Finite Temperature Effects in Dark Matter Production

Joachim Kopp
Particle Physics Seminar | ETH Zurich | April 24, 2018

Evidence for Dark Matter

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Galaxy Clusters

Virial Theorem: $E_{\rm kin} = -\frac{1}{2} E_{\rm pot}$

Zwicky, 1930s: $E_{\rm kin} = -\frac{1}{2} E_{\rm pot} \times 170$

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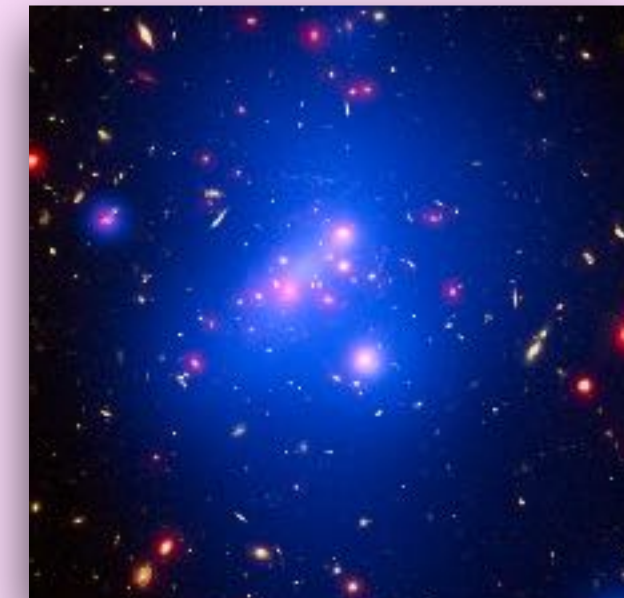
Galaxy Clusters



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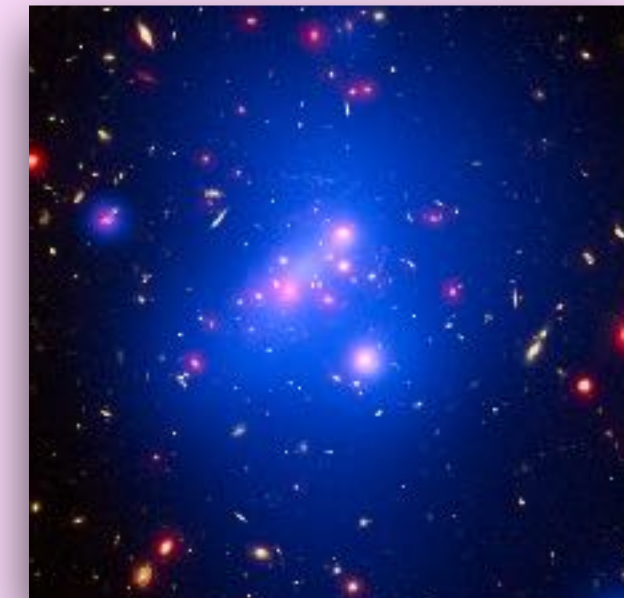
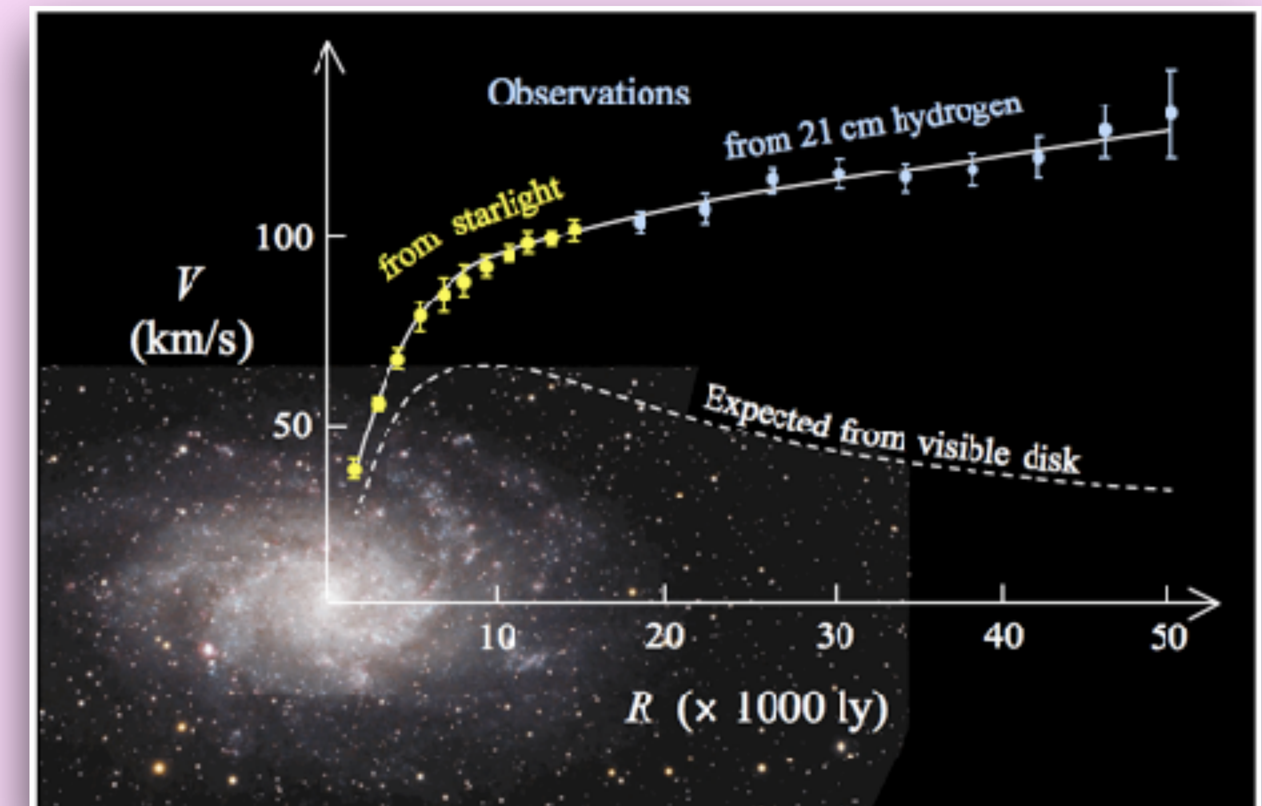


Virial Theorem: $E_{\mathrm{kin}} =$

Zwicky, 1930s: $E_{\mathrm{kin}} =$

Galaxy Rotation Curves



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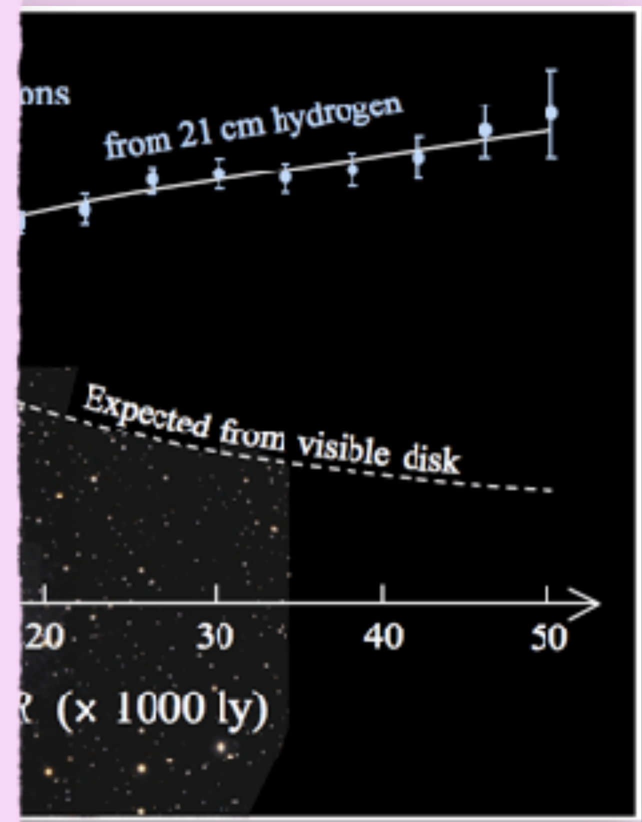
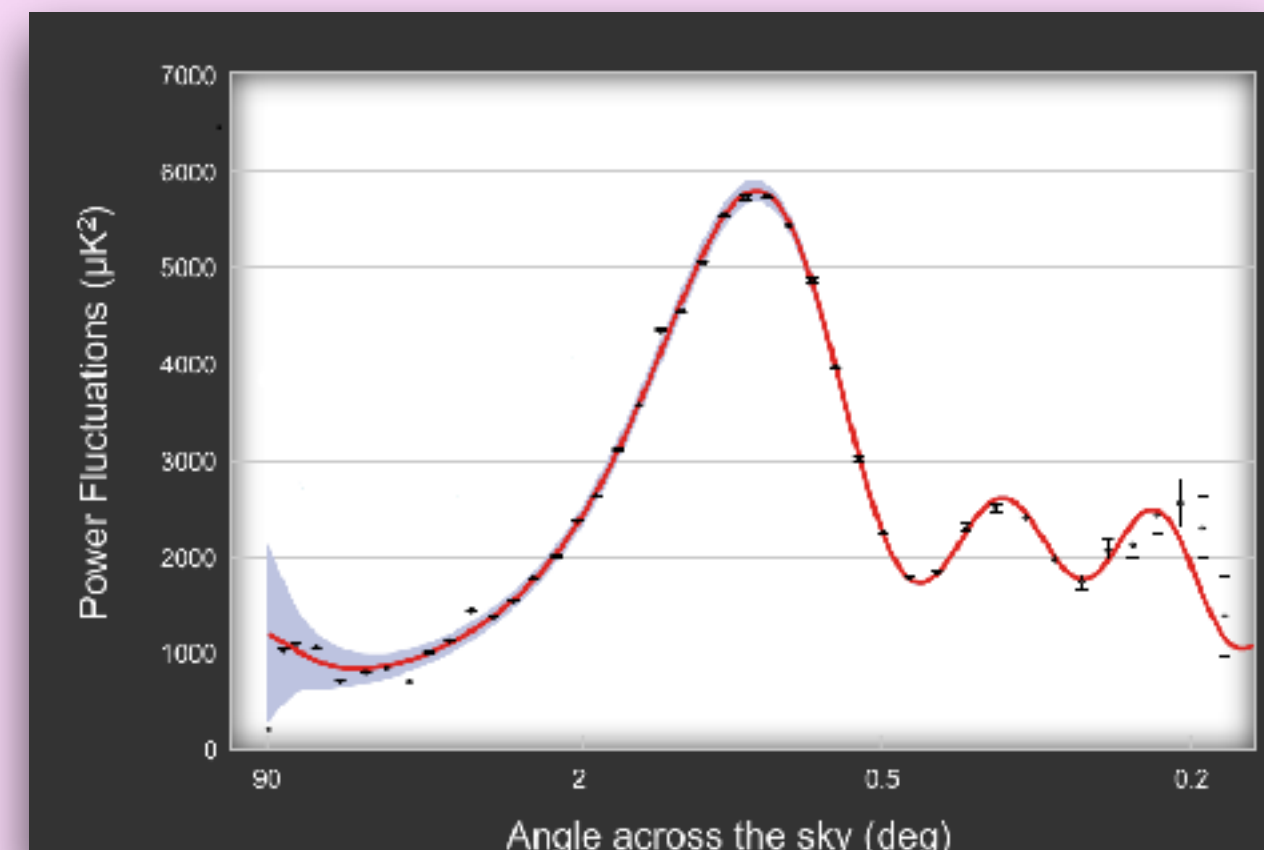


Cosmic Microwave Background



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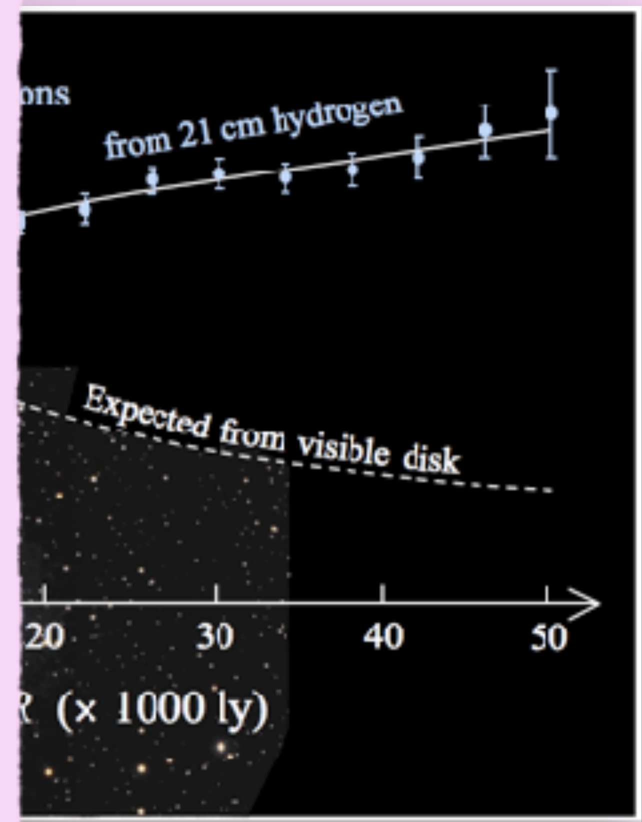

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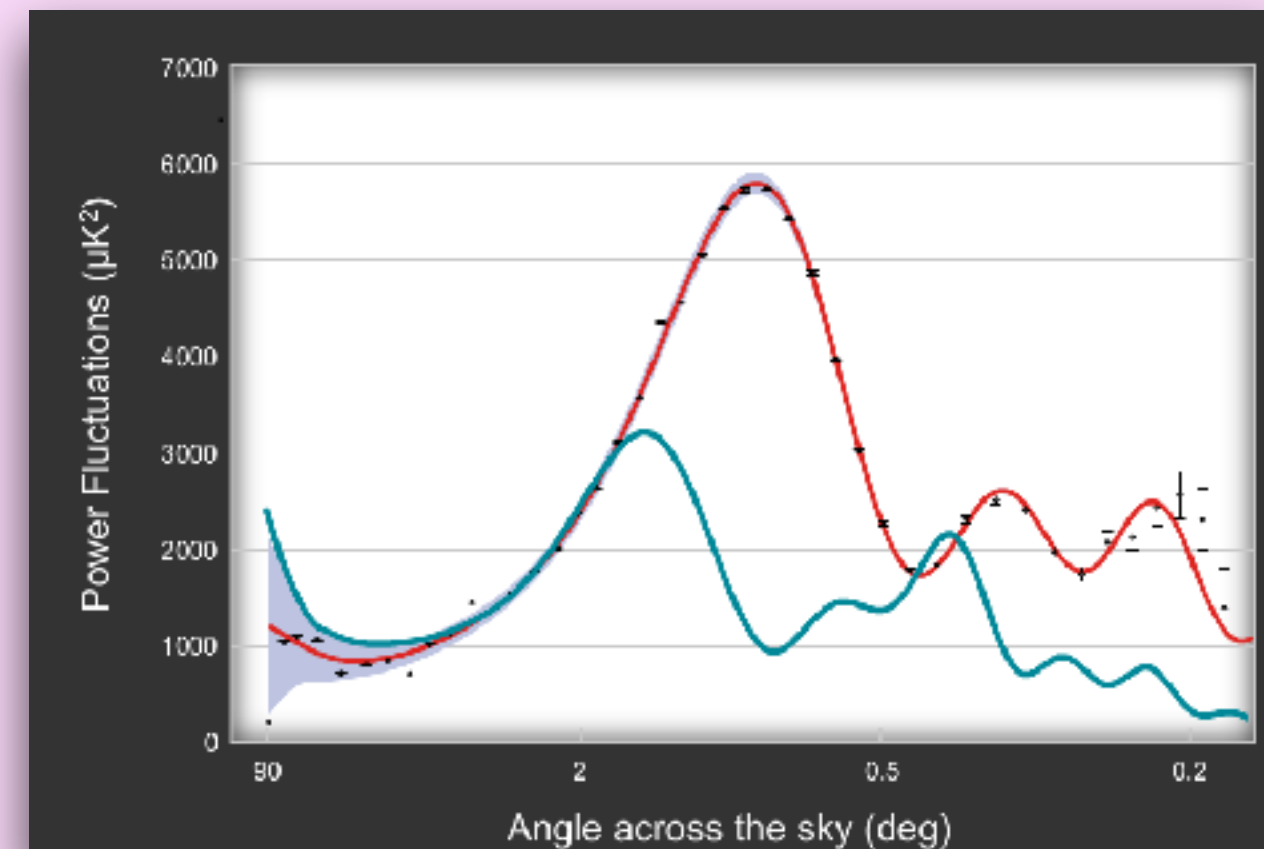

