \vec{p} = \vec{0}) \overset{\text{e.g.}}{=} \frac{\lambda T^2}{4}$$

Propagator pole receives FT correction

Also for fermions, but negligible for us

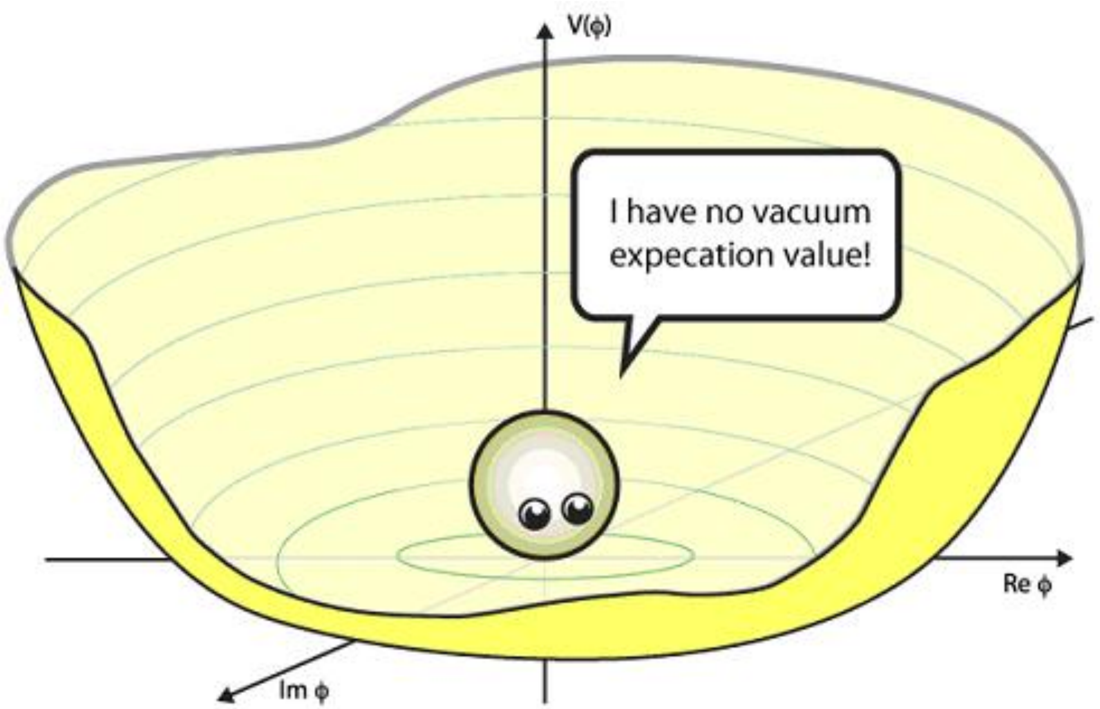
- Particle Physics at Finite Temperature

We can apply our usual zero-T Feynman rules, after substituting T-dependent masses

What about vevs?

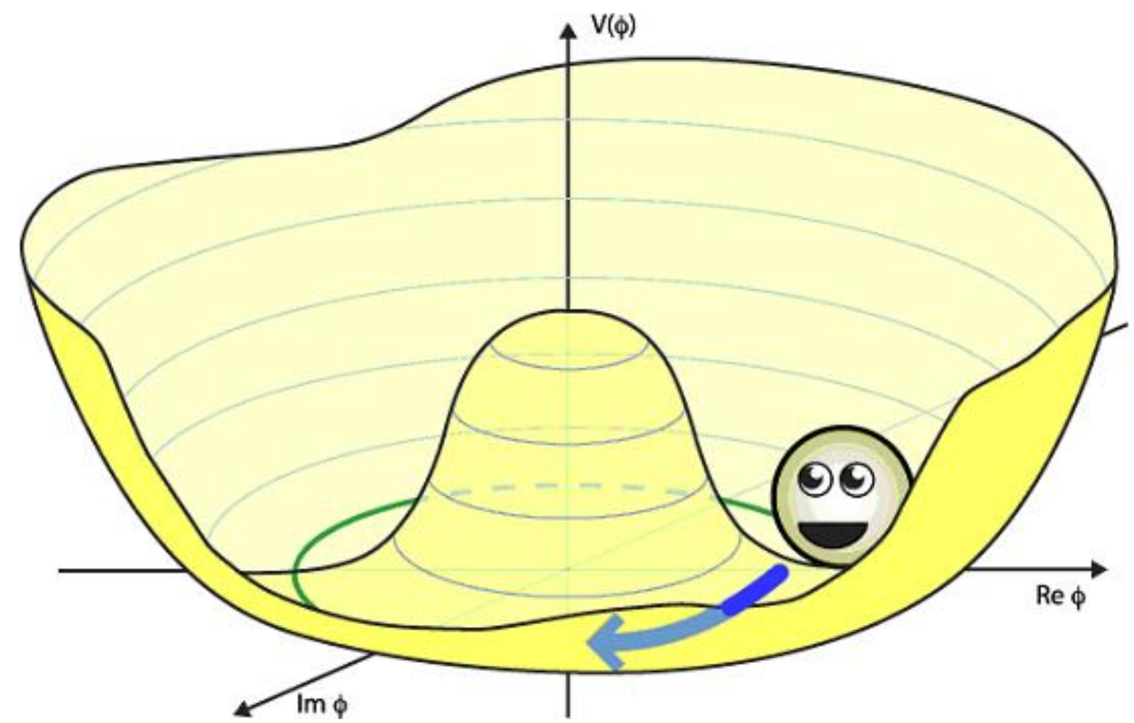
• The Effective Potential

$T \gg T_{\mathrm{EW}}$



[Philip Tanedo]

$T \sim 0$



The effective potential can be calculated in FTQFT using a loop expansion, with leading contribution

$$V^{\mathrm{eff}} = V^{\mathrm{tree}} + V^{\mathrm{CW}} + V^{T} + V^{\mathrm{daisy}}$$

Instantaneous Freeze-out

• Instantaneous Freeze-out

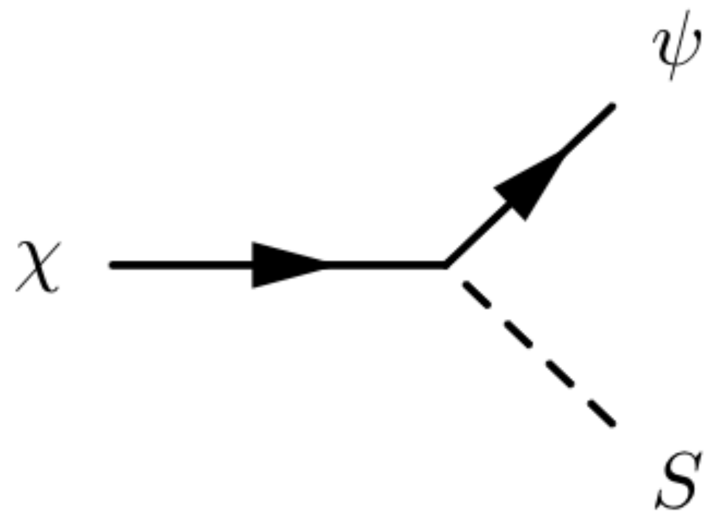
$$\mathcal{L} \supset \cancel{\overset{\sim 0}{y_\chi} \bar{\chi}\chi S} + \overset{2}{y_\psi} \bar{\psi}\psi S + [\overset{\sim 10^{-7}}{y_{\chi\psi}} \bar{\psi}\chi S + h.c.] + m_\chi \bar{\chi}\chi + \tilde{m}_\psi \bar{\psi}\psi$$

$$+ \mu_H^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 + \frac{1}{2}\mu_S^2 S^2 - \frac{\overset{1}{\lambda_{S4}}}{4!} S^4$$

$$\cancel{- \frac{\lambda_{S3}}{3!} \mu_S S^3} \cancel{- \lambda_{p3}\mu_S S(H^\dagger H)} - \frac{\underset{10^{-5} - 10^{-3}}{\lambda_{p4}}}{2} S^2 (H^\dagger H)$$

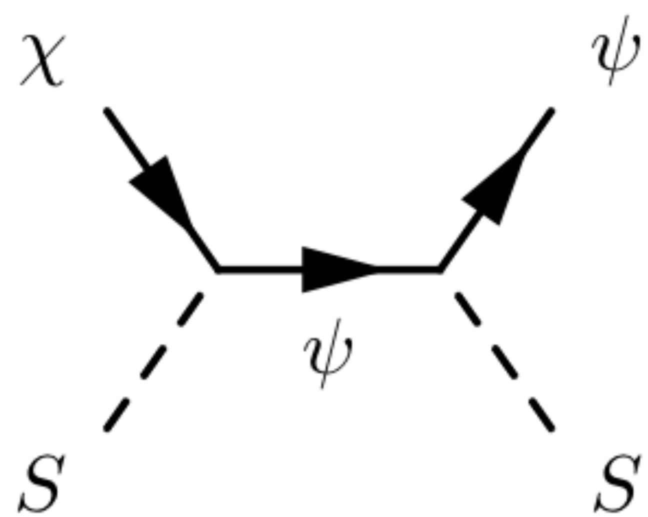
- ψ and S will remain in contact with the thermal bath throughout
- $m_\psi(T) = \tilde{m}_\psi + y_\psi \langle S \rangle (T)$