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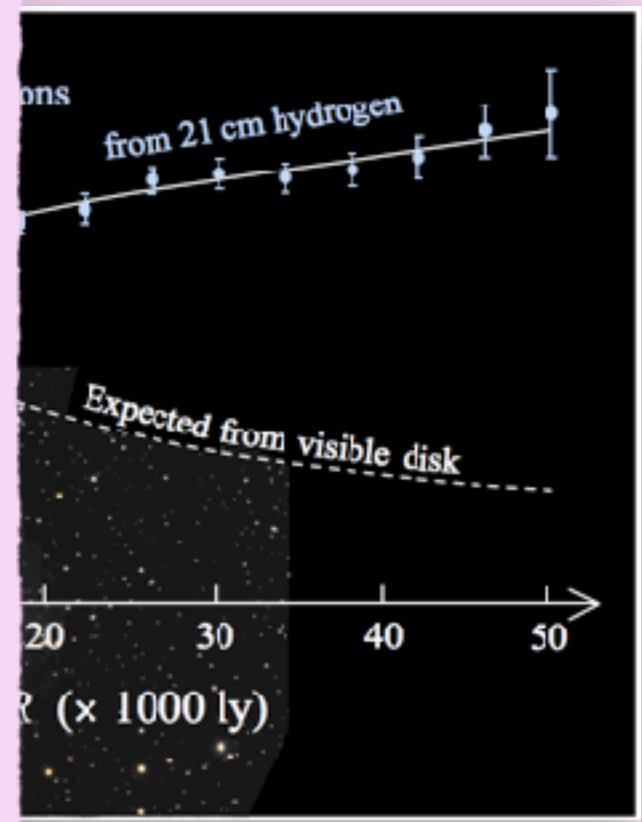

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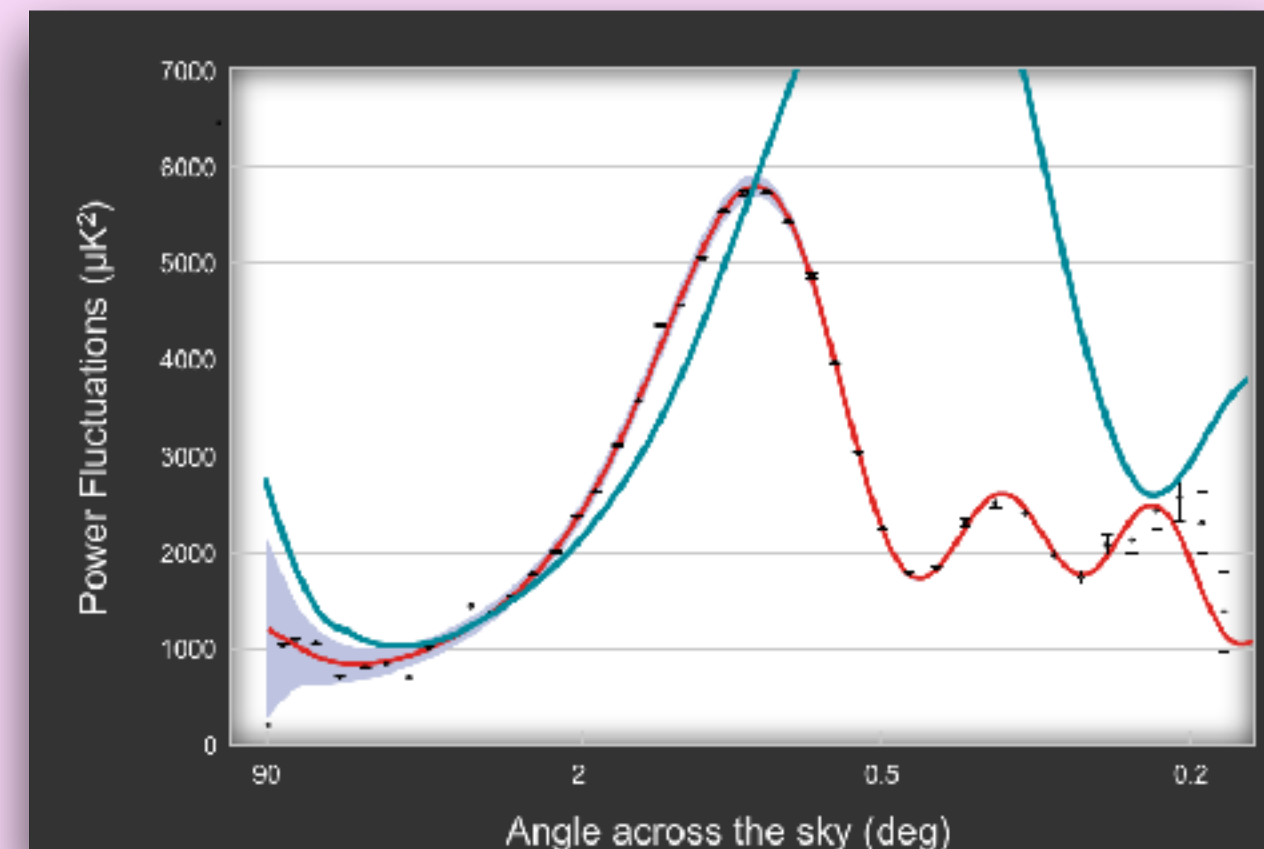
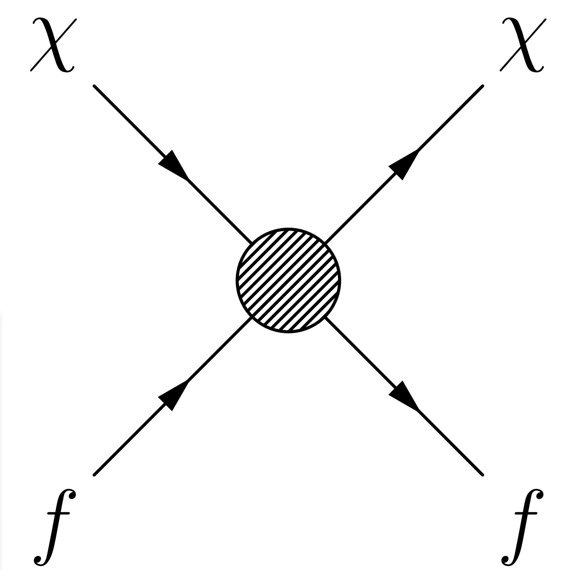


Standard Lore: Thermal Freeze-Out

- ☑ Early on: DM in thermal equilibrium with SM

  e.g. via $\bar{\chi}\chi \longleftrightarrow \bar{f}f$



- ☑ Number density: $n_{\chi,\mathrm{eq}} = \int \frac{d^3p}{(2\pi)^3} \exp\left[-E_\chi(\vec{p})/T\right]$

- ☑ T drops, interactions freeze out

- ☑ Described by Boltzmann equation

$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\left(n_\chi^2 \langle\sigma(\chi\chi \to \bar{f}f)v_{\mathrm{rel}}\rangle - n_f^2 \langle\sigma(\bar{f}f \to \chi\chi)v_{\mathrm{rel}}\rangle\right)$$

Standard Lore: Thermal Freeze-Out

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- ☑ Detailed balance: $n_f^2 \langle \sigma(\bar{f}f \to \chi\chi) v_{\rm rel} \rangle = n_{\chi,\rm eq}^2 \langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle$
- ☑ Final Boltzmann equation

$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle \left(n_\chi^2 - n_{\chi,\rm eq}^2 \right)$$

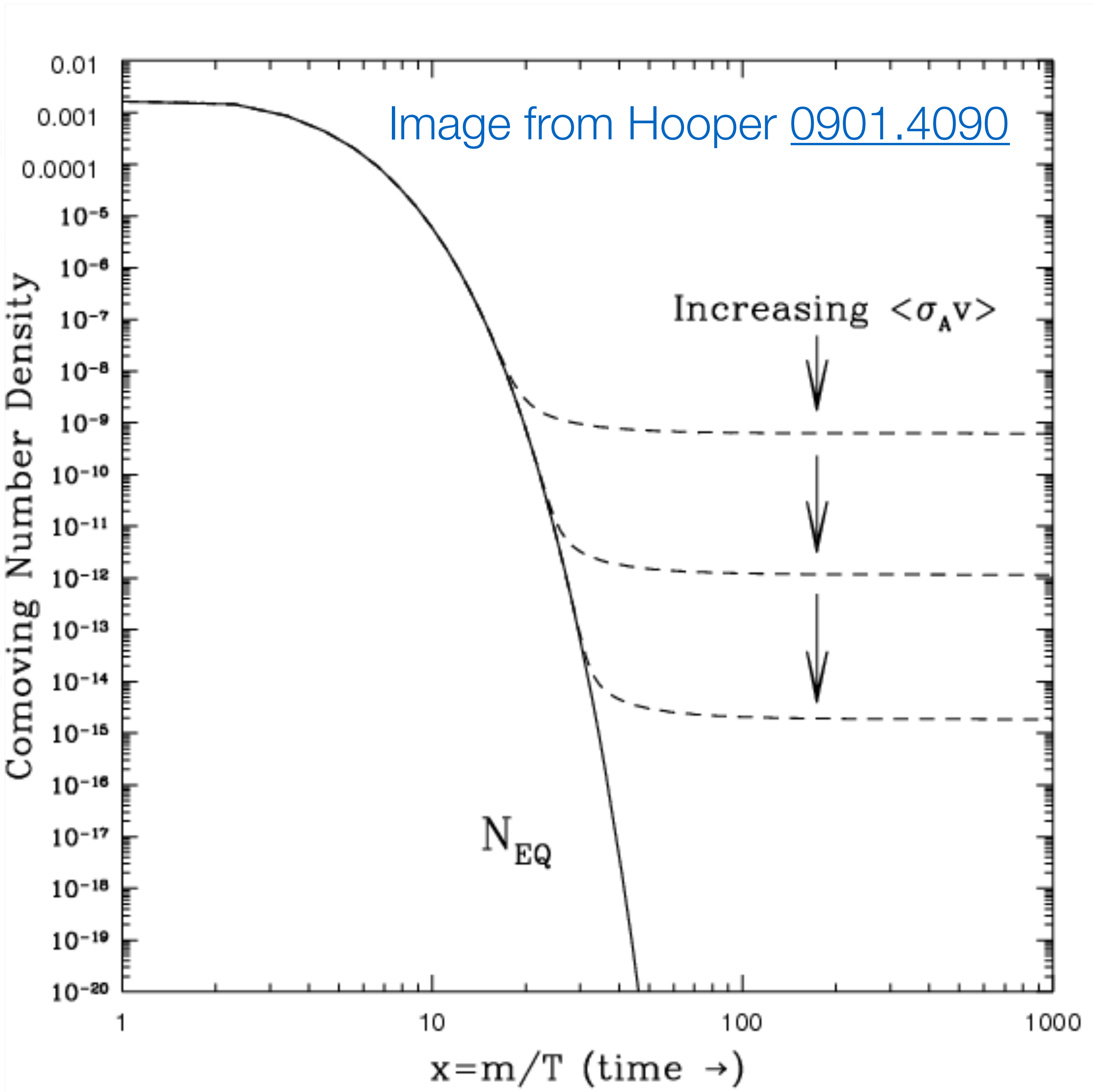
Standard Lore: Thermal Freeze-Out

$\frac{dn_\chi}{dt} + 3$ … $\rightarrow \chi\chi)v_{\mathrm{rel}}\rangle\Big)$

☑ Detailed … $\chi\chi \rightarrow \bar{f}f)v_{\mathrm{rel}}\rangle$

☑ Final Bo…

$\frac{dn_\chi}{dt} +$ …



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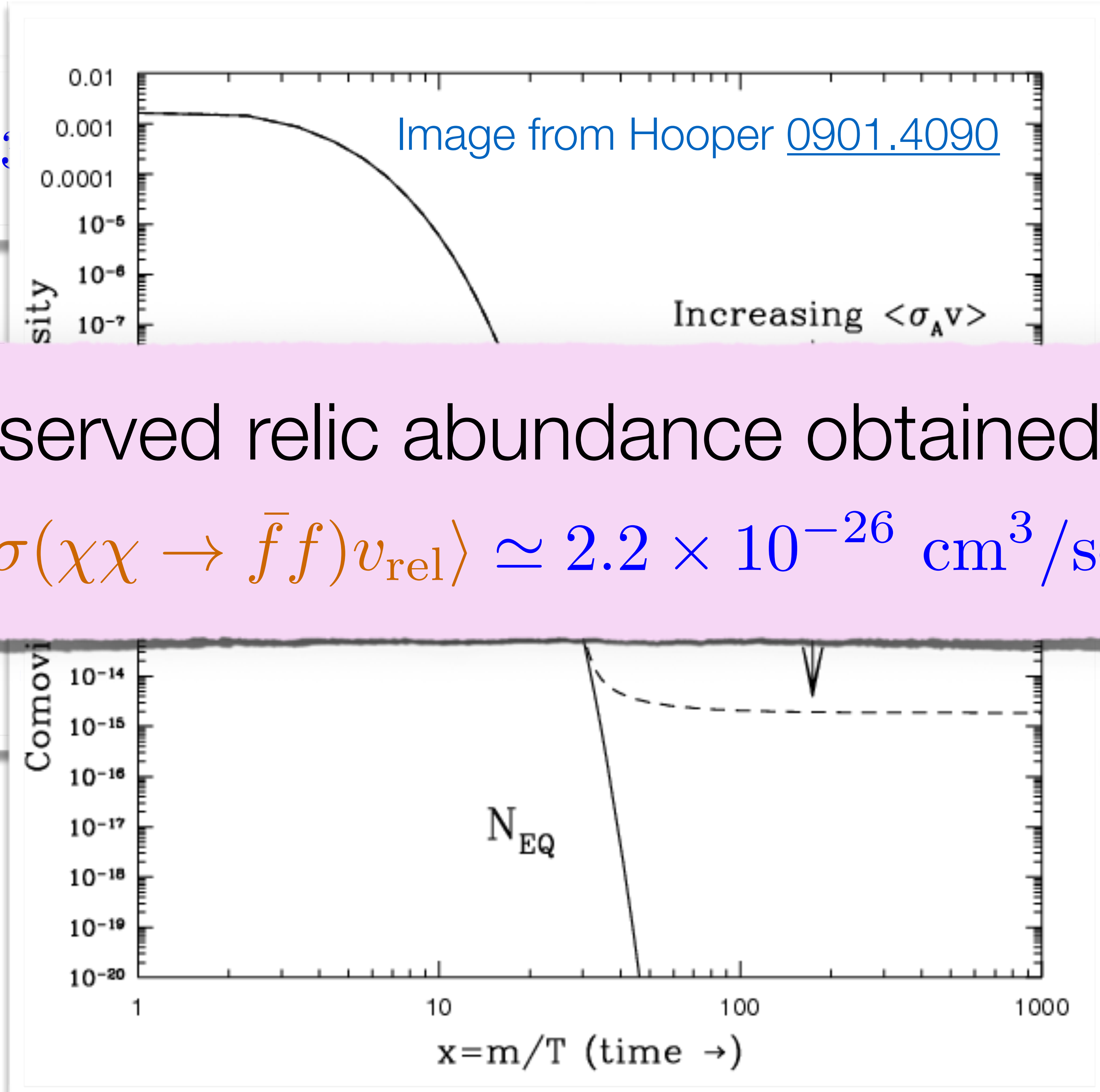
Standard Lore: Thermal Freeze-Out



observed relic abundance obtained for

$$\langle \sigma(\chi\chi \to \bar{f} f) v_{\rm rel} \rangle \simeq 2.2 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$$

Standard Lore: Thermal Freeze-Out

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- ☑ Expect new particles at ~ 100 GeV
- ☑ SM-like couplings ~ α_{em} ~ 0.01
- ☑ Expect $\langle \sigma(\chi\chi \to \bar{f} f) v_{\rm rel} \rangle \simeq \mathrm{few} \times 10^{-26}~\mathrm{cm}^3/\mathrm{sec}$