- Instantaneous Freeze-out



Open when

$$m_\chi > m_\psi(T) + m_S(T)$$

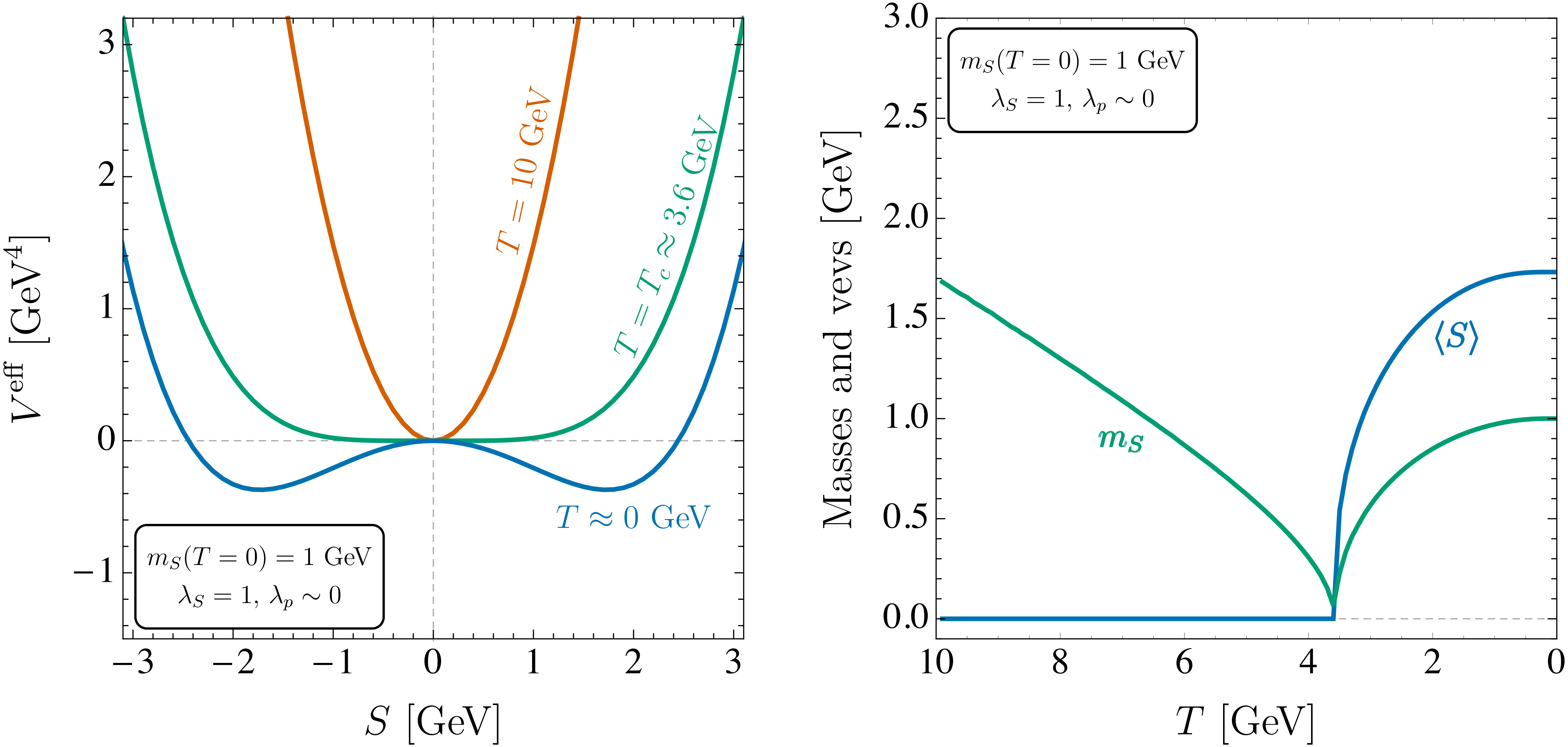


Suppressed by

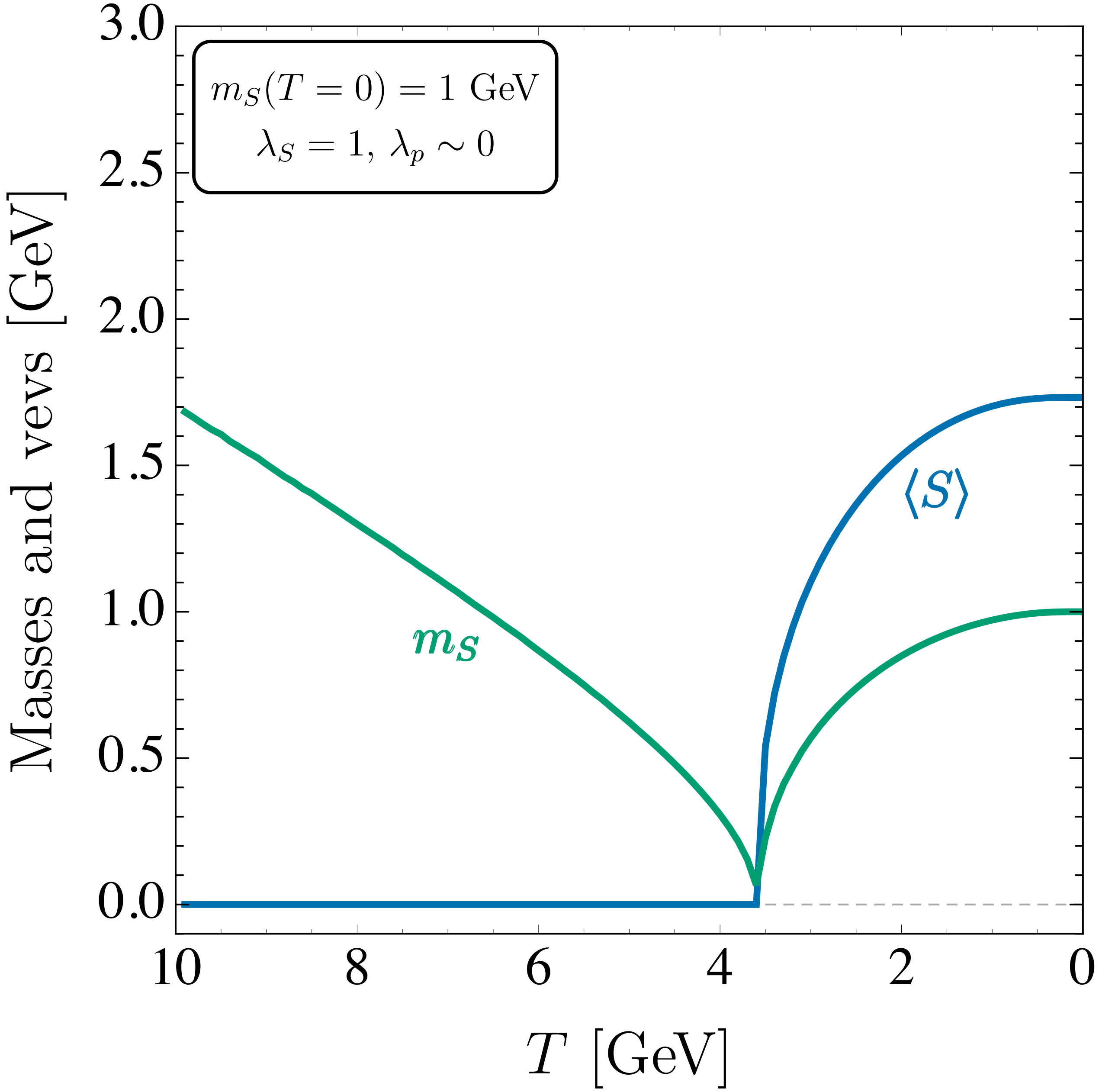
$$x^3 = \left(\frac{m_\chi}{T}\right)^3$$

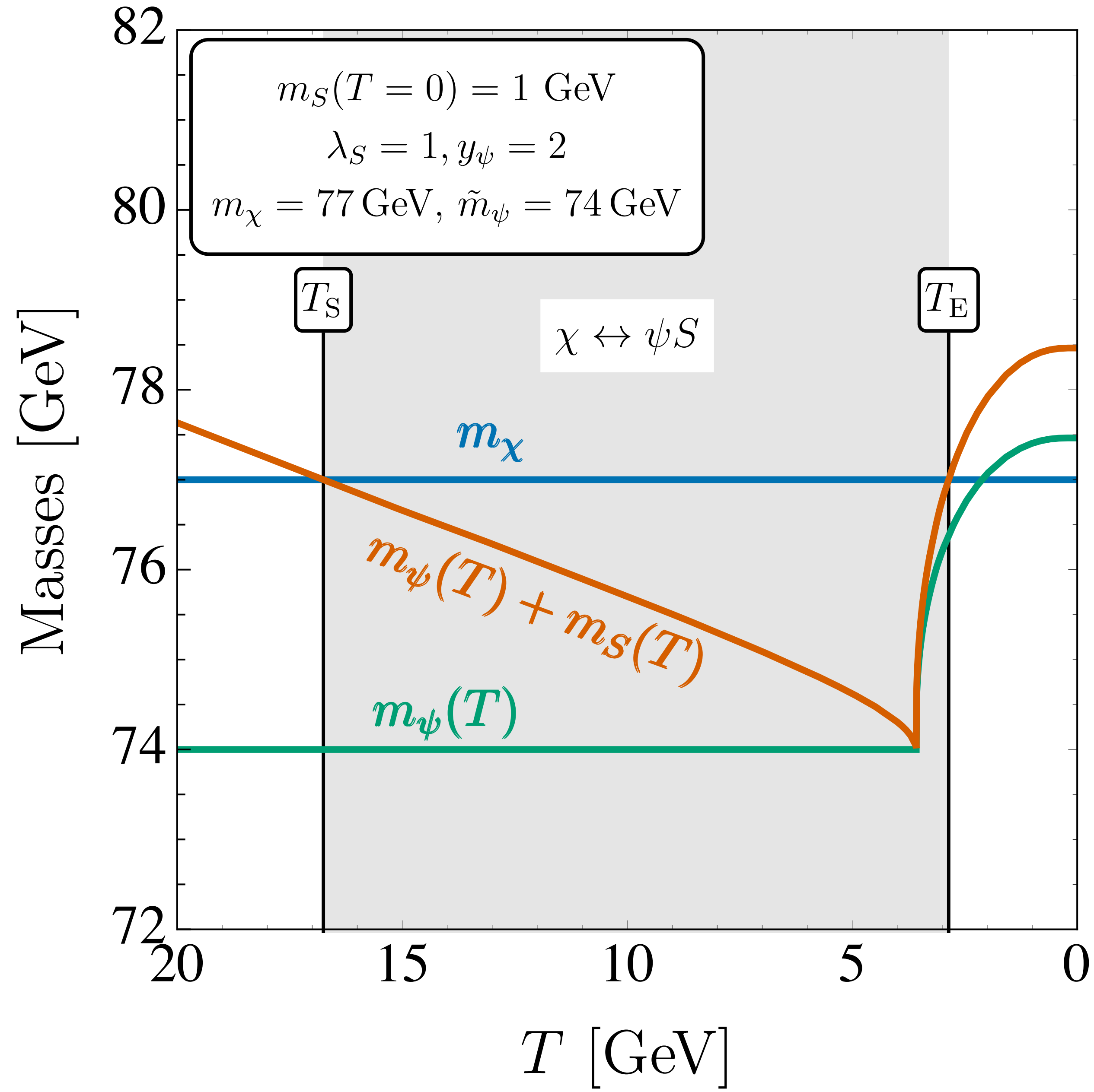
• Instantaneous Freeze-out

Portal coupling is small, so $V^{\text{eff}}(H,S,T) = V^{\text{eff}}(H,T) + V^{\text{eff}}(S,T)$

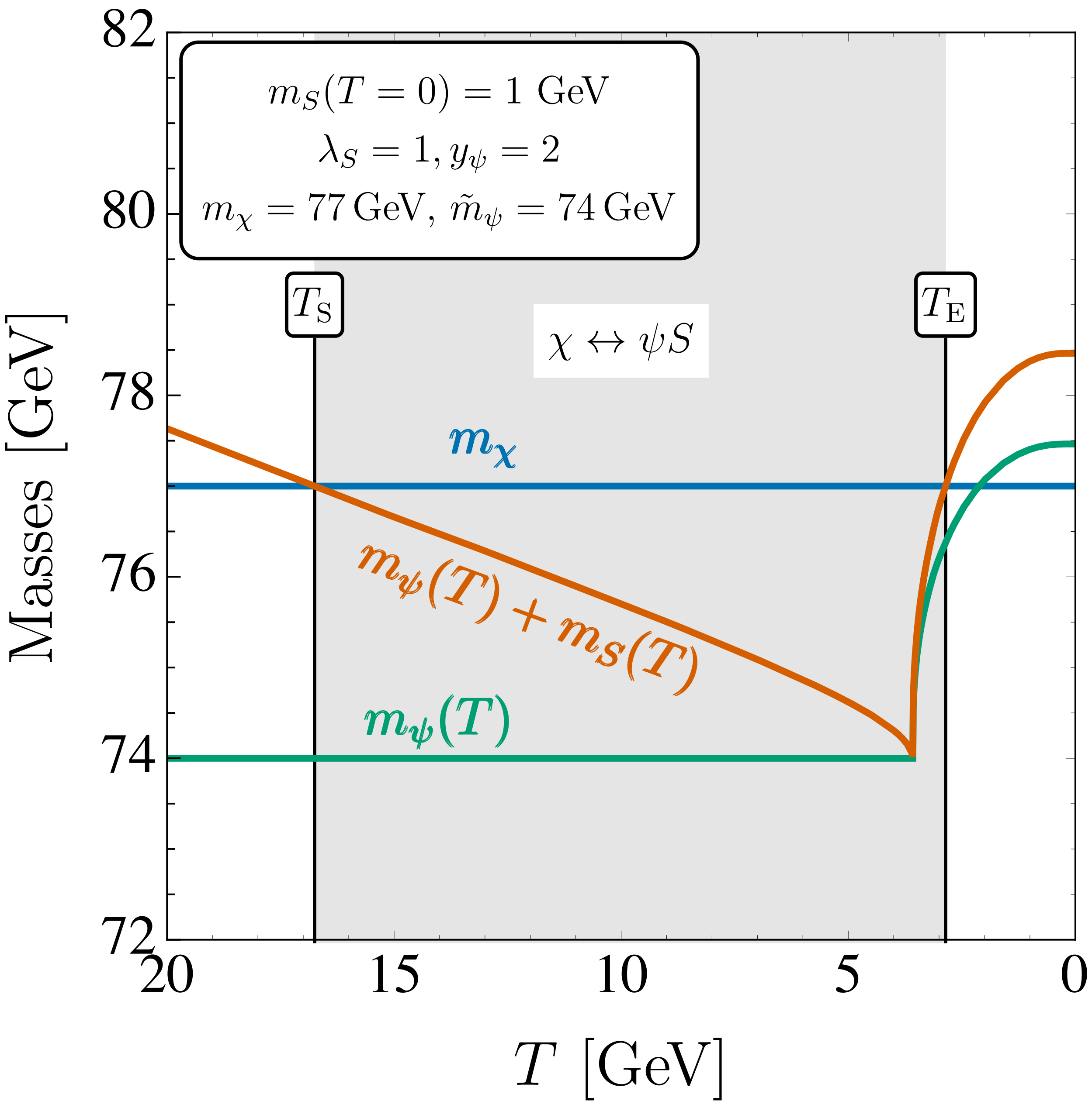


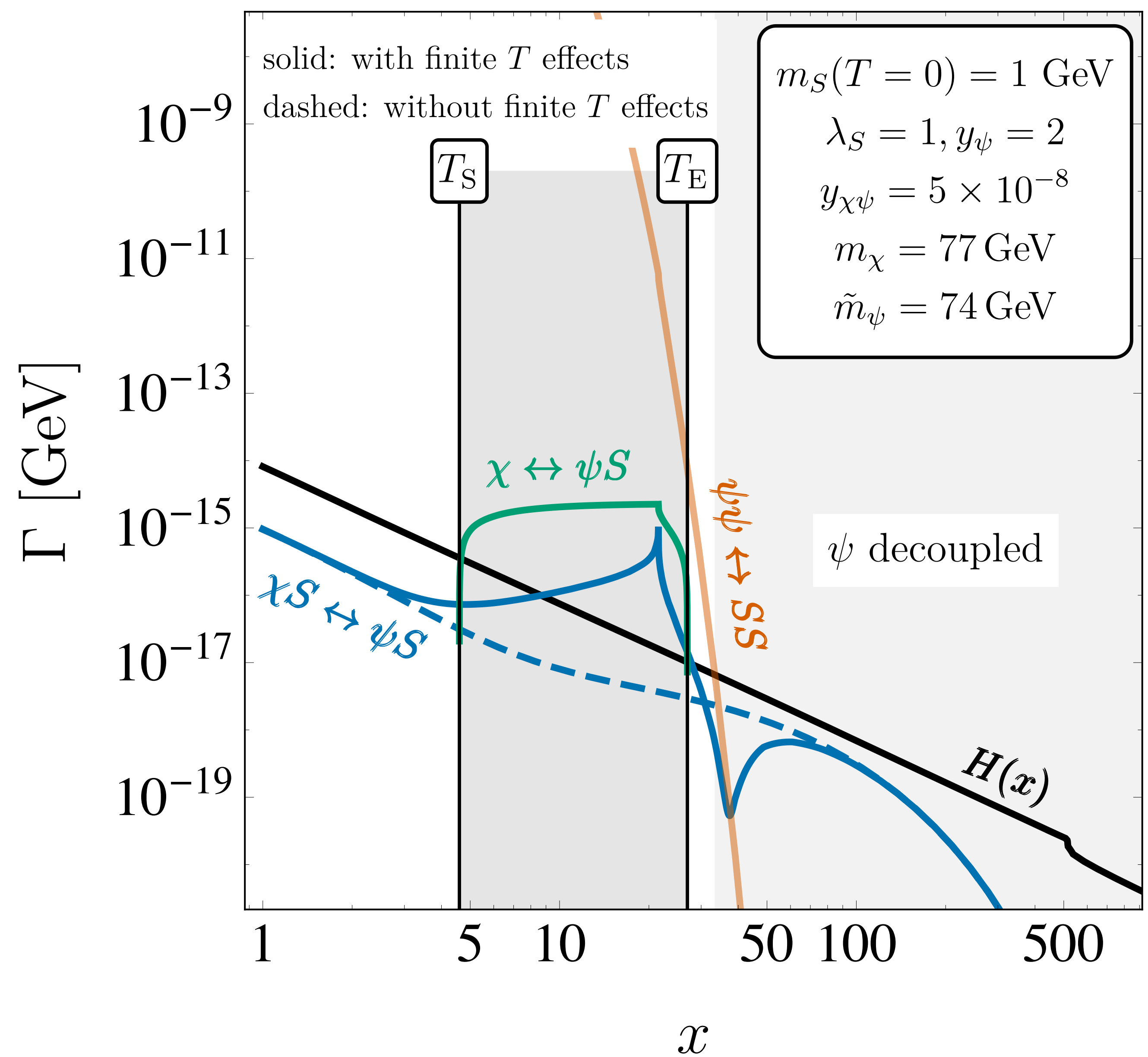
• Instantaneous Freeze-out



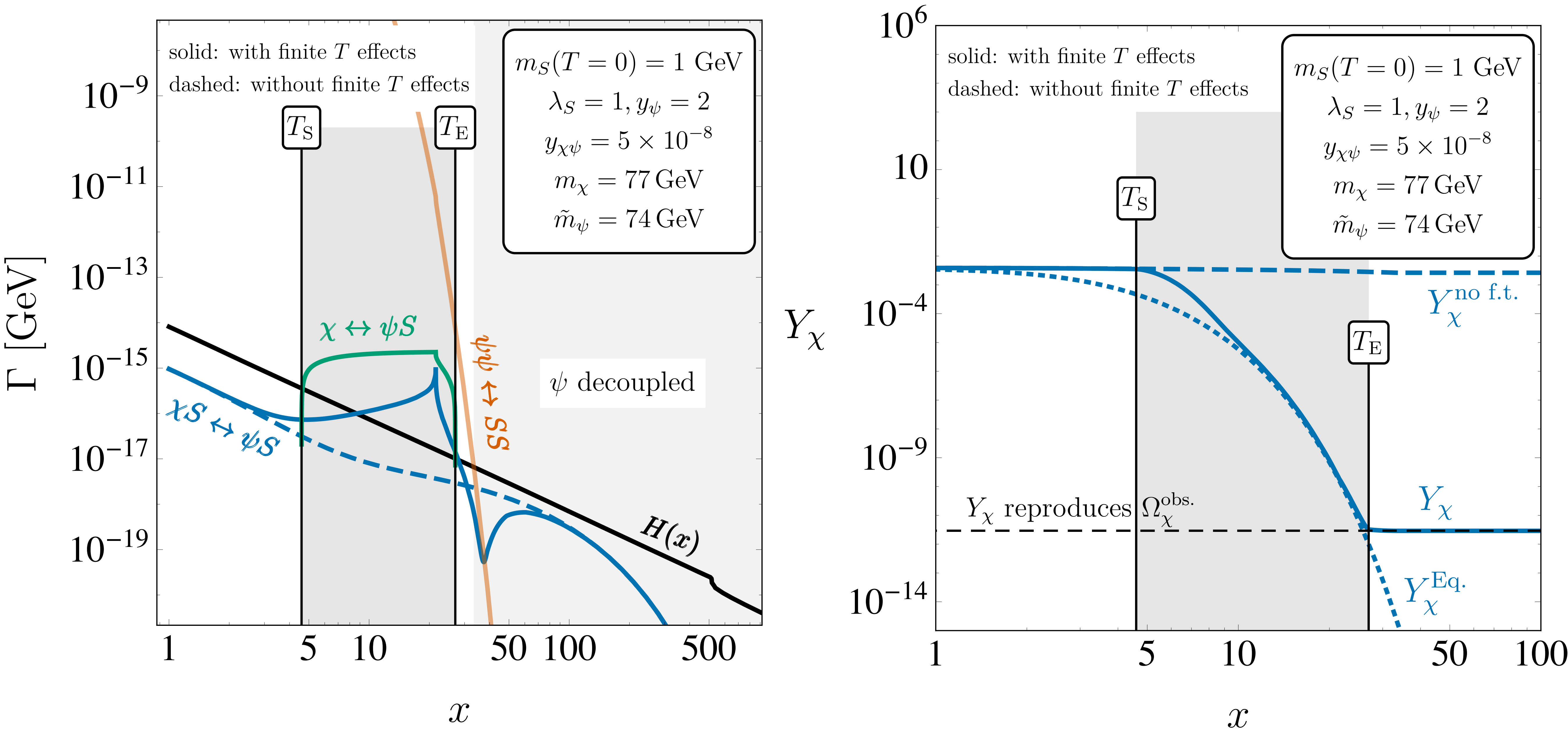


• Instantaneous Freeze-out





• Instantaneous Freeze-out



We have demonstrated a new method of obtaining the relic abundance
Without finite T effects, yield would be 10 orders of magnitude too large

Kinematically Induced Freeze-in

• Kinematically Induced Freeze-in

we'll assume ψ stays in thermal equilibrium via other NP

0.01 $\quad \sim 10^{-12}$

$$\mathcal{L} \supset \cancel{y_\chi \bar{\chi}\chi S} + y_\psi \bar{\psi}\psi S + [y_{\chi\psi}\bar{\psi}\chi S + h.c.] + m_\chi \bar{\chi}\chi + \tilde{m}_\psi \bar{\psi}\psi$$

$$+ \mu_H^2 H^\dagger H - \lambda_H (H^\dagger H)^2 + \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_{S4}}{4!}S^4 \quad 1$$

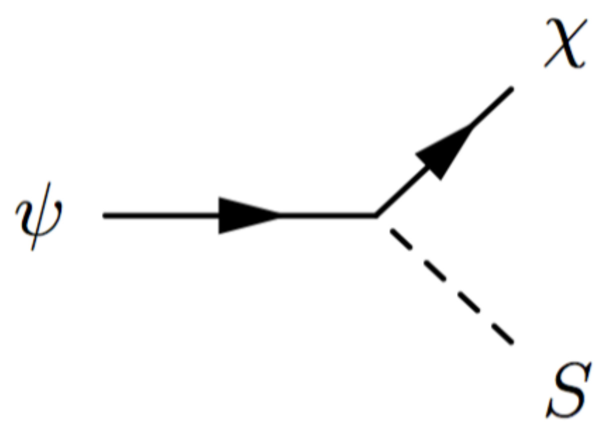
$$\cancel{- \frac{\lambda_{S3}}{3!}\mu_S S^3} - \cancel{\lambda_{p3}\mu_S S(H^\dagger H)} - \frac{\lambda_{p4}}{2} S^2 (H^\dagger H)$$