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WIMP Miracle

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Phase Transitions in the Early Universe

- Properties of the primordial plasma change dramatically during phase transitions
- Electroweak phase transition (T ~ 160 GeV)
  - Electroweak symmetry broken $SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$
  - Higgs acquires vev v_H, fermions and gauge bosons become massive
  - cross-over in the SM, but can be 1st or 2nd order in BSM models
  - order parameter: v_H
- QCD phase transition (T ~ 200 MeV)
  - chiral symmetry broken $SU(3)_L \times SU(3)_R \to SU(3)_V$
  - order parameter: $\langle q_L q_R \rangle$

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Outline

- ☑ The Vev Flip-Flop: Temporarily Unstable Dark Matter
- ☑ Kinematically Induced Freeze-In: Impact of Thermal Masses
- ☑ Vev Flip-Flop Freeze-In: Switching Production Channels On/Off
- ☑ Summary

The Vev Flip-Flop

Temporarily Unstable Dark Matter

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Temporarily Unstable Dark Matter

- Question: Impact of Phase Transitions on DM Physics?
- Example:
  - symmetry stabilizing DM is broken in phase transition
  - DM partly decays
  - 2nd phase transition restores symmetry

The Vev Flip-Flop

- Toy Model: SM + singlet scalar S

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

- Typical behavior: 2-step phase transition
  - High T: $\langle S\rangle = 0$, $\langle H\rangle = 0$
  - Intermediate T: $\langle S\rangle \neq 0$, $\langle H\rangle = 0$
  - Low T: $\langle S\rangle = 0$, $\langle H\rangle \neq 0$

Profumo et al. 0705.2425
Cline Laporte Yamashita Kraml 0905.2559
Espinosa Konstandin Riva 1107.5441
Cui Randall Shuve 1106.4834,
Cline Kainulainen 1210.4196
Fairbairn Hogan 1305.3452
Curtin Meade Yu 1409.0005

- Challenge: Make DM decay/annihilation rate $\propto \langle S\rangle$

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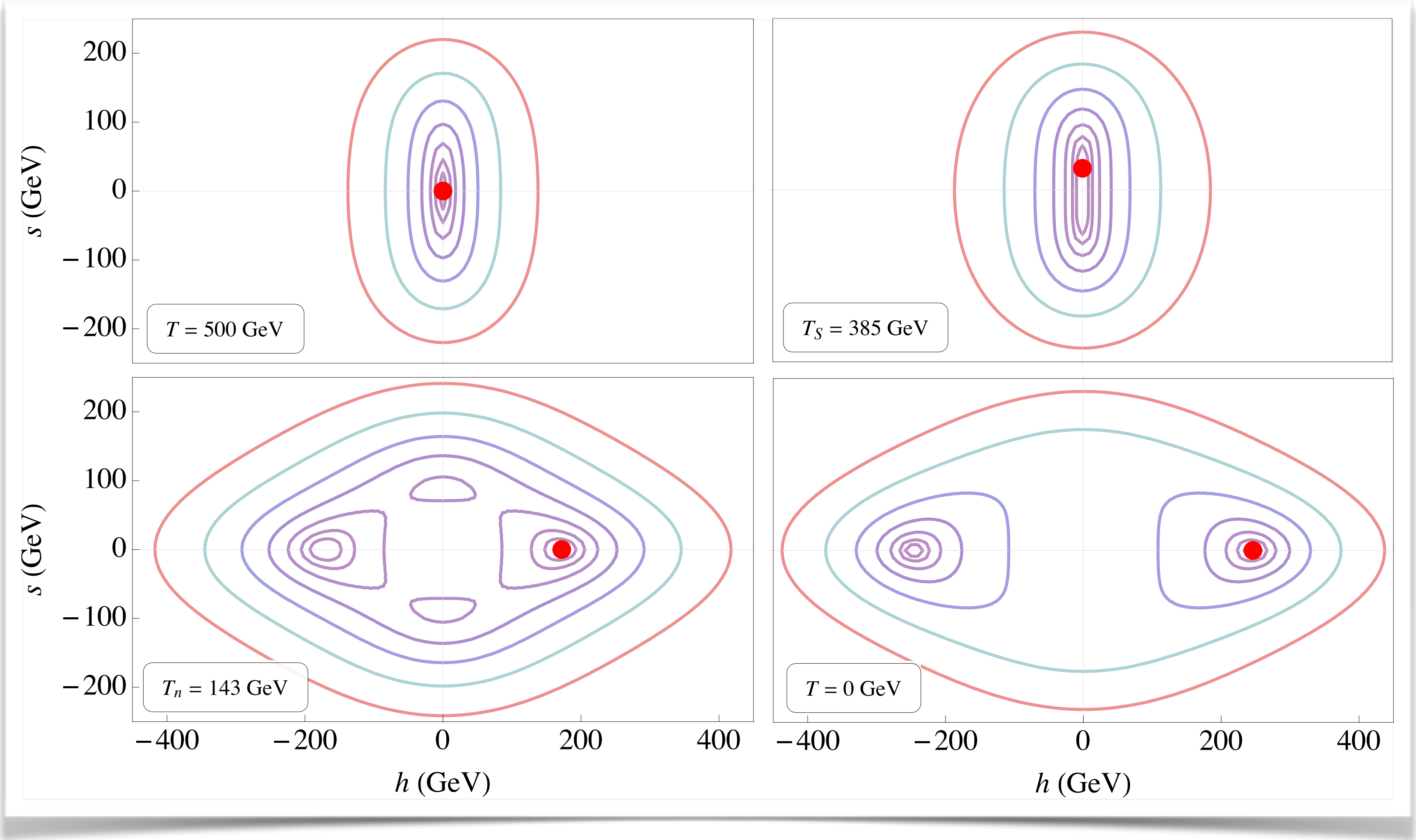
The Vev Flip-Flop



- $T > 400$ GeV: $\langle S \rangle = 0$, $\langle H \rangle = 0$ ($V_{\rm eff}$ dominated by thermal corrections)
- $T \sim 400$ GeV: S develops vev ➠ DM unstable
- $T \sim 150$ GeV: H develops vev ➠ Feedback through $\lambda_p (H^\dagger H)(S^\dagger S)$
  ➠ $m_{S,\rm eff}$ changes sign, $\langle S \rangle \to 0$, DM stable

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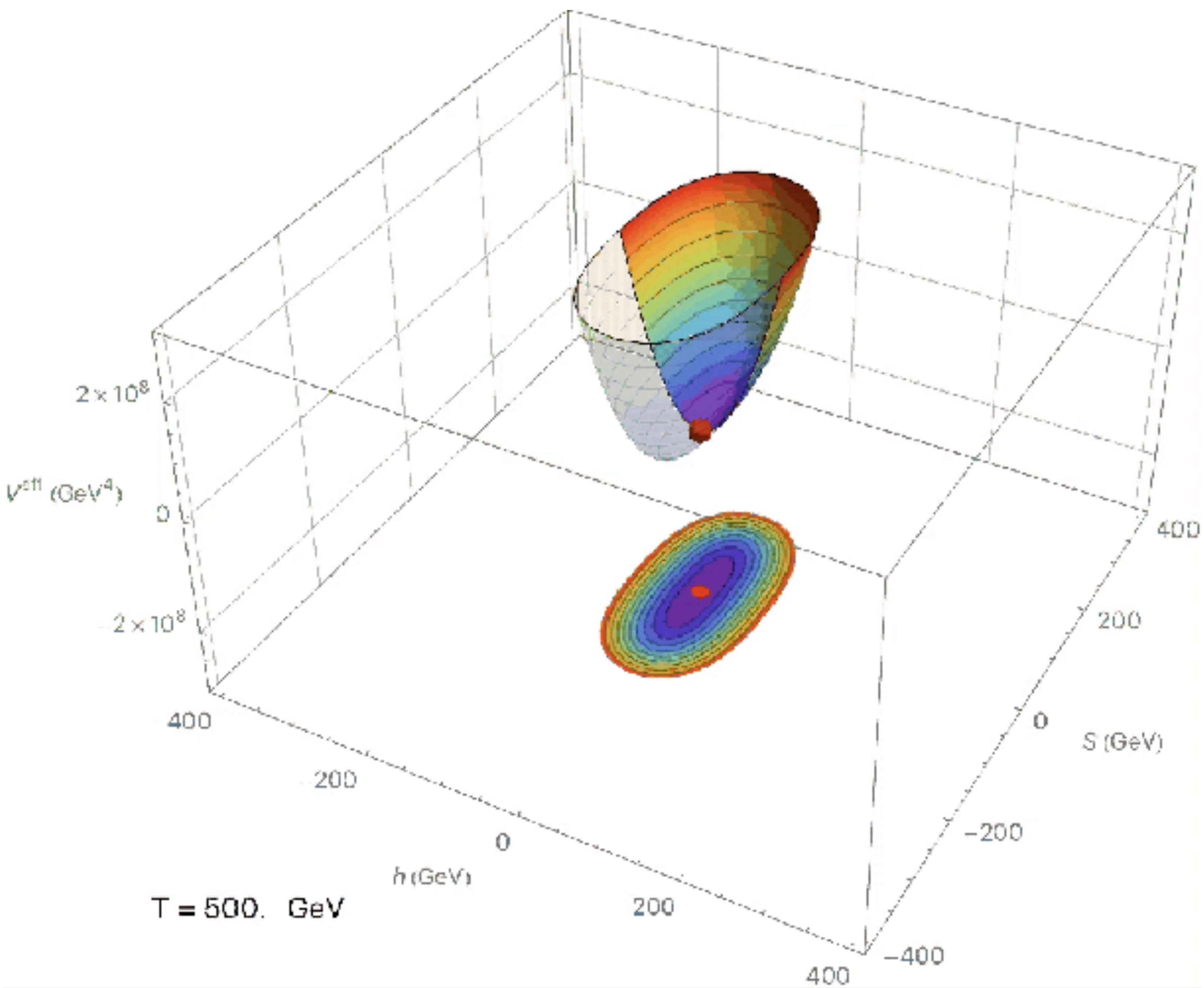
The Vev Flip-Flop



Computed by Mike Baker using `CosmoTransitions`

Wainwright 1109.4189, Kozaczuk Profumo Haskins Wainwright 1407.4134

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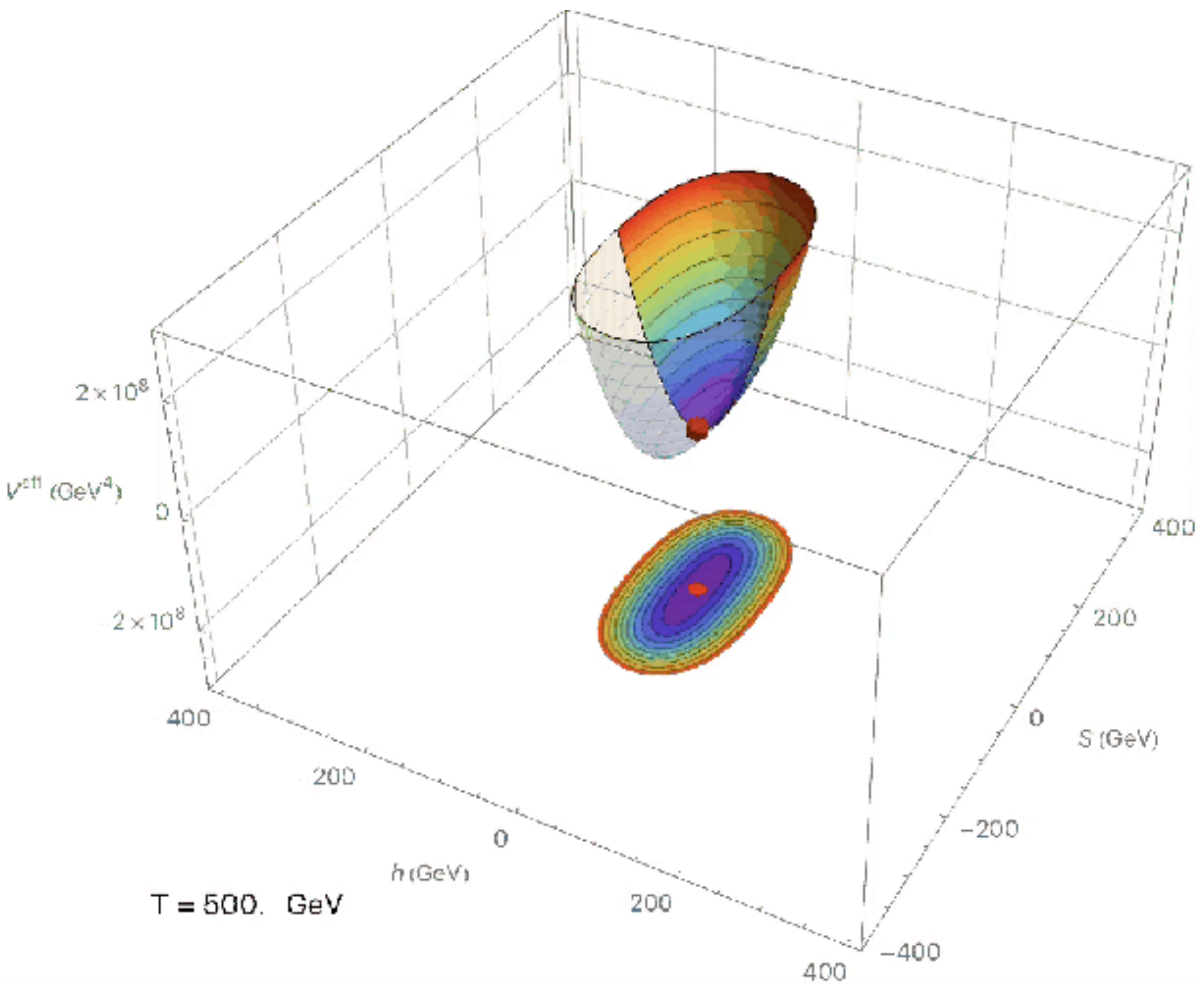

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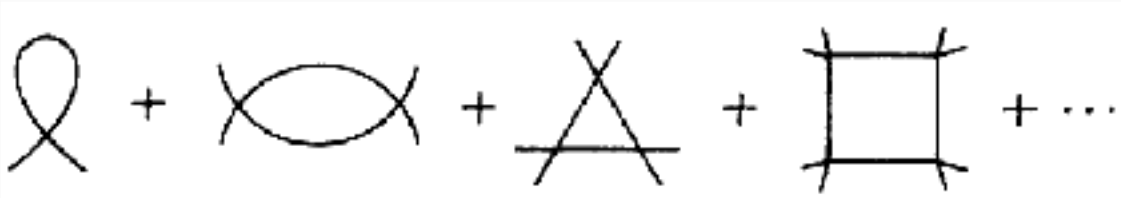
Scalar Potentials at Finite Temperature

☑ 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



$$V^{\text{CW}}[\phi] = \sum_{n=1}^{\infty} \int \frac{d^4k}{(2\pi)^4} \frac{1}{2n} \left(\frac{2\lambda\phi}{k^2 - m^2} \right)^n$$

- Sum over *n*
- Regularize, evaluate integral
- Renormalize by adding counterterms

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

Scalar Potentials at Finite Temperature

- 1-loop finite T Dolan Jackiw 1974
  - Impose periodic boundary conditions on path integral

$$Z[J] = \exp[-\tfrac{1}{2}\int d^4x\, d^4y\, J(x) D(x-y) J(y)]$$

  - Propagator (Green's function) at finite T is

$$D(x-y) = \frac{\mathrm{tr}\left[e^{-\beta\hat{H}} T\phi(x)\phi(y)\right]}{\mathrm{tr}\left[e^{-\beta\hat{H}}\right]}$$

evaluate by solving $(\partial_\mu\partial^\mu + m^2) D(x-y) = -i\delta^{(4)}(x-y)$ (periodic b.c.)