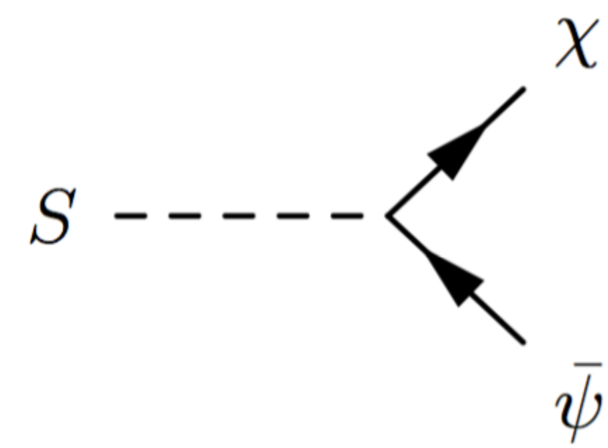
$\sim 10^{-3}$

- $m_\psi \neq m_\psi(T)$

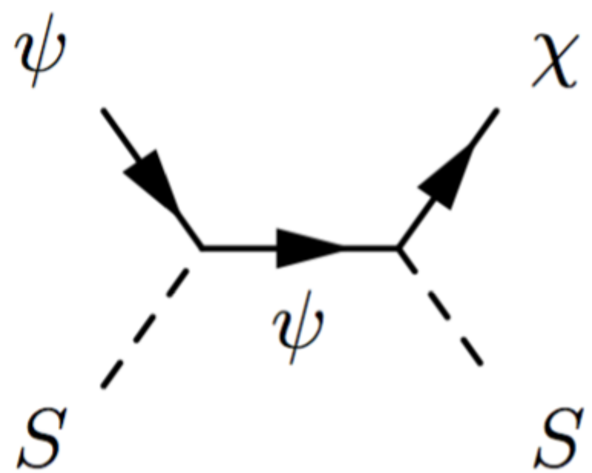
• Kinematically Induced Freeze-in

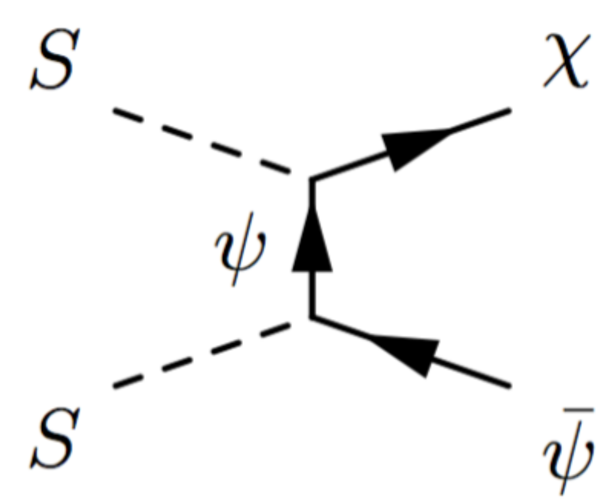
Assume χ begins with negligible abundance





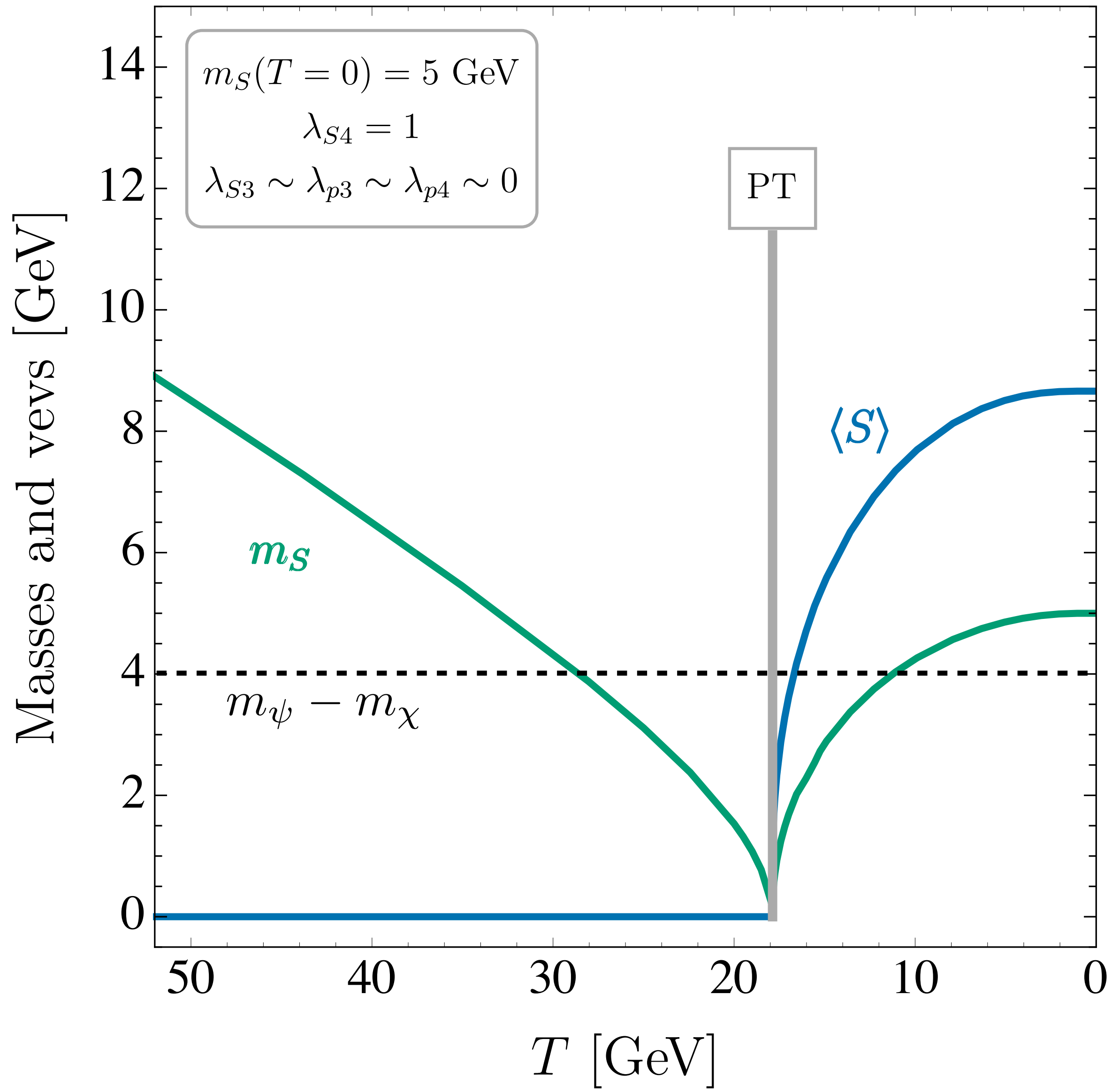
$m_\psi > m_\chi + m_S(T)$ $\qquad$ $m_S(T) > m_\chi + m_\psi$

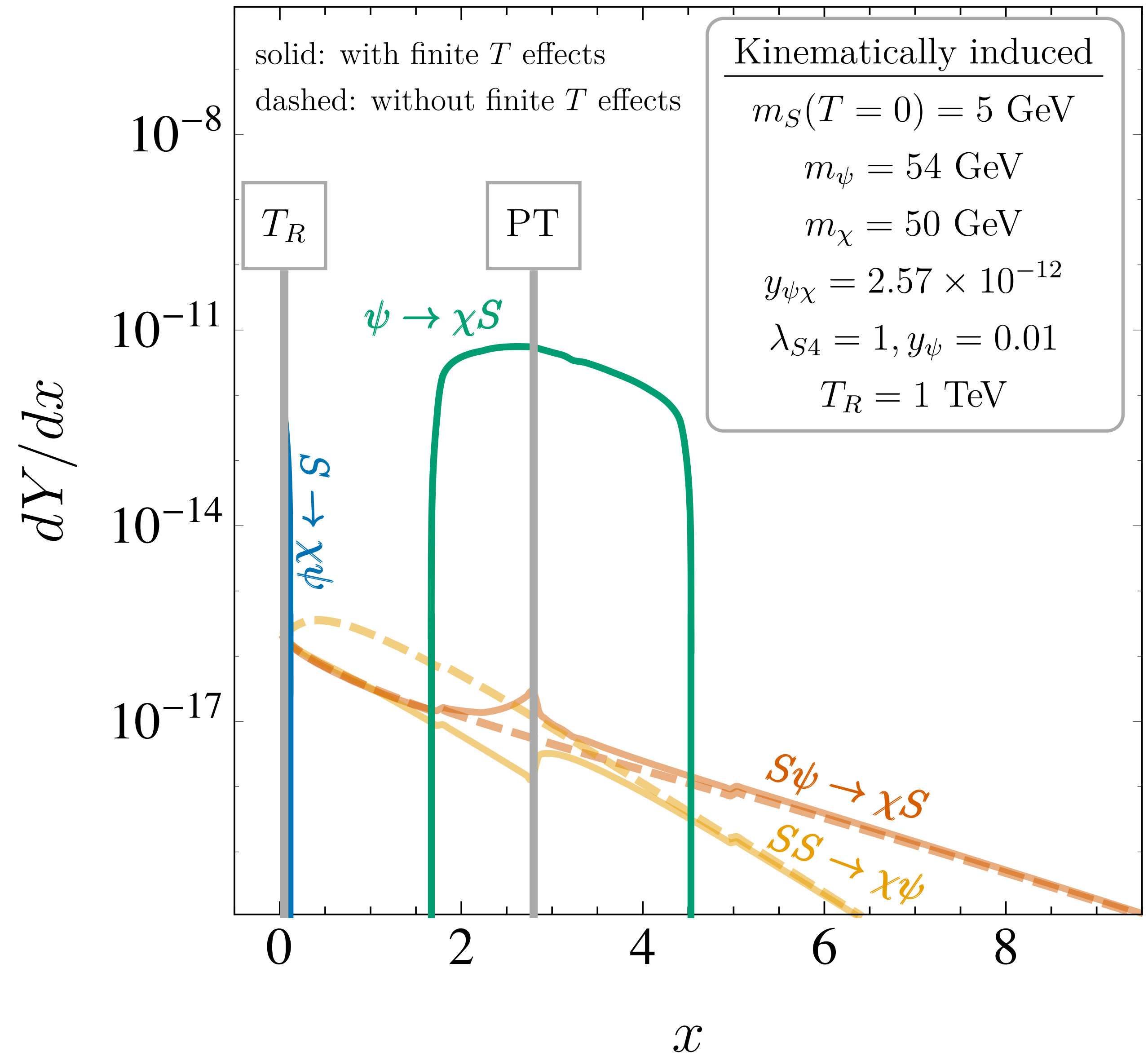




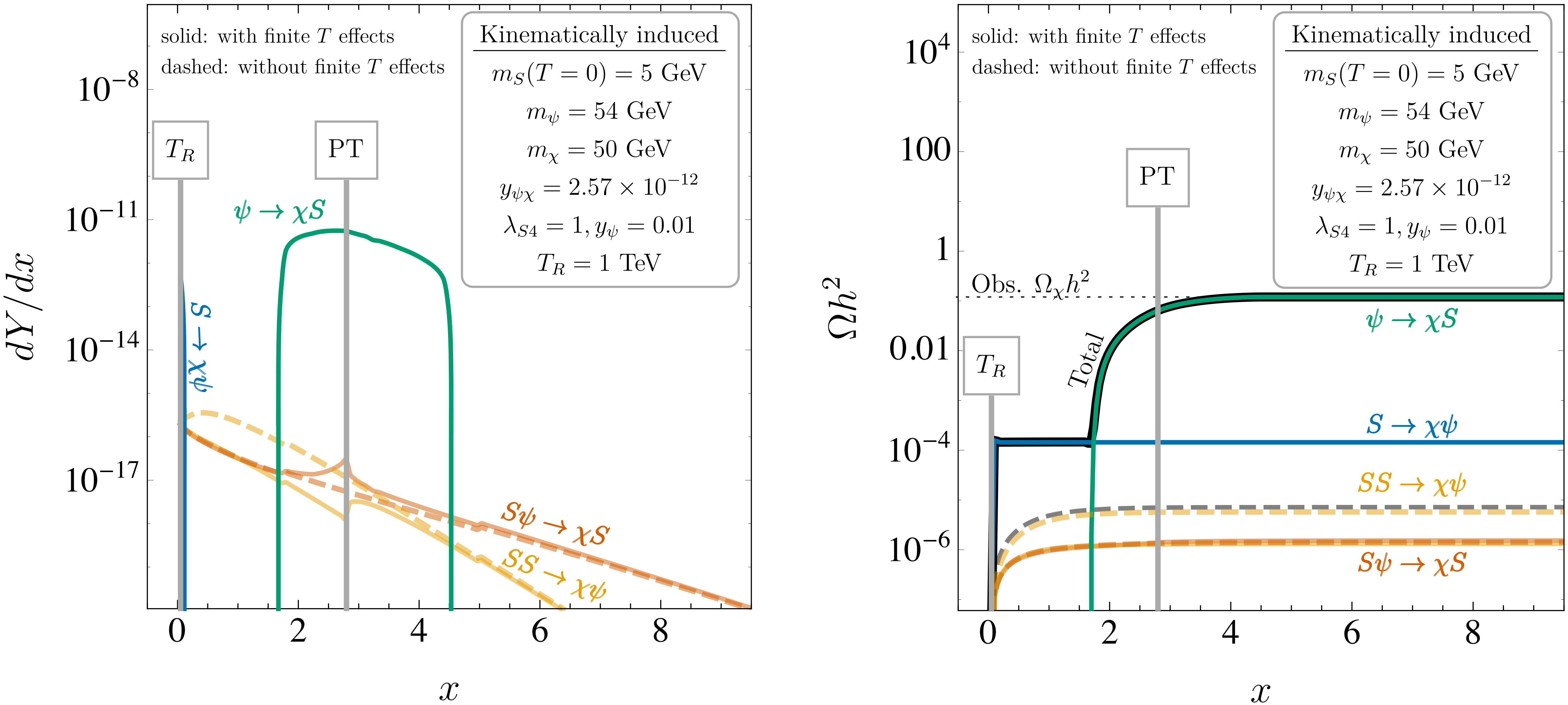
Suppressed by $y_\psi = 0.01$

• Kinematically Induced Freeze-in - Results





• Kinematically Induced Freeze-in - Results



Thermal effects increase relic abundance by orders of magnitude

Decaying Dark Matter

• Vev Flip-Flop: Decaying Dark Matter

~ -1 $\qquad$ $\sim 10^{-7}$

$$\mathcal{L} \supset \cancel{y_\chi \bar{\chi}\chi S} + y_\psi \bar{\psi}\psi S + [y_{\chi\psi}\bar{\psi}\chi S + h.c.] + m_\chi \bar{\chi}\chi + \tilde{m}_\psi \bar{\psi}\psi$$