  - 1-loop expansion of V_{eff}: $V^{(1)} = \frac{i}{2}\mathrm{tr}\log D^{-1}$

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

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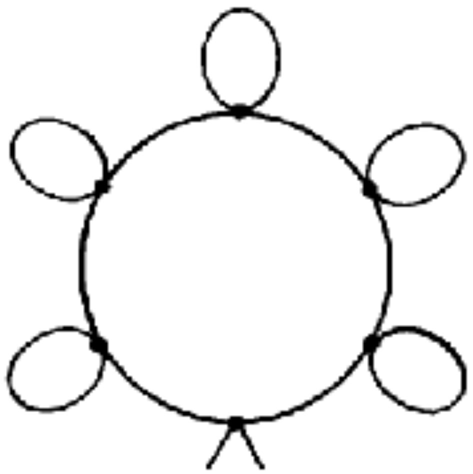
Scalar Potentials at Finite Temperature

Resummed "Daisy" Corrections   Dolan Jackiw 1974, Carrington 1992

- *n* one-vertex bubbles, one *n*-vertex bubble:

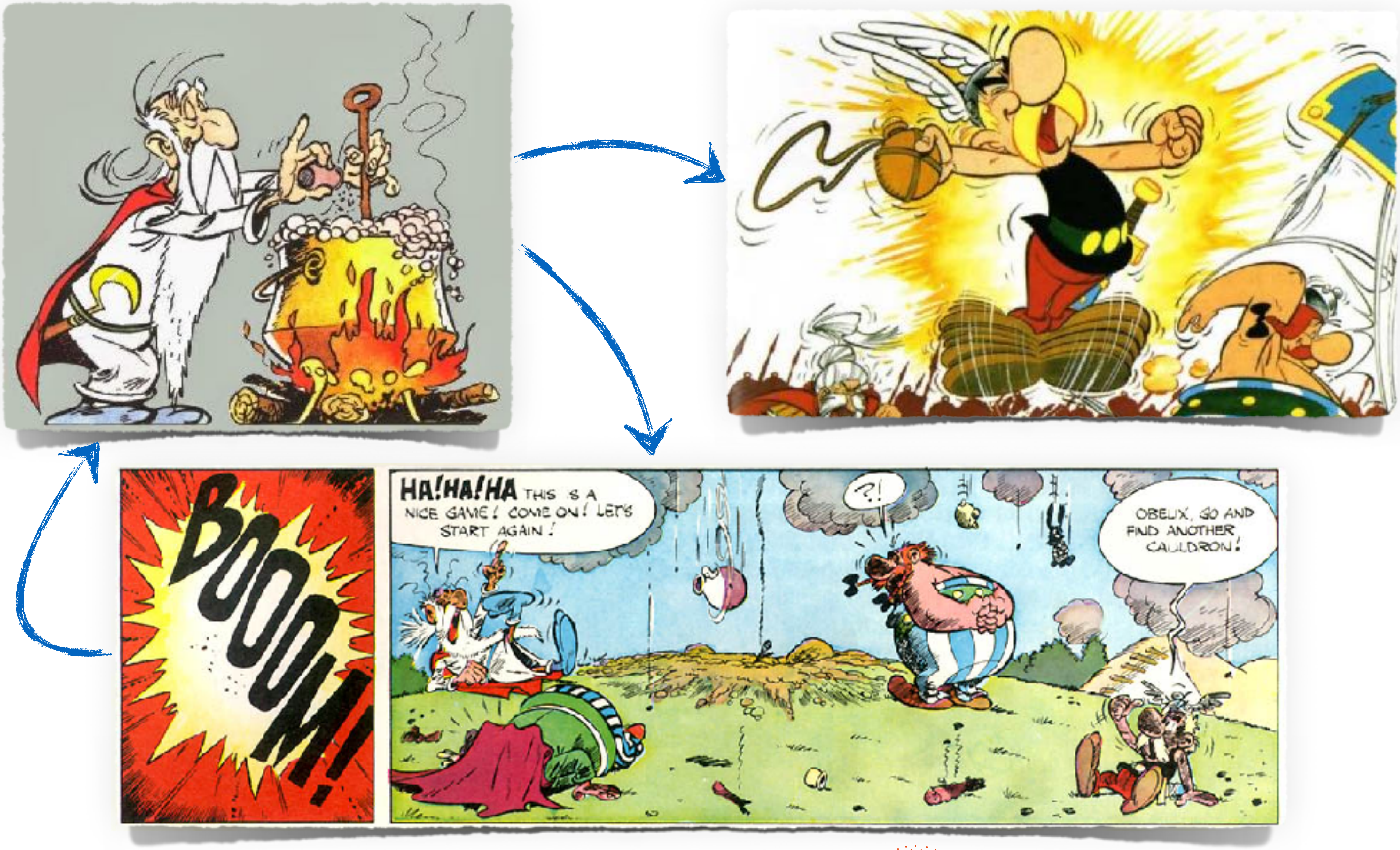
$$\sum_n \left(\int \frac{d^4k}{(2\pi)^4} \tilde{D}(k) \right)^n \cdot \int \frac{d^4k}{(2\pi)^4} \left(\tilde{D}(k) \right)^n$$



- One-vertex bubbles yield thermal mass $\Pi(T)$

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

Dark Matter Model Building Flowchart



A Toy Model

Field	Spin	SM	$\mathbb{Z}_3$	mass scale
S_3	0	$(1,3,0)$	$S_3 \to e^{2\pi i/3} S_3$	100 GeV
χ	$\frac{1}{2}$	$(1,1,0)$	$\chi \to e^{2\pi i/3} \chi$	TeV
Ψ_3	$\frac{1}{2}$	$(1,3,0)$	$\Psi_3 \to e^{-2\pi i/3} \Psi_3$	TeV
Ψ'_3	$\frac{1}{2}$	$(1,3,0)$	$\Psi'_3 \to e^{-2\pi i/3} \Psi'_3$	TeV

Baker JK 1608.07578

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DM candidate

Baker JK 1608.07578

A Toy Model

stabilizes DM

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DM candidate

DM decay products

Baker JK 1608.07578

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new scalar

DM candidate

DM decay products

stabilizes DM

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$$\mathcal{L} \supset y_\chi S_3^\dagger \bar{\chi} \Psi_3 + y_\chi' S_3^\dagger \bar{\chi} \Psi_3' + y_\Psi \epsilon^{ijk} S_3^i \overline{\Psi_3^j} (\Psi_3'^k)^c + h.c.$$

A Toy Model

stabilizes DM

new scalar

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- ☑ $\langle S \rangle$ leads to mixing between χ, ψ_3, ψ_3' alters ψ_3, ψ_3' masses
- ☑ χ decays via $\chi \to W\psi_3$, $S\psi_3$ when $\langle S \rangle \neq 0$

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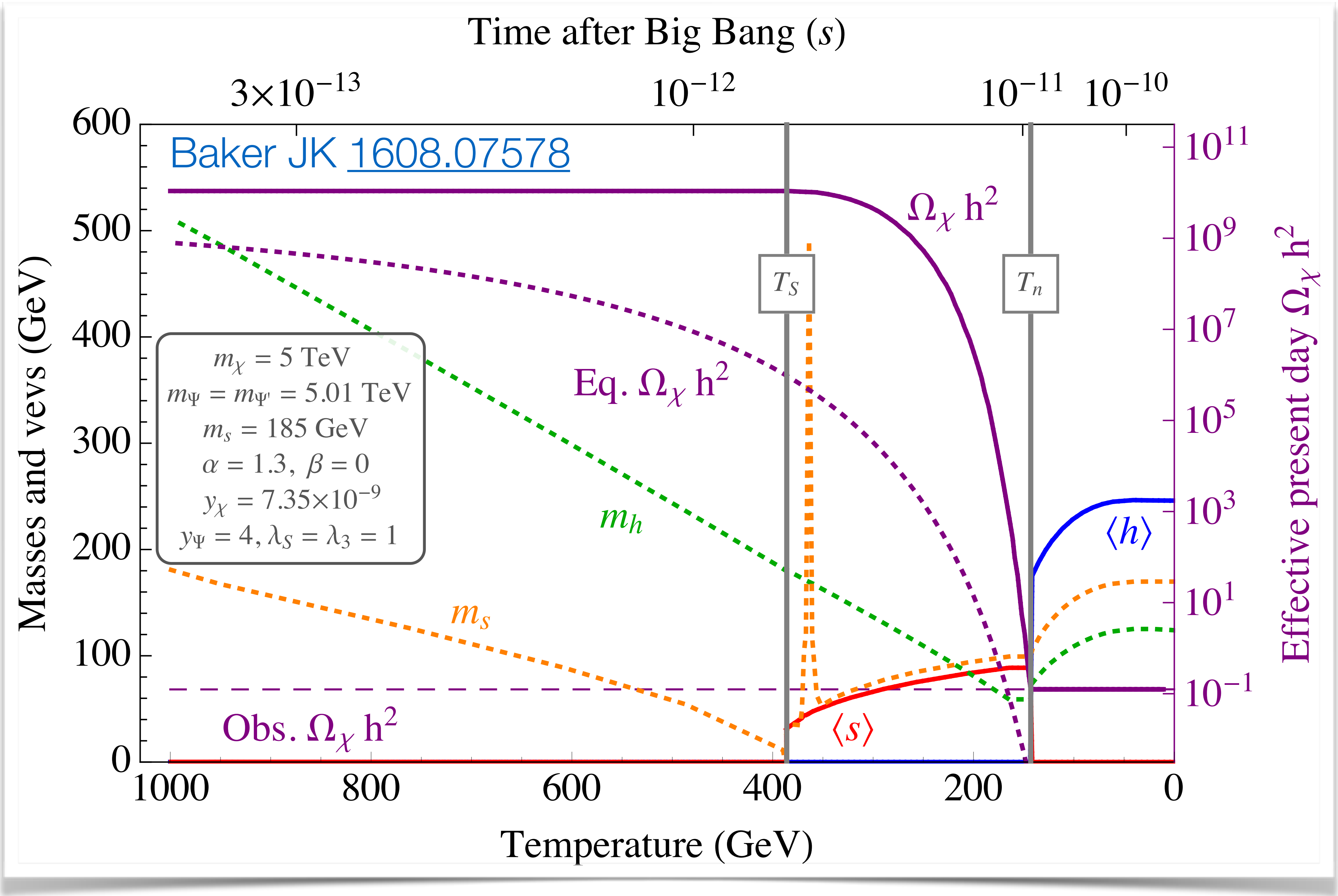
Cosmological Evolution



Parameter Space

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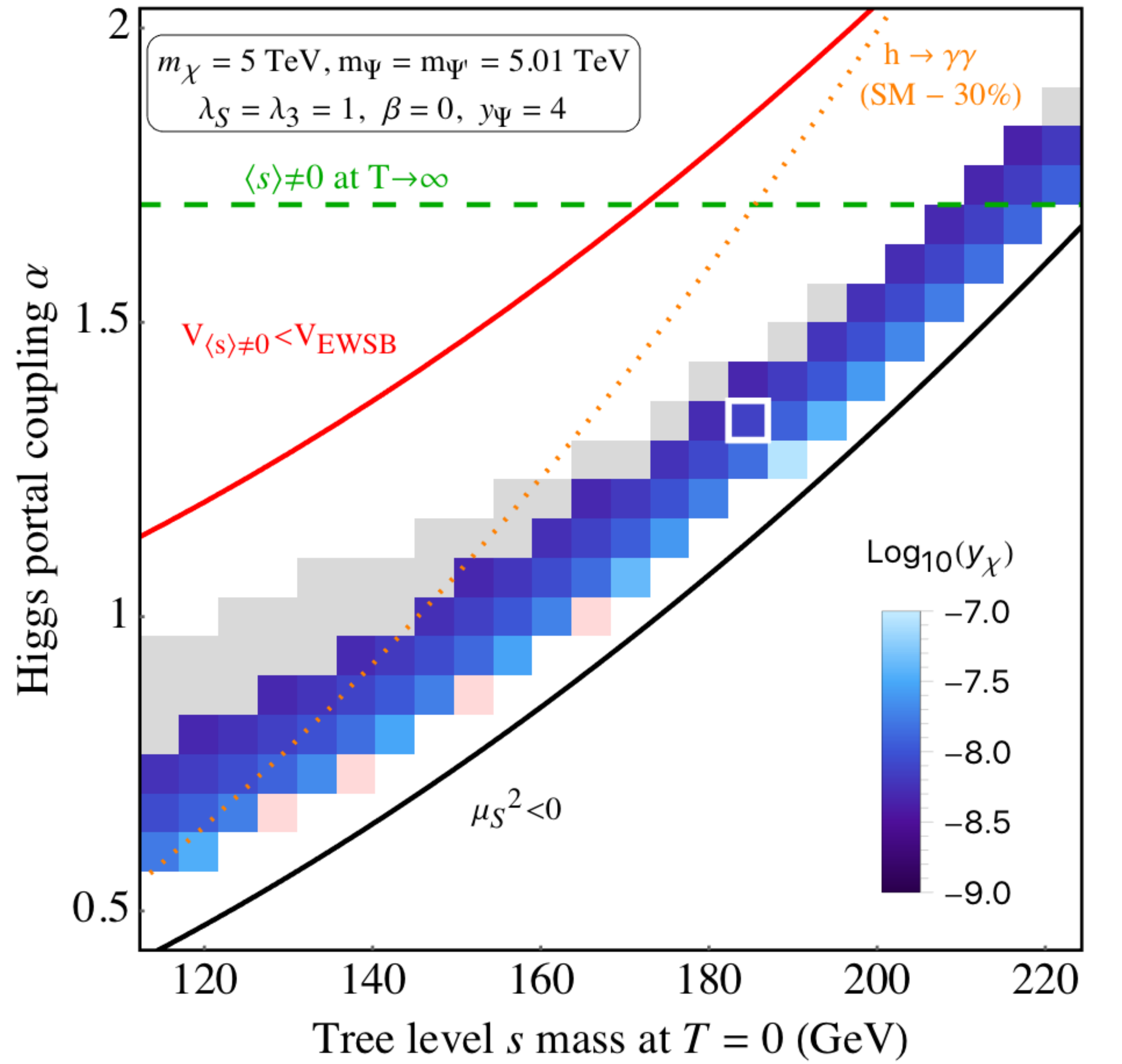
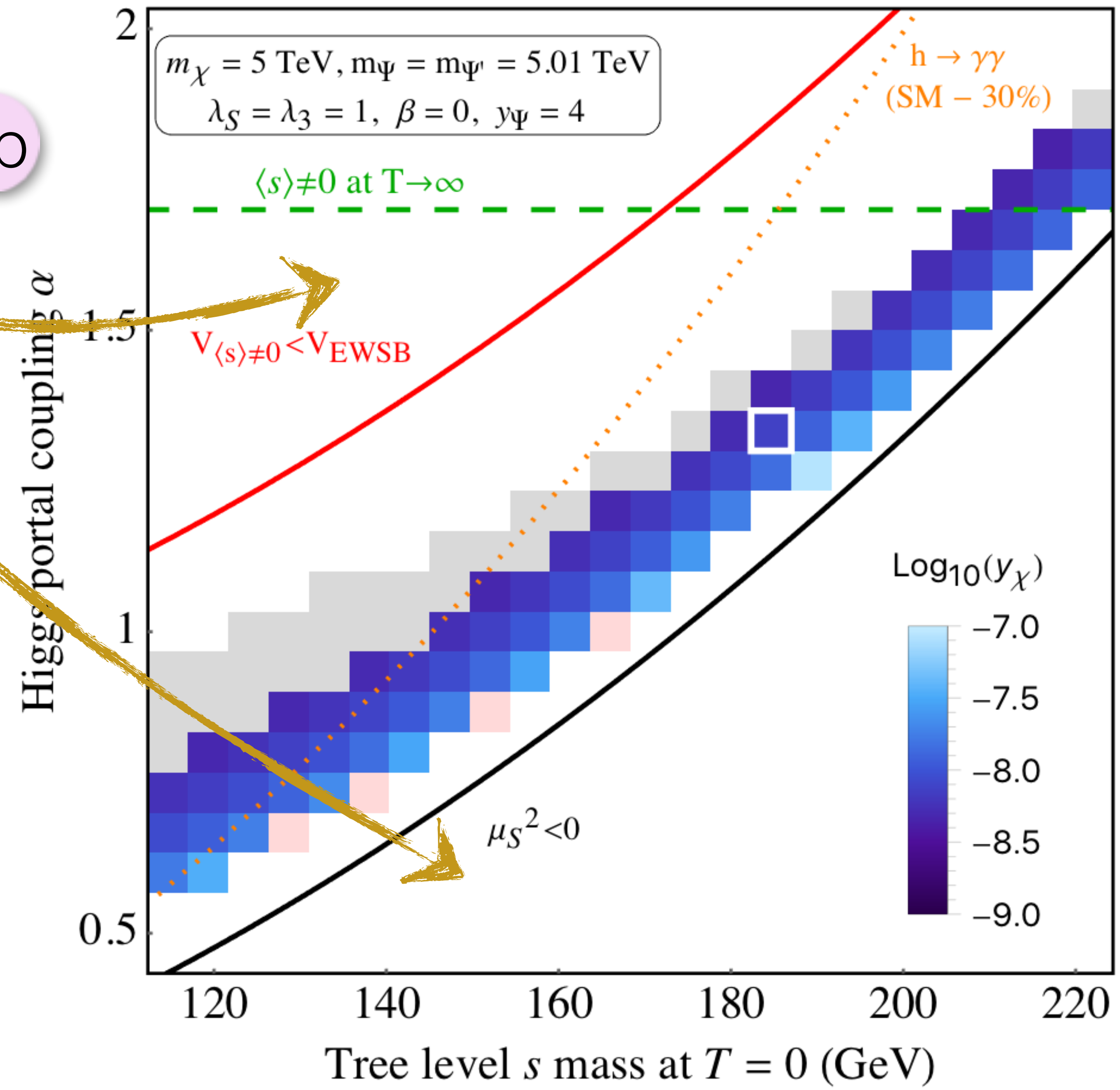


Parameter Space

no vev flip-flop

Baker JK 1608.07578

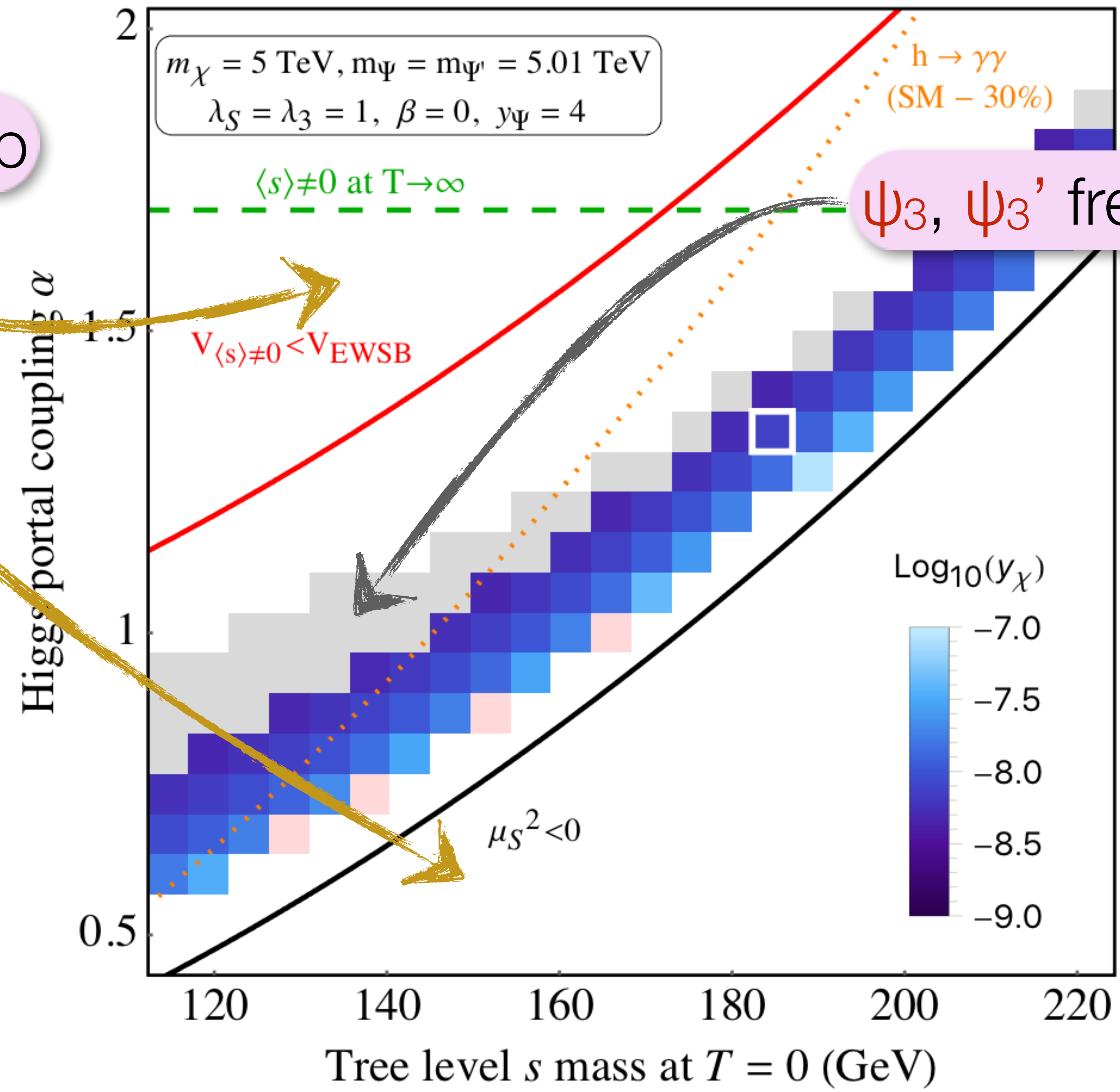


Parameter Space

Baker JK [1608.07578]

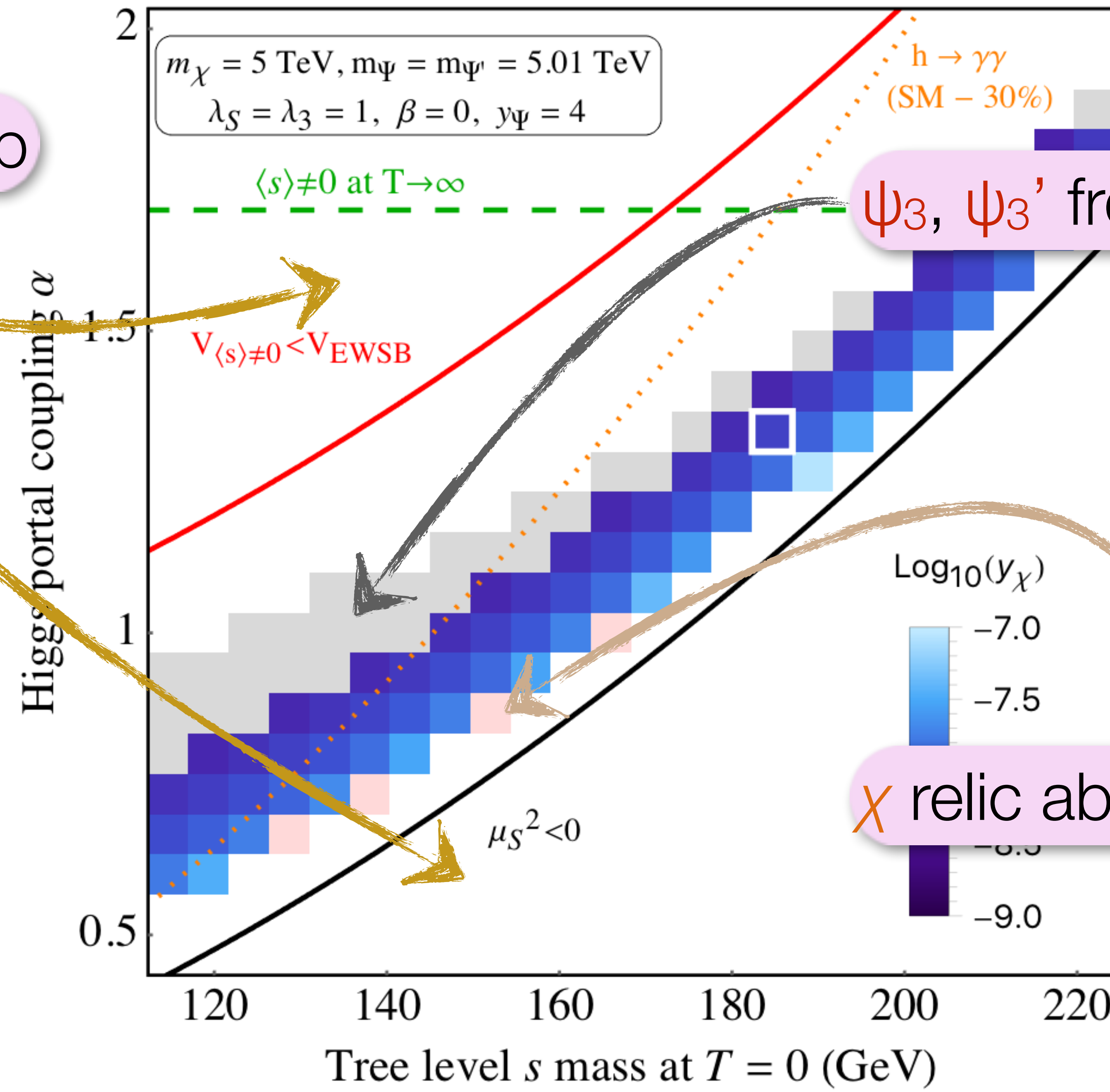
no vev flip-flop

ψ_3, ψ_3' freeze out too early



Parameter Space

Baker JK [1608.07578]

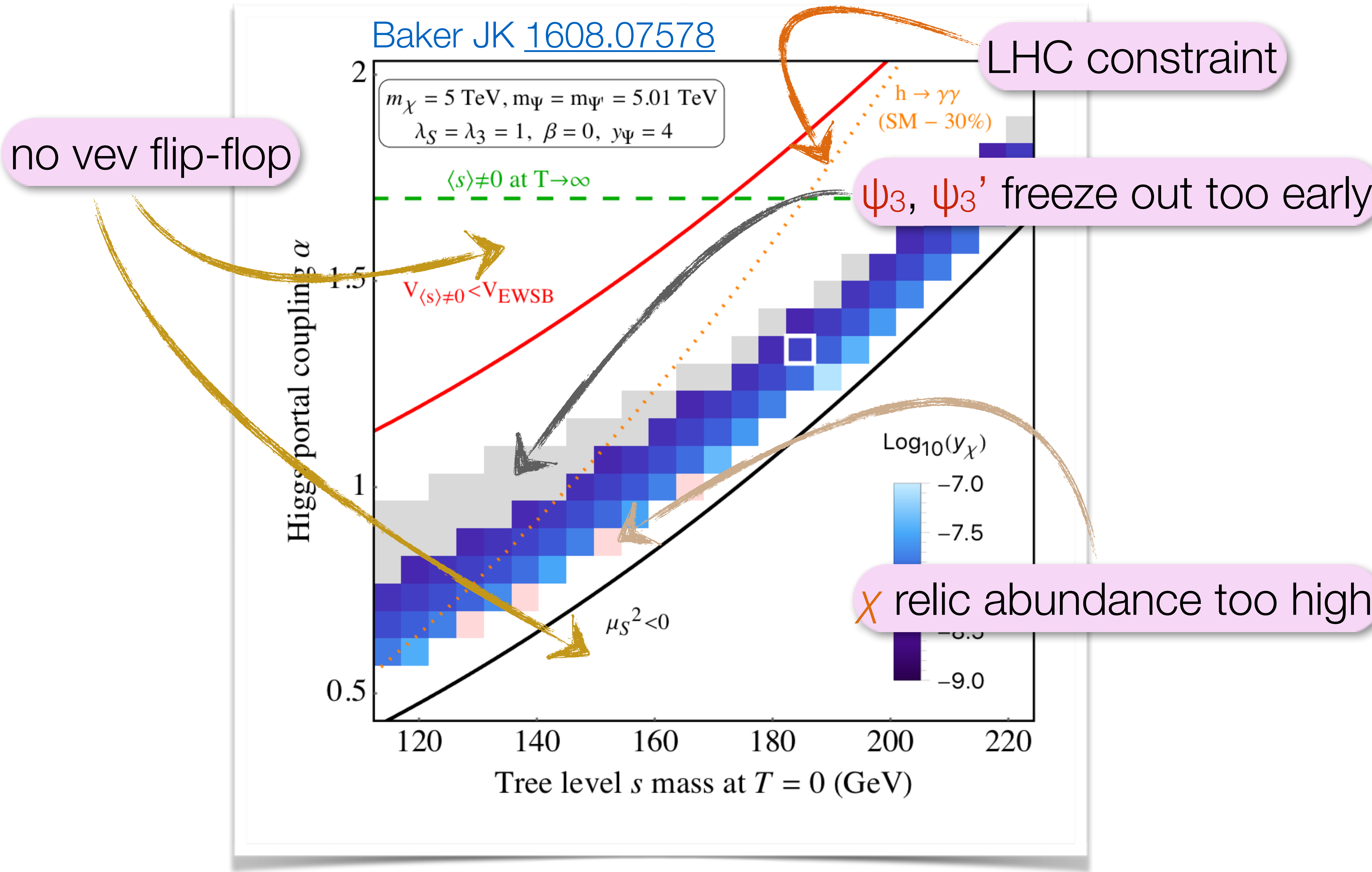


no vev flip-flop

ψ3, ψ3' freeze out too early

χ relic abundance too high

Parameter Space



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Thermal Effects in DM Freeze-In

DM Freeze-In in Higgs Portal Models

- Toy Model: SM + singlet scalar S + DM fermion χ + fermion ψ

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)(\partial^\mu S) + \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi$$
$$+ \left[y_{\psi\chi}\,\bar{\psi}S\chi + h.c.\right] + y_\chi\,\bar{\chi}\chi S + y_\psi\,\bar{\psi}\psi S - V(H,S)$$

- Scalar Potential:

$$V(H,S) = -\mu_H^2 H^\dagger H + \lambda_{H4}\,(H^\dagger H)^2 - \frac{1}{2}\mu_S^2 S^2 + \frac{\lambda_{S4}}{4!}S^4$$
$$+ \frac{\lambda_{S3}}{3!}\,\mu_S S^3 + \lambda_{p3}\mu_S\,S(H^\dagger H) + \frac{\lambda_{p4}}{2}\,S^2(H^\dagger H)\,.$$

Baker Breitbach JK Mittnacht 1712.03962

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$$+ \left[y_{\psi\chi}\,\bar{\psi}S\chi + h.c.\right] + y_\chi\,\bar{\chi}\chi S + y_\psi\,\bar{\psi}\psi S - V(H,S)$$

- Scalar Potential:

assumed small

$$V(H,S) = -\mu_H^2 H^\dagger H + \lambda_{H4}\,(H^\dagger H)^2 - \frac{1}{2}\mu_S^2 S^2 + \frac{\lambda_{S4}}{4!}S^4$$
$$+ \frac{\lambda_{S3}}{3!}\mu_S S^3 + \lambda_{p3}\mu_S\,S(H^\dagger H) + \frac{\lambda_{p4}}{2}\,S^2(H^\dagger H)\,.$$