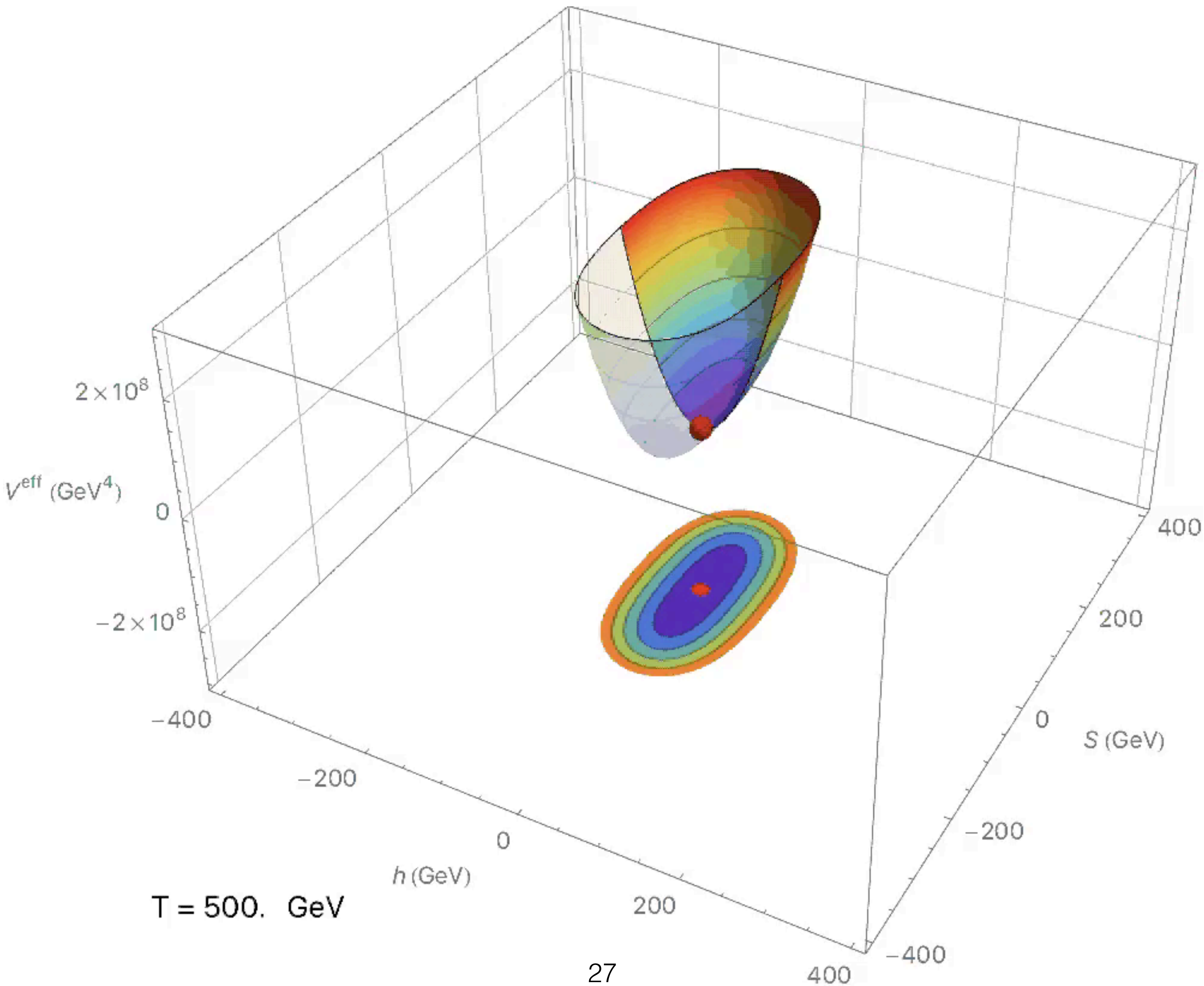
$$+ \mu_H^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 + \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_{S4}}{4!} S^4 \qquad \sim 1$$

$$- \cancel{\frac{\lambda_{S3}}{3!}\mu_S S^3} - \cancel{\lambda_{p3}\mu_S S(H^\dagger H)} - \frac{\lambda_{p4}}{2} S^2 (H^\dagger H)$$