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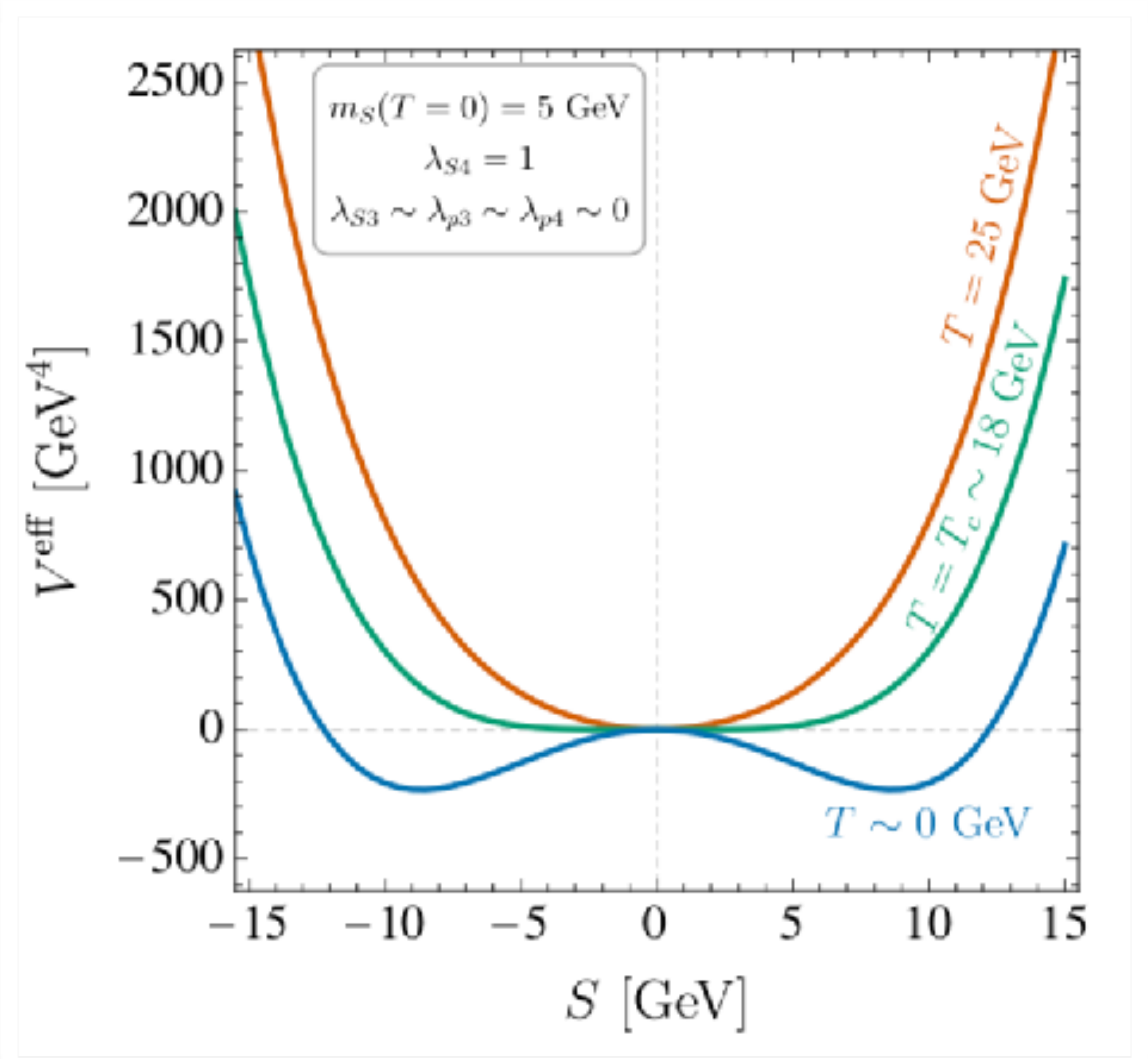
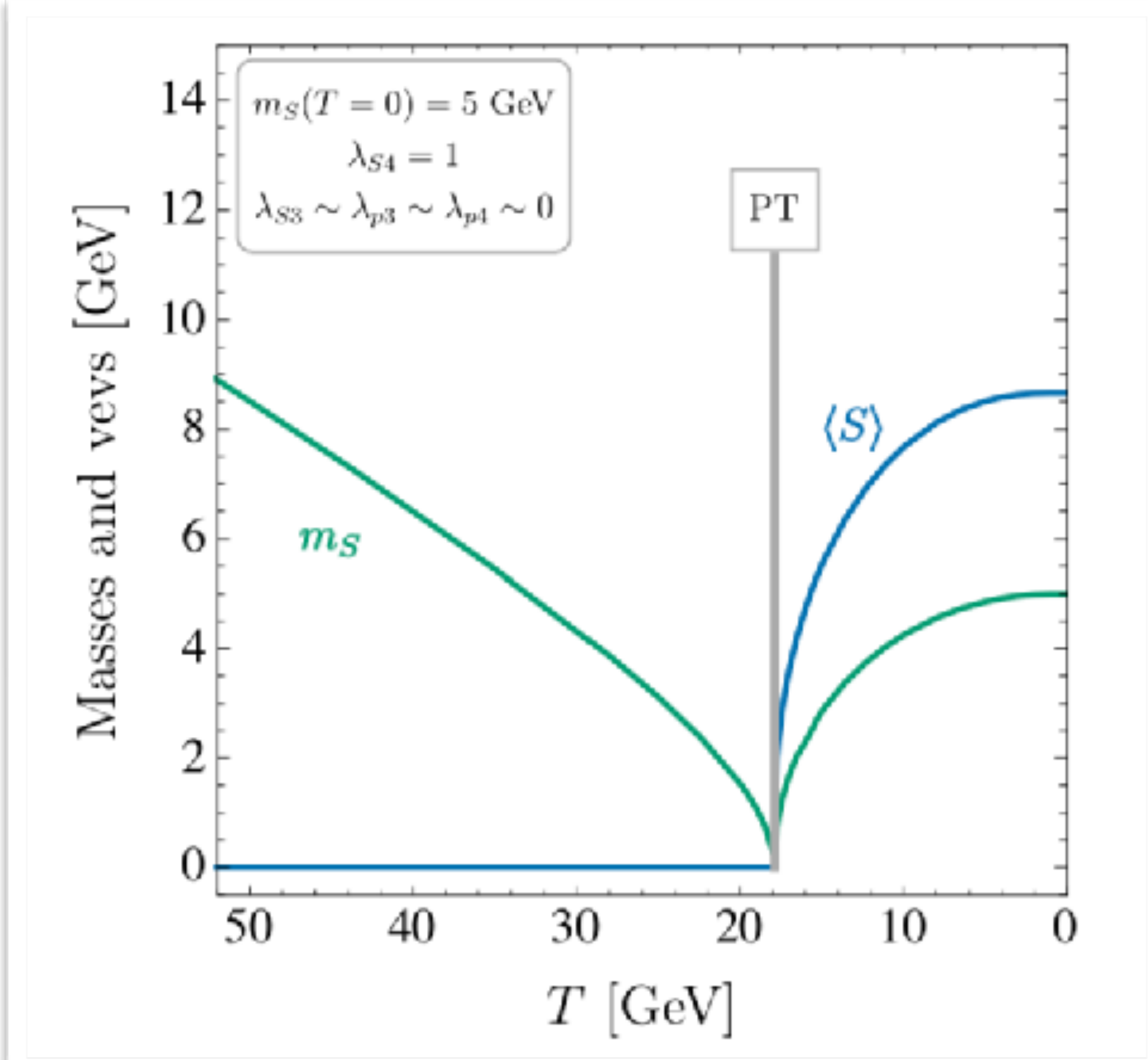
Effective Potential and Thermal Masses





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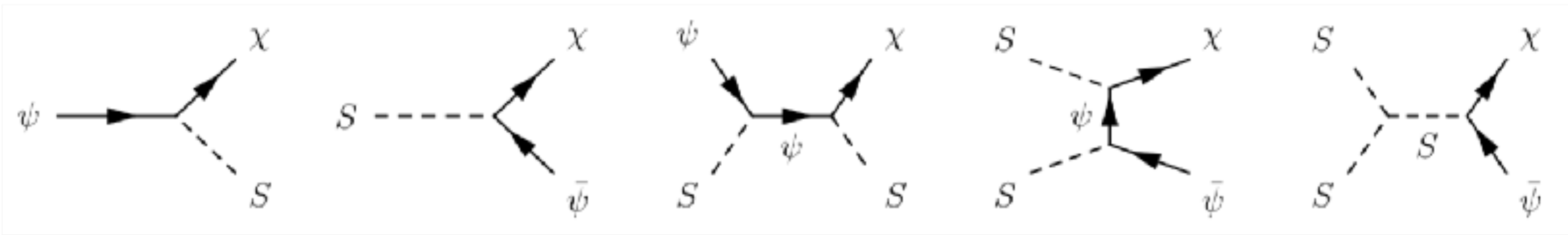
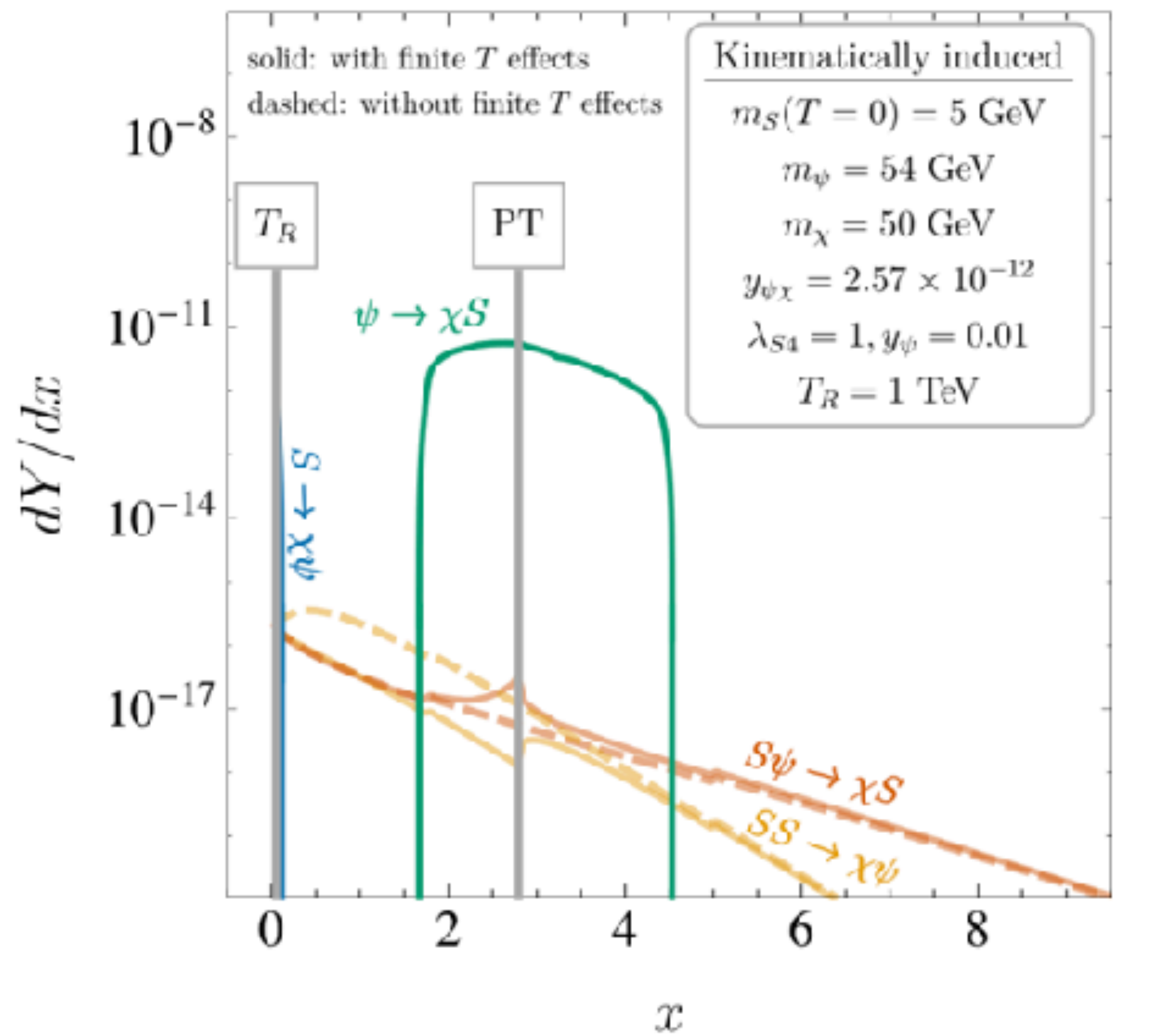
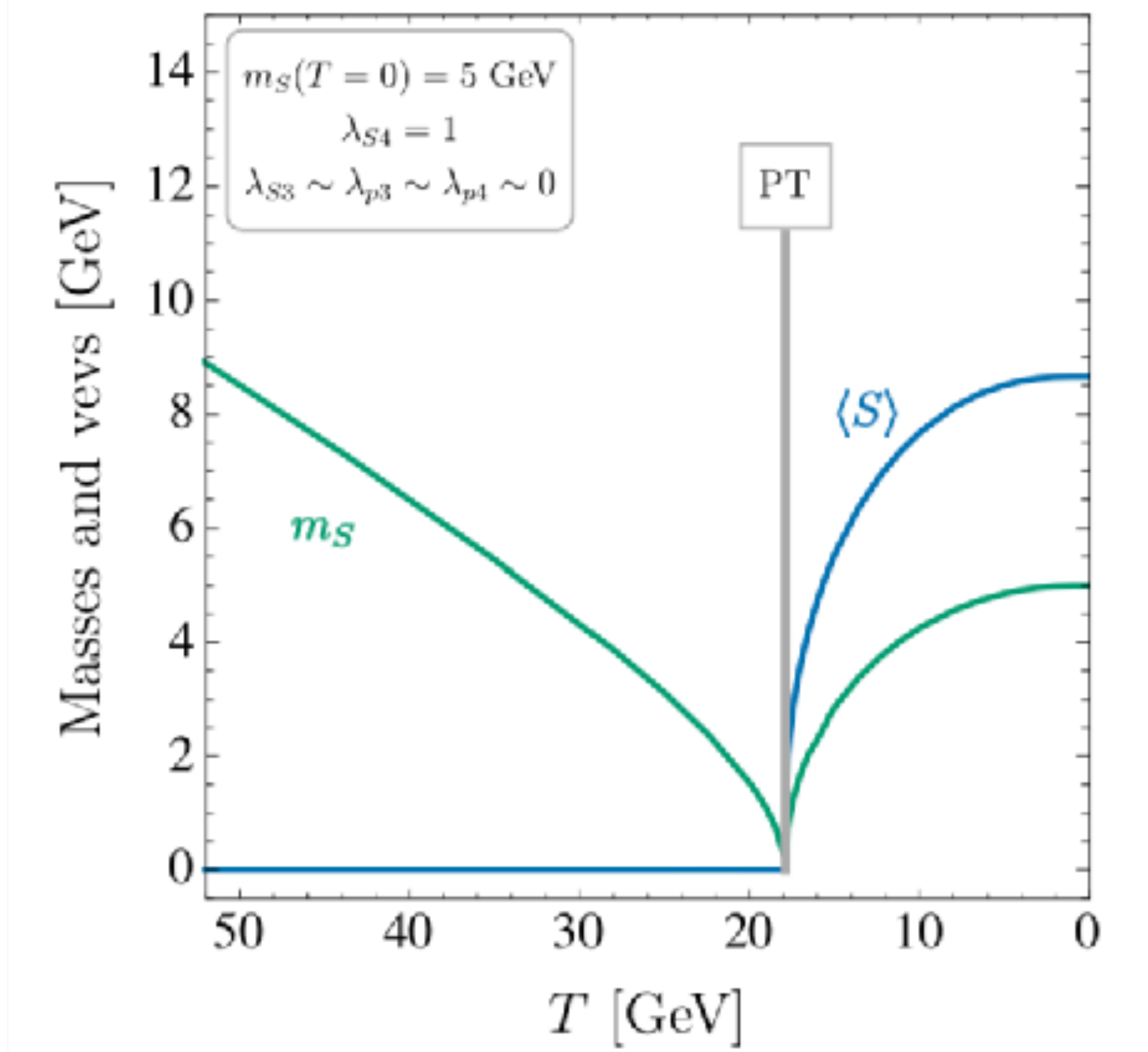
DM Freeze-In



ψ
χ
S
S
ψ̄

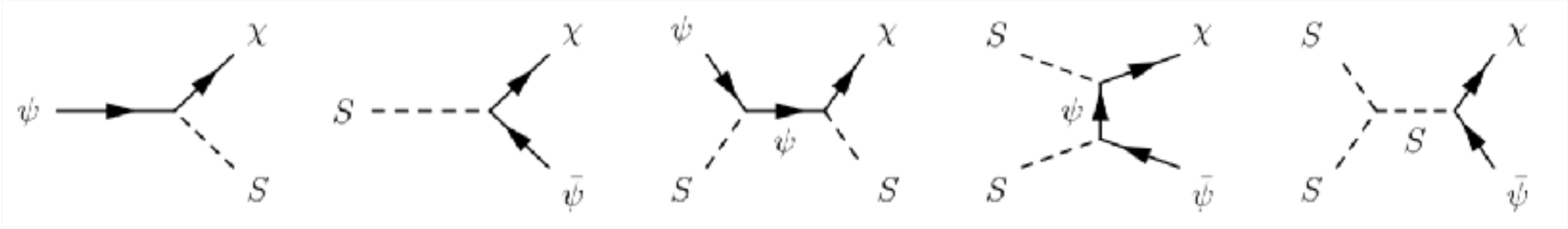


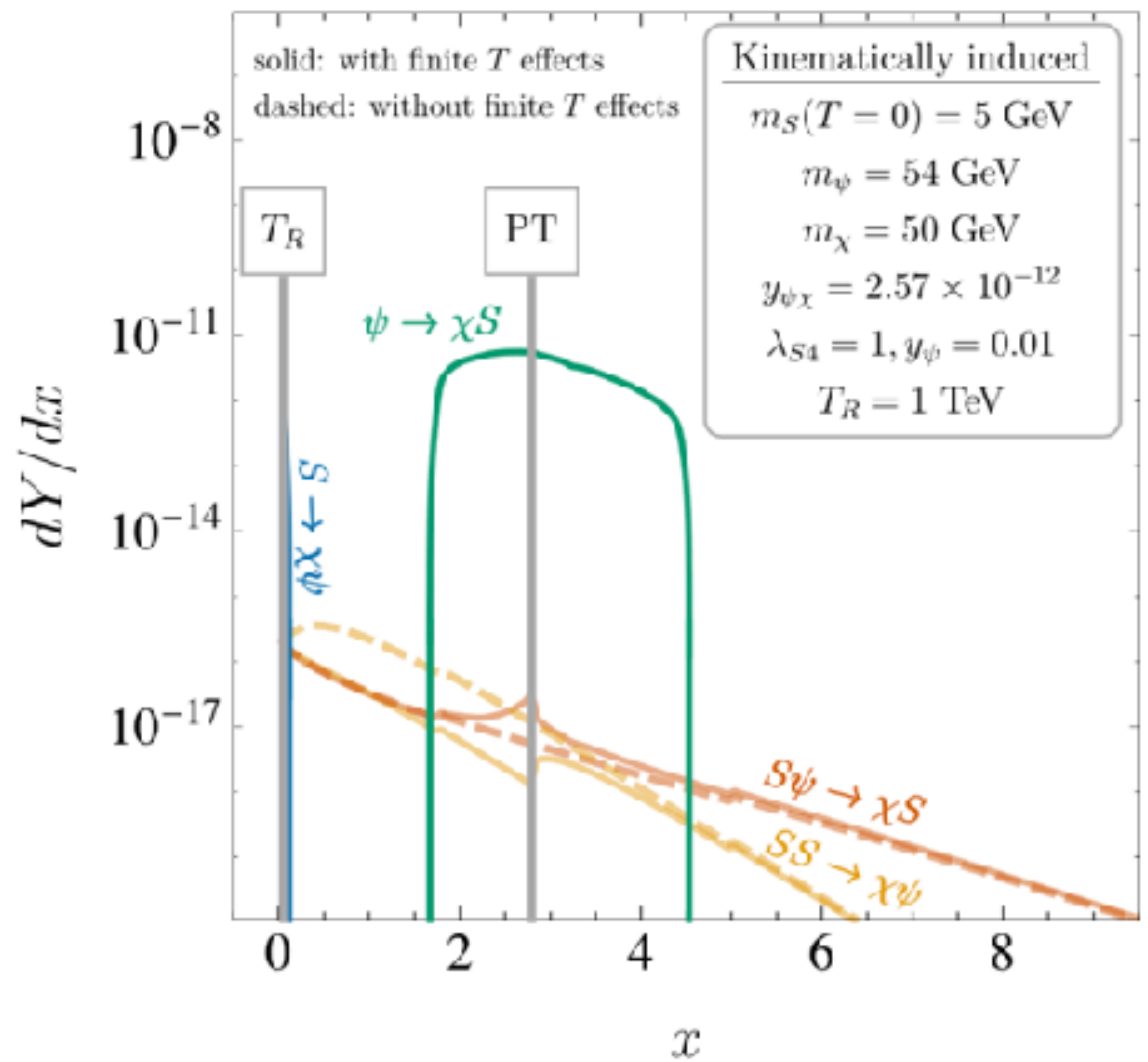
solid: with finite T effects
dashed: without finite T effects
Kinematically induced
$m_S(T=0) = 5$ GeV
$m_\psi = 54$ GeV
$m_\chi = 50$ GeV
$y_{\psi\chi} = 2.57 \times 10^{-12}$
$\lambda_{S4} = 1, y_\psi = 0.01$
$T_R = 1$ TeV
T_R
PT
$\psi \to \chi S$
$S \to \chi\bar{\psi}$
$S\psi \to \chi S$
$SS \to \chi\psi$
dY/dx
x

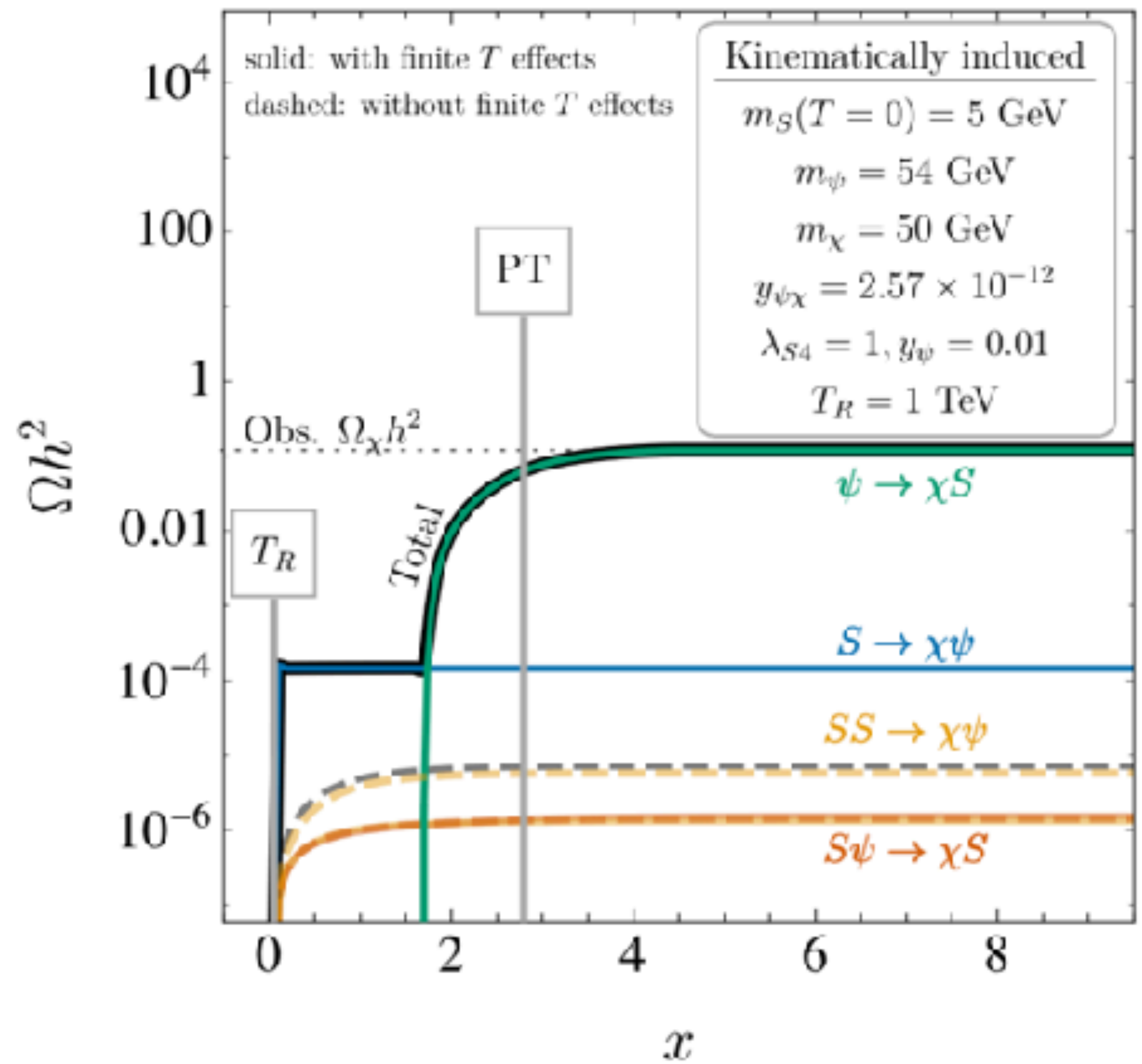


$m_S(T=0) = 5$ GeV
$\lambda_{S4} = 1$
$\lambda_{S3} \sim \lambda_{p3} \sim \lambda_{p4} \sim 0$
PT
$\langle S \rangle$
m_S
Masses and vevs [GeV]
T [GeV]

DM Freeze-In







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Variation: Vev Flip-Flop Freeze-In

- Toy Model: SM + singlet scalar S + DM fermion χ

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)(\partial^\mu S) + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + y_\chi \bar{\chi}\chi S - V(H,S)$$

- Scalar Potential:

$$V(H,S) = -\mu_H^2 H^\dagger H + \lambda_{H4}\,(H^\dagger H)^2 - \frac{1}{2}\mu_S^2 S^2 + \frac{\lambda_{S4}}{4!} S^4 + \frac{\lambda_{S3}}{3!}\,\mu_S S^3 + \lambda_{p3}\mu_S\, S(H^\dagger H) + \frac{\lambda_{p4}}{2}\, S^2 (H^\dagger H)\,.$$

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$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)(\partial^\mu S) + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + y_\chi \bar{\chi}\chi S - V(H, S)$$

assumed small

- Scalar Potential:

$$V(H, S) = -\mu_H^2 H^\dagger H + \lambda_{H4} (H^\dagger H)^2 - \frac{1}{2}\mu_S^2 S^2 + \frac{\lambda_{S4}}{4!} S^4$$
$$+ \frac{\lambda_{S3}}{3!}\mu_S S^3 + \lambda_{p3}\mu_S S(H^\dagger H) + \frac{\lambda_{p4}}{2} S^2 (H^\dagger H)\,.$$

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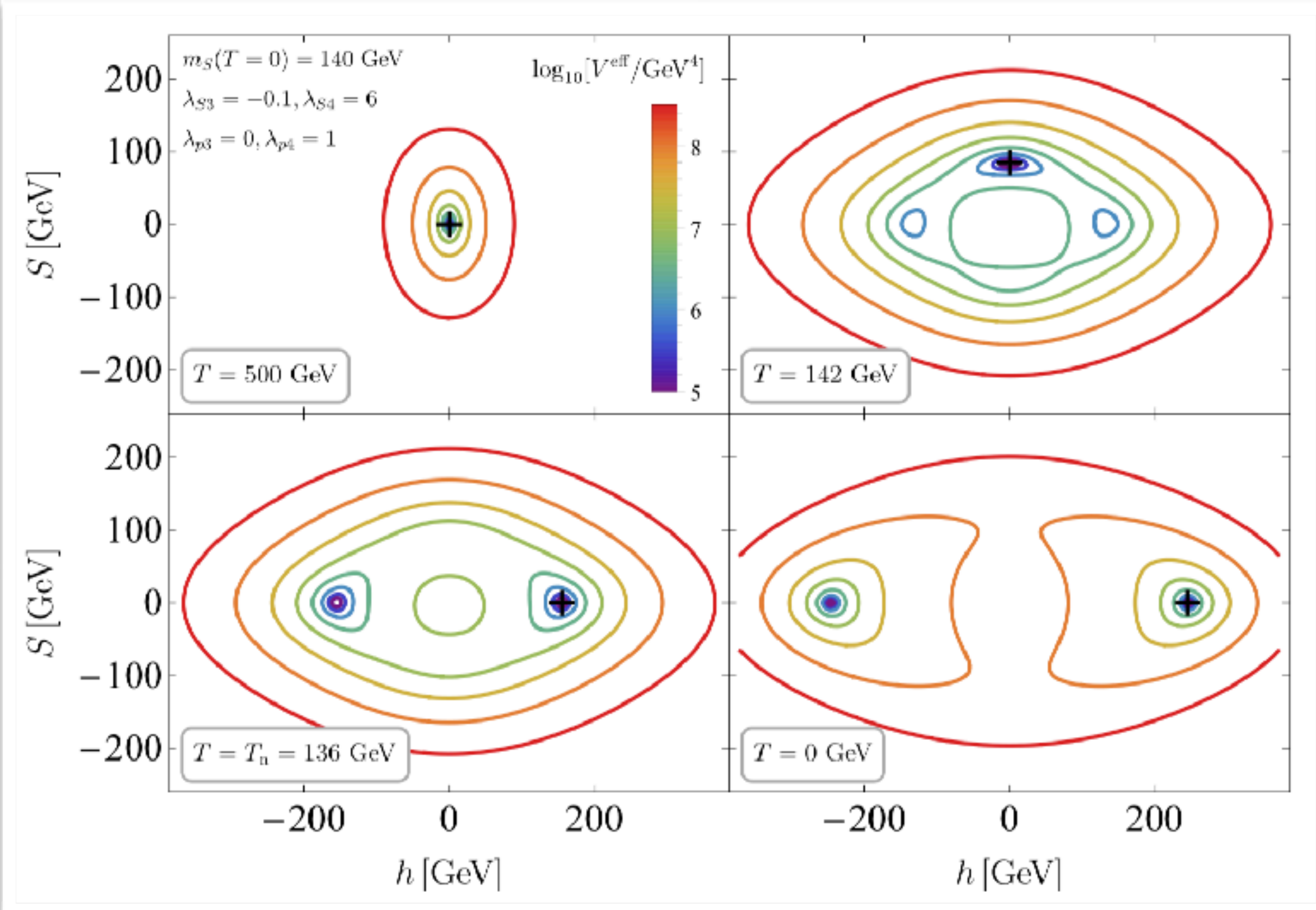
Vev Flip-Flop in the Scalar Potential