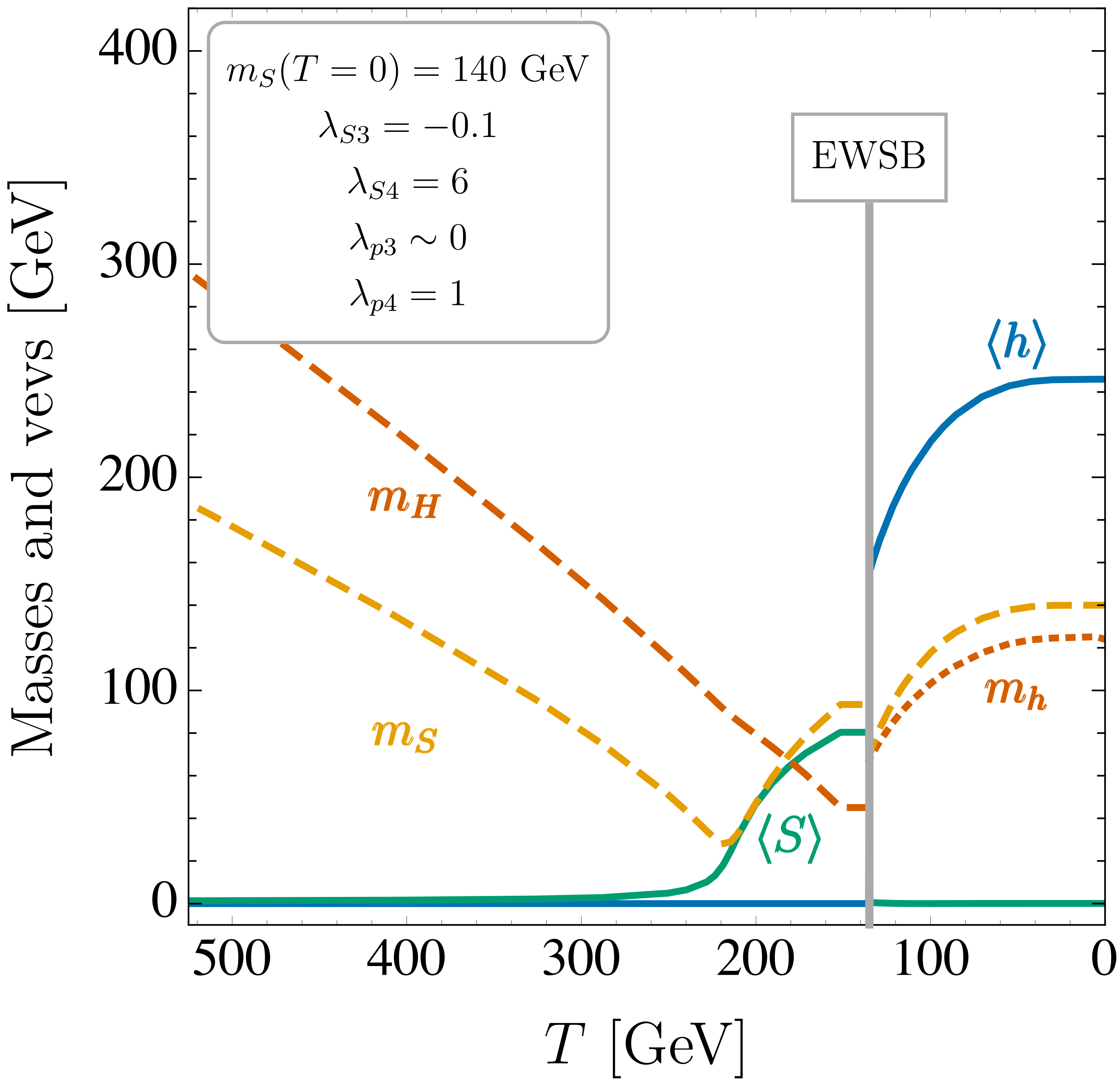
~ 1

$$V^{\text{eff}}(H, S, T) \neq V^{\text{eff}}(H, T) + V^{\text{eff}}(S, T)$$

- Two Step Phase Transition: Effective Potential

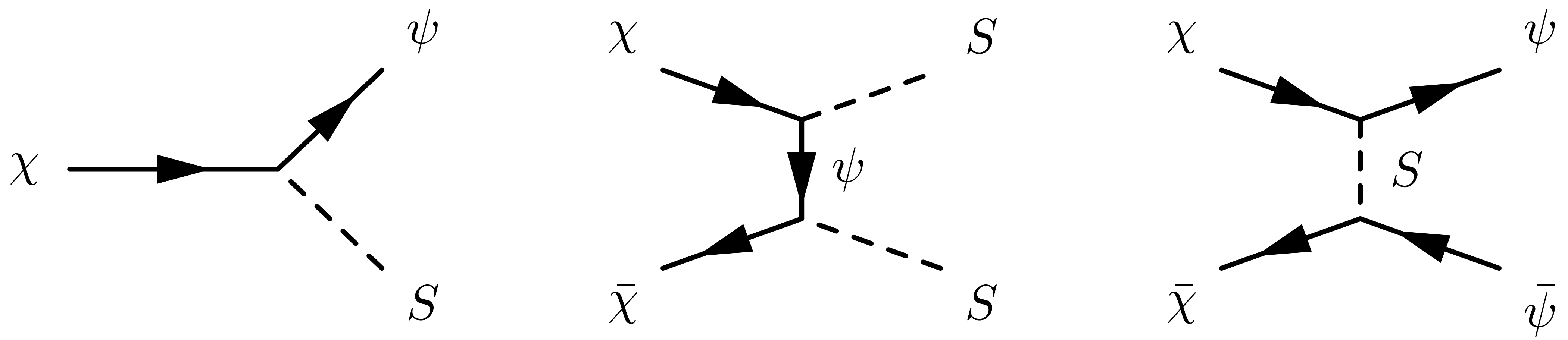


- Two Step Phase Transition: Effective Potential



• Vev Flip-Flop: Decaying Dark Matter

Assume χ begins with thermal abundance

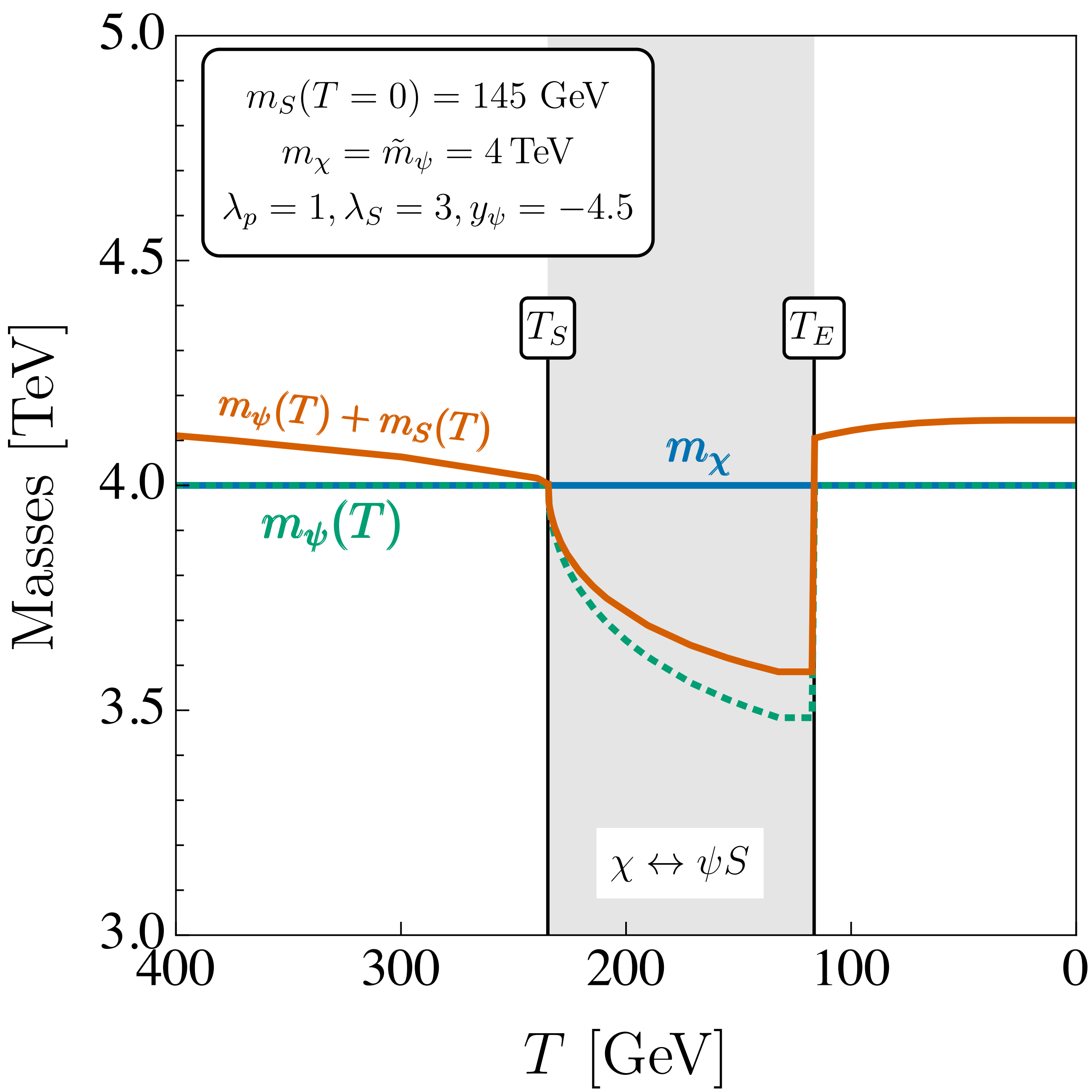


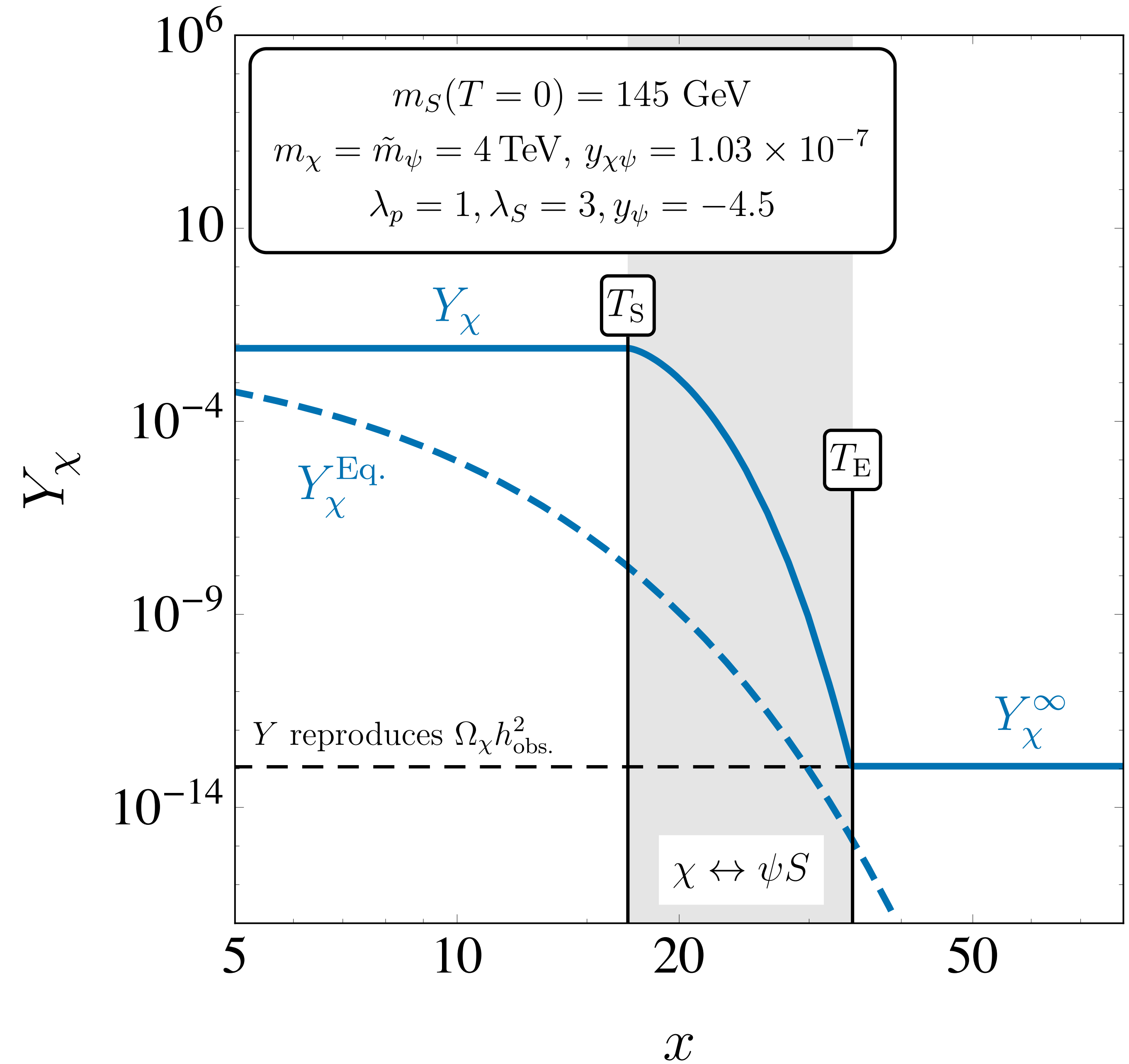
Open when

$$m_\chi > m_\psi(T) + m_S(T)$$

Suppressed by $y_{\chi\psi} \sim 10^{-7}$

- Vev Flip-Flop: Decaying Dark Matter





We have demonstrated another new method of obtaining the relic abundance

Conclusions

• Conclusions

- Thermal effects are important in the early universe!
- Temperature dependent masses affect kinematic thresholds
- NP scalars may temporarily obtain vevs
- This can have a dramatic influence on DM abundance
- Illustrated this with three scenarios, more are possible

Thank you!