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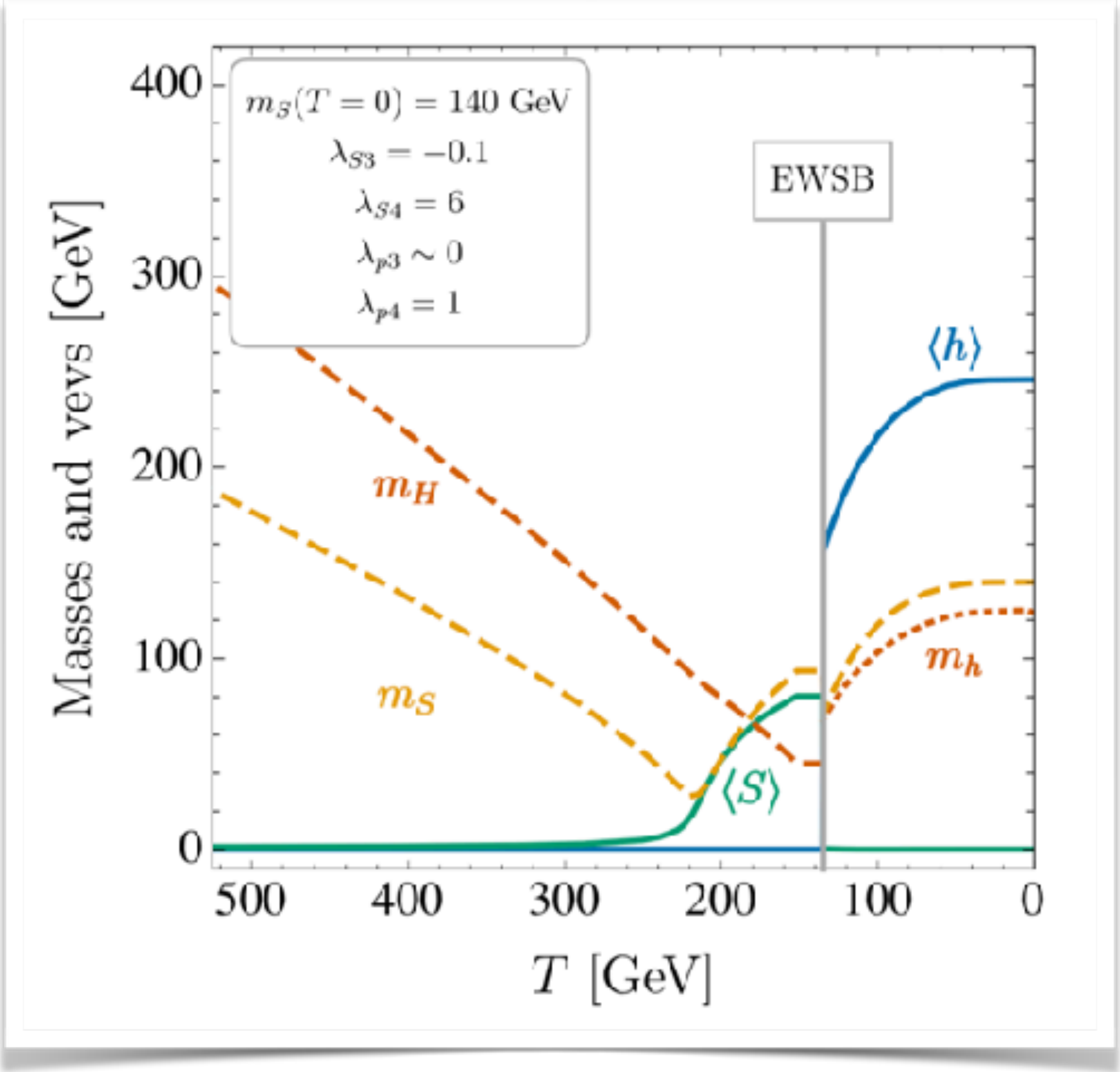
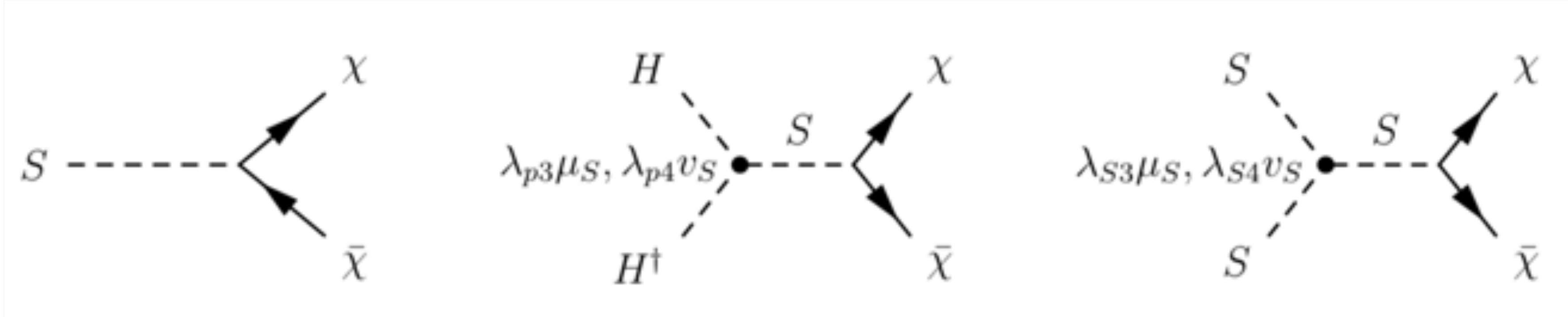
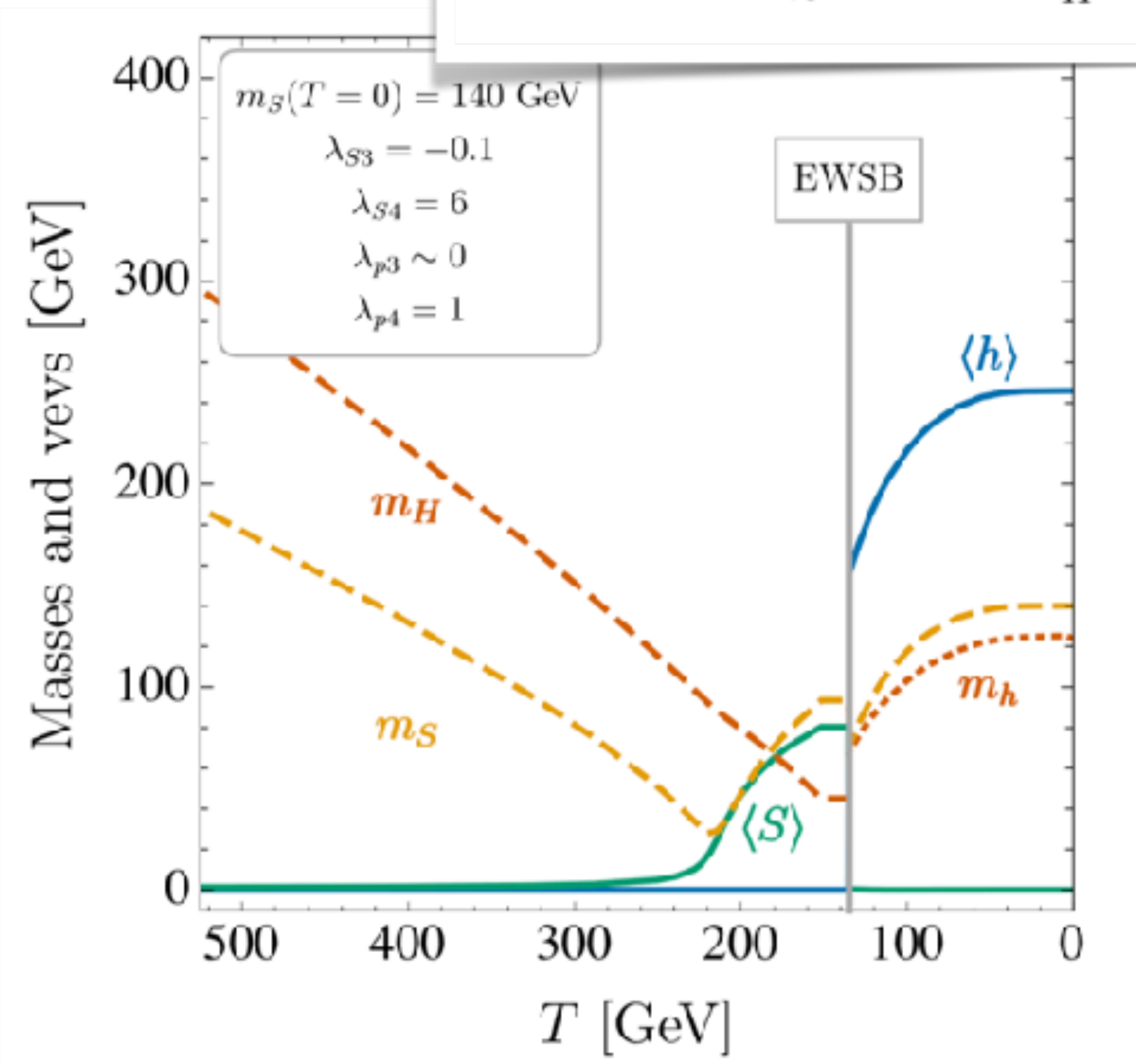
Scalar Masses and Vevs, DM Freeze-In

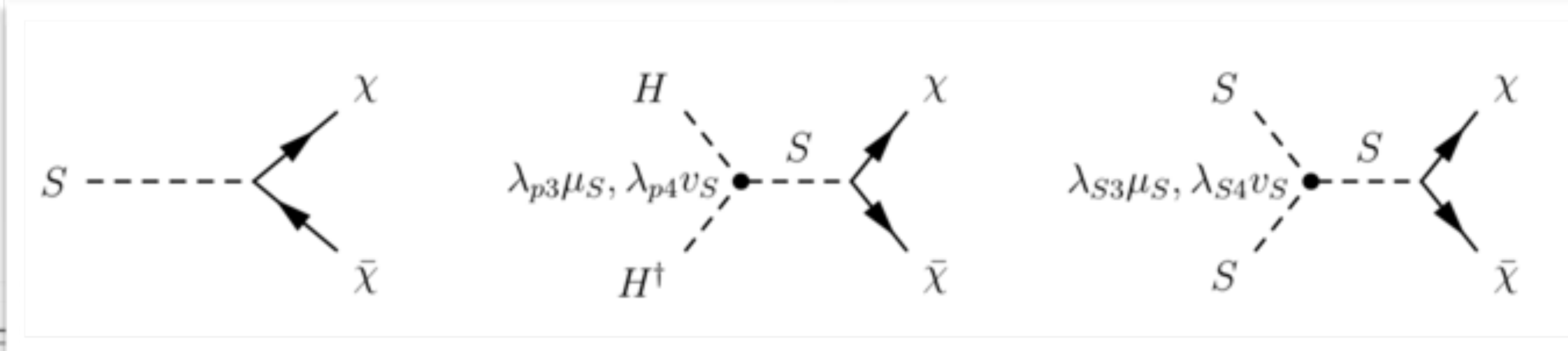


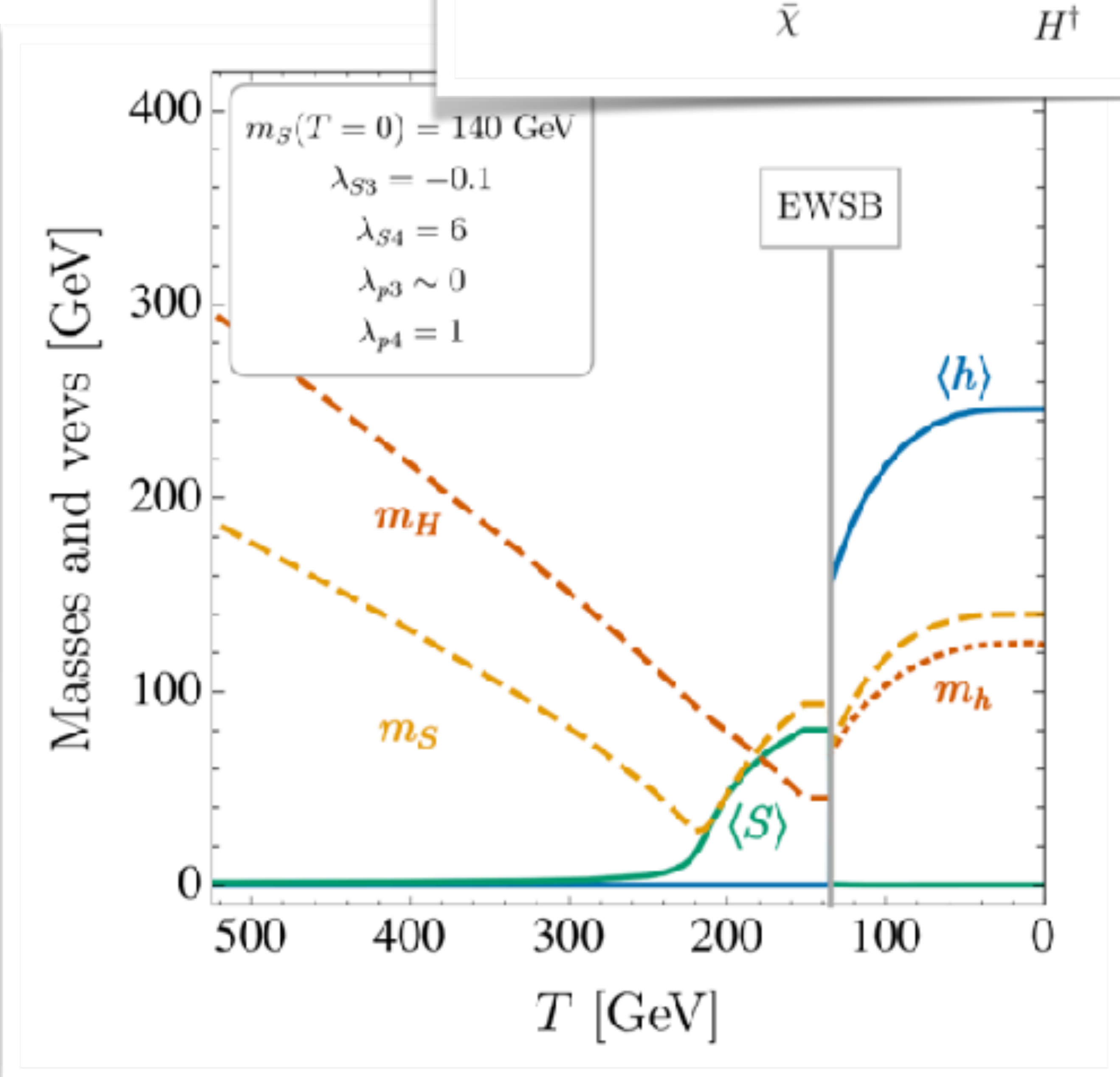
Scalar Masses and Vevs, DM Freeze-In

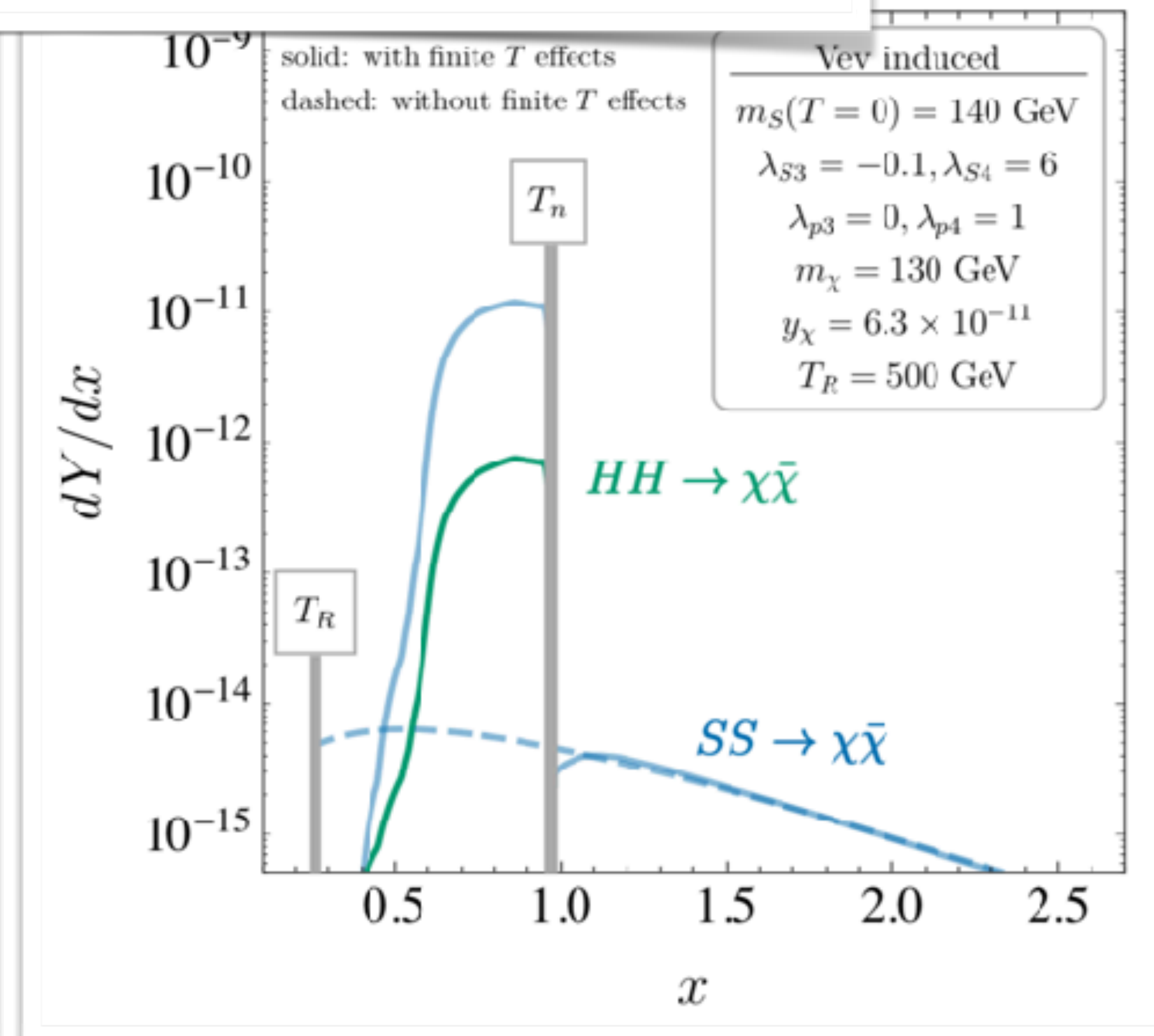