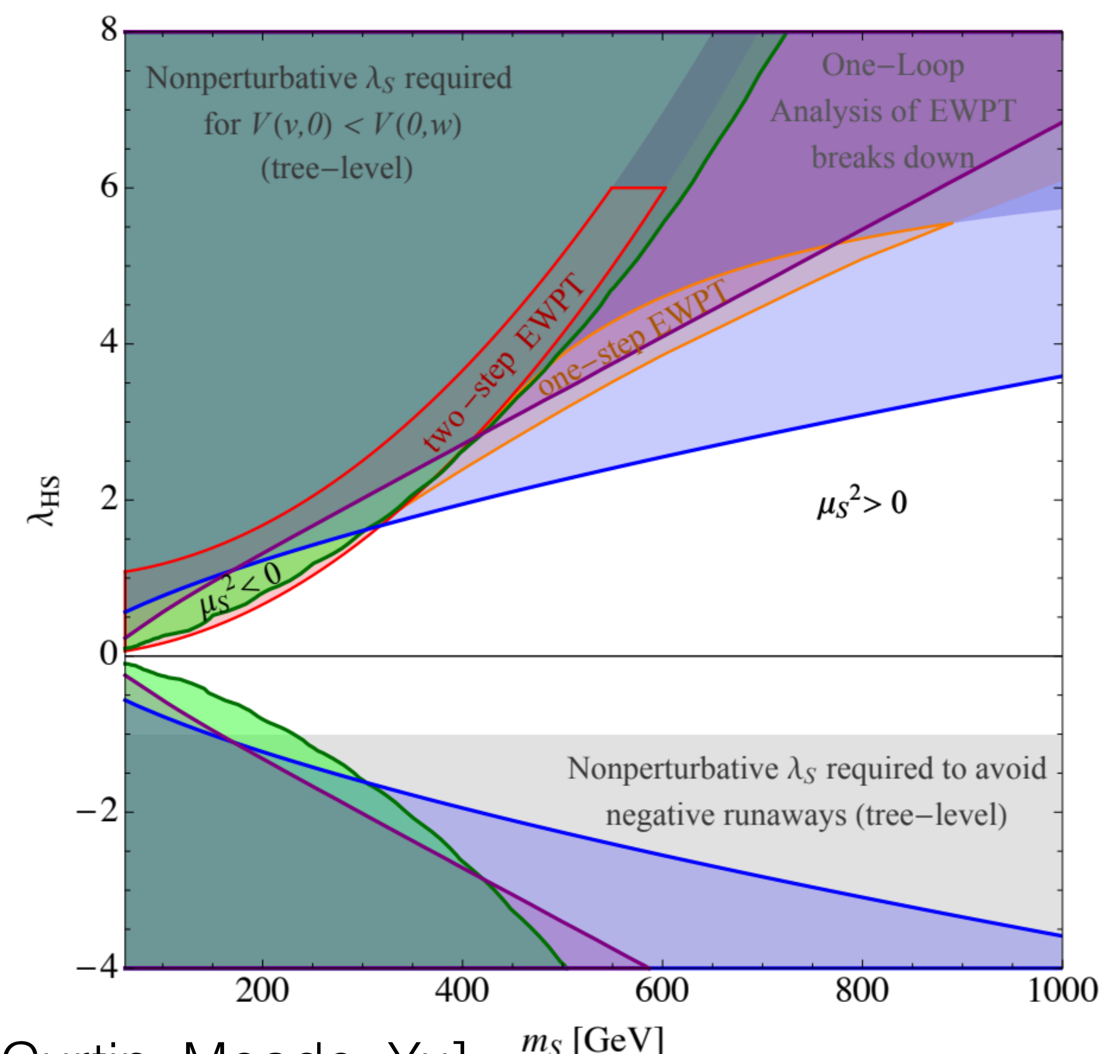
Experimental Probes

- Experimental Probes

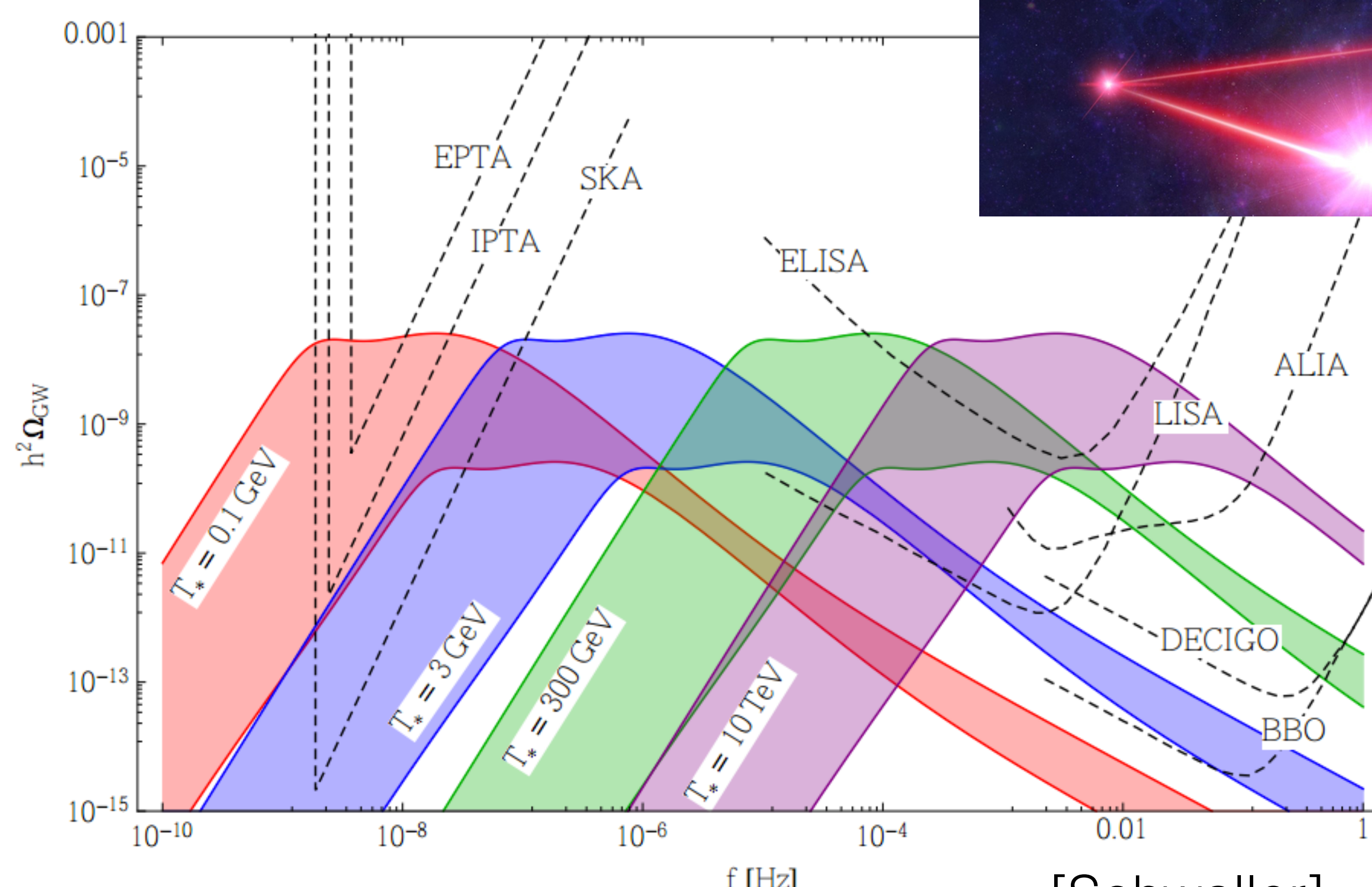
Detection of χ hindered by small couplings

But S and ψ couplings can be relatively large, so can be produced

Two-step phase transition scenarios may give a subdominant population of S and ψ



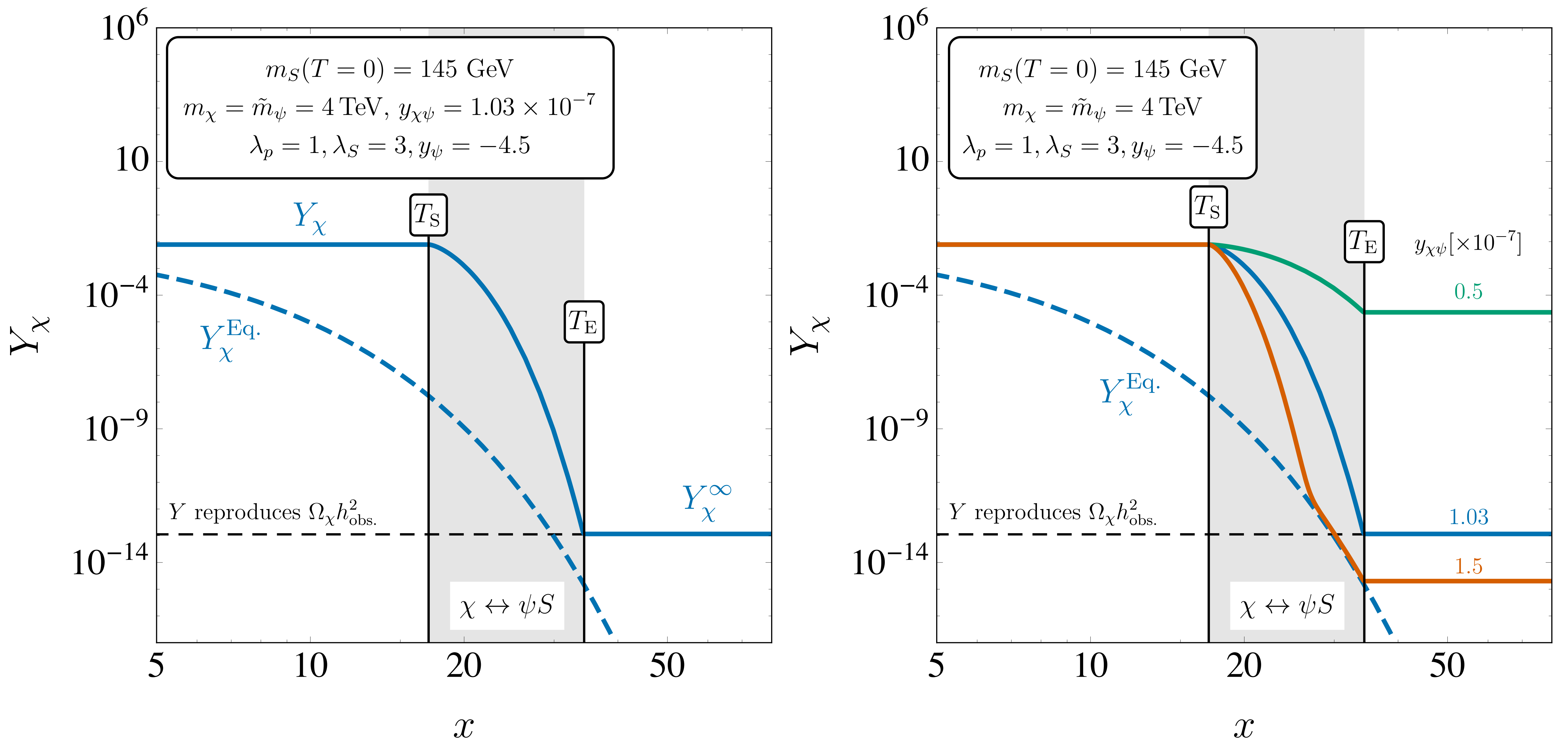
[Curtin, Meade, Yu]



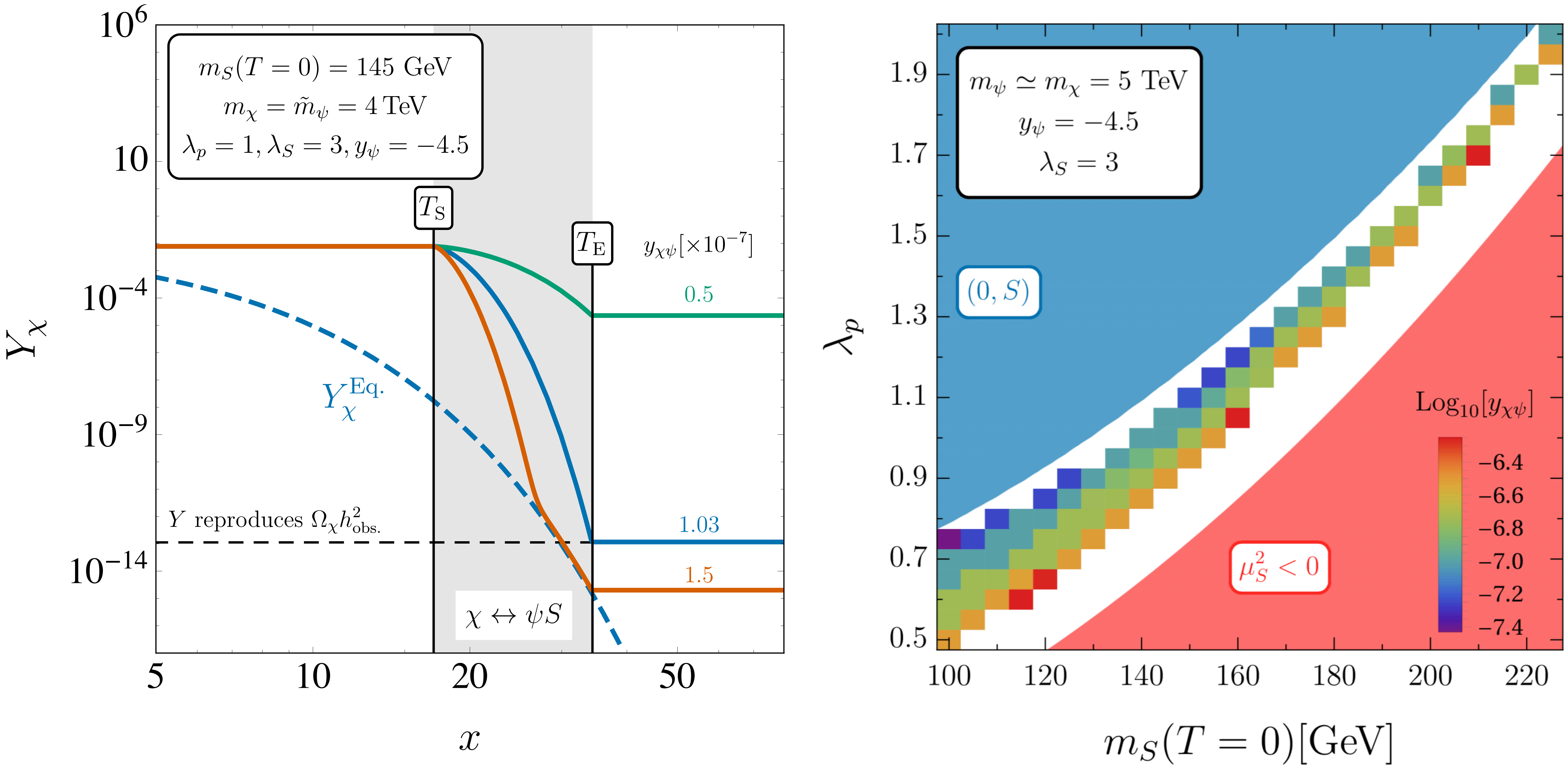
[Schwaller]

Parameter Space

• Vev Flip-Flop: Decaying Dark Matter



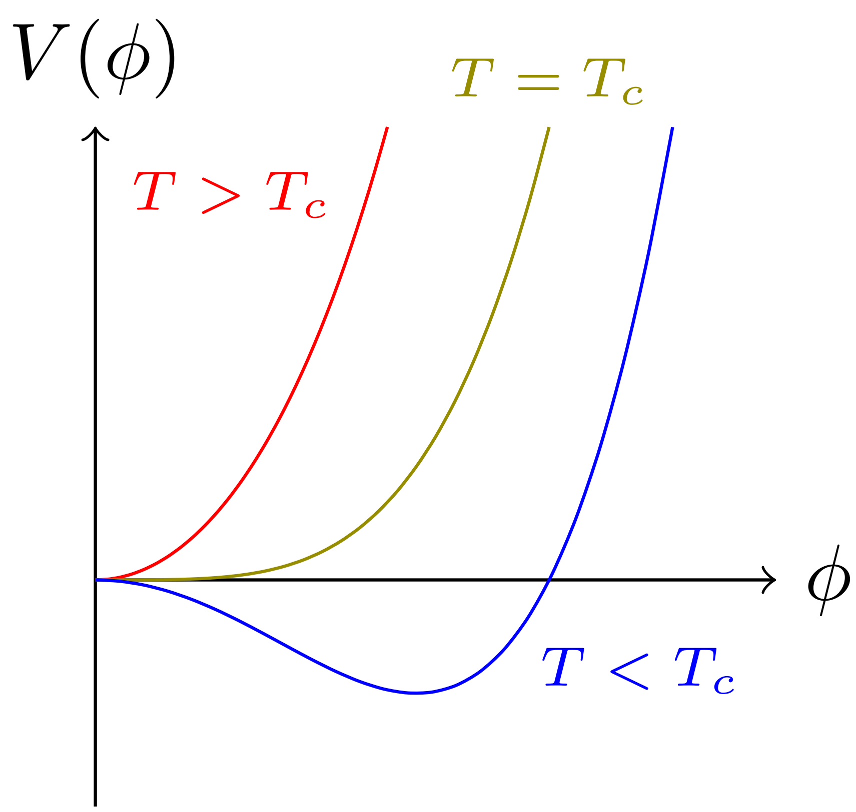
• Vev Flip-Flop: Decaying Dark Matter



Two Step Phase Transition

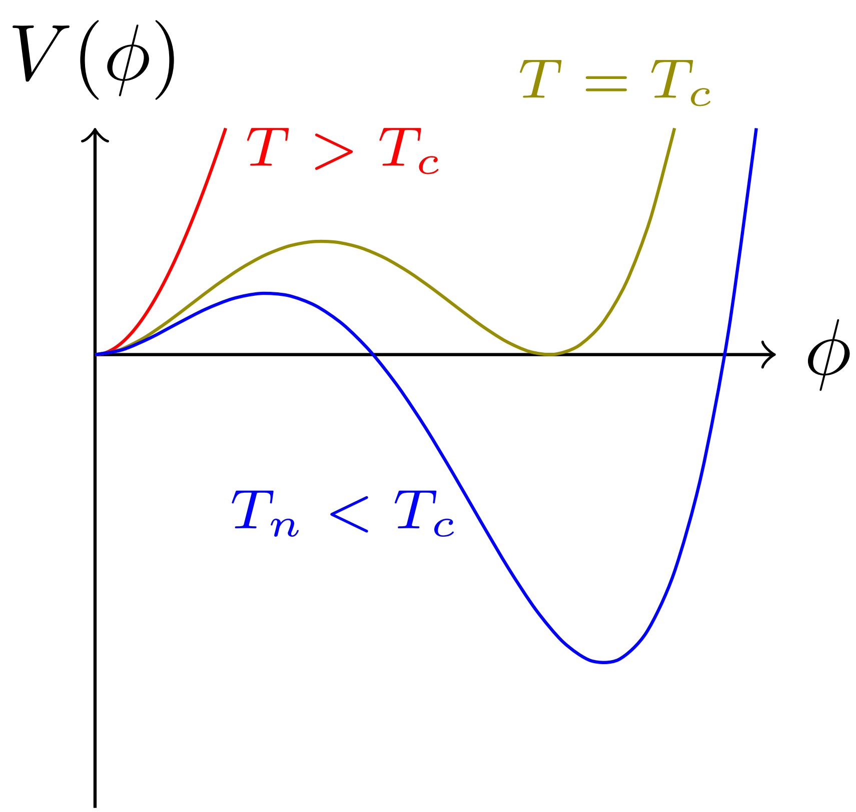
- Phase Transitions

<u>Second Order Phase Transitions</u>



$$T_{\mathrm{PT}} = T_c$$

<u>First Order Phase Transitions</u>



$$T_n < T_c$$

- Bubble nucleation and Cosmotransitions

Bubble nucleation rate per volume:

$$\frac{\Gamma}{V} = Ae^{-S_E/T}$$

$$+m_\chi \bar{\chi}\chi + \tilde{m}_\psi \bar{\psi}\psi$$

P(one bubble nucleation per Hubble volume) ~ 1

$$\frac{S_E}{T} \sim 140$$

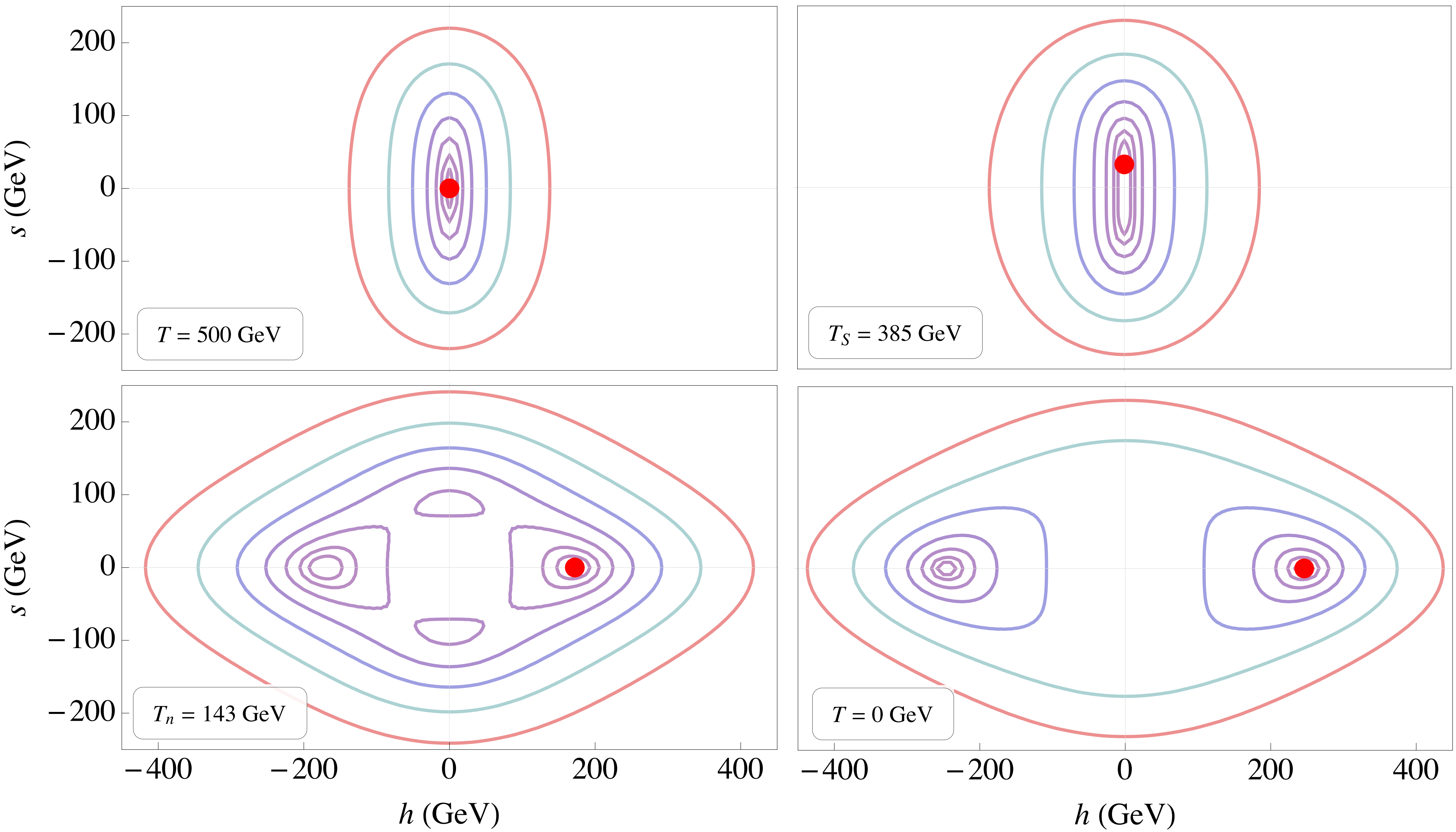
Linde, 1983

Anderson & Hall, 1992

Use `cosmotransitions`

Wainwright, 2011

- Vev Flip-Flop: Effective Potential



The Effective Potential

• The Effective Potential

At zero temperature:

"It would be wonderful if, in the full quantum field theory, there were a function whose minimum gave the exact value of $\langle\phi\rangle$. We will exhibit a function with these properties, called the *effective potential*."

(Peskin & Schroeder)

$$V^{\mathrm{eff}} = V^{\mathrm{tree}} + V^{\mathrm{1\text{-}loop}} + \ldots$$

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

E.g., $m_t^2(h) = \frac{1}{2} y_t^2 h^2$

Coleman & Weinberg, 1973

- The Effective Potential

In finite temperature QFT, we can't rely on asymptotic states. Instead, we apply ideas from thermodynamics, then express the partition function as a path integral in imaginary time with periodic boundary conditions. The one-loop expansion of the effective potential then becomes

$$V^{\mathrm{eff}} = V^{\mathrm{tree}} + \sum_i \frac{n_i T}{2} \sum_{n=-\infty}^{+\infty} \int \frac{d^3\vec{k}}{(2\pi)^3} \log\left[\vec{k}^2 + \omega_n^2 + m_i^2(h,S)\right] + \ldots$$

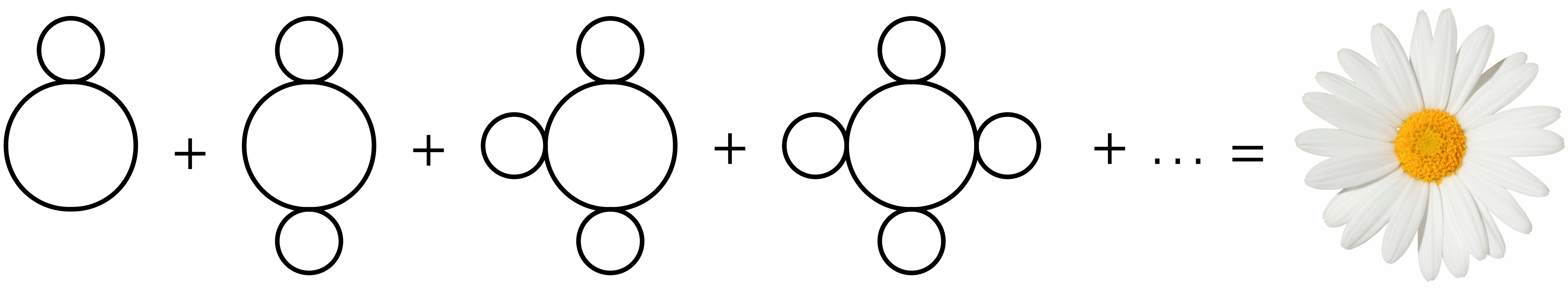
$$V^{\mathrm{eff}} = V^{\mathrm{tree}} + V^{\mathrm{CW}} + V^{T} + V^{\mathrm{daisy}}$$

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

Dolan & Jackiw, 1974

• The Effective Potential

$$V^{\mathrm{eff}} = V^{\mathrm{tree}} + V^{\mathrm{CW}} + V^{T} + V^{\mathrm{daisy}}$$



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

E.g., $\Pi_{h,G^0,G^+} = \frac{1}{48}T^2\left(9g^2 + 3g'^2 + 24\lambda_H + 12y_t^2 + 2\lambda_p\right)$

Dolan & Jackiw, 1974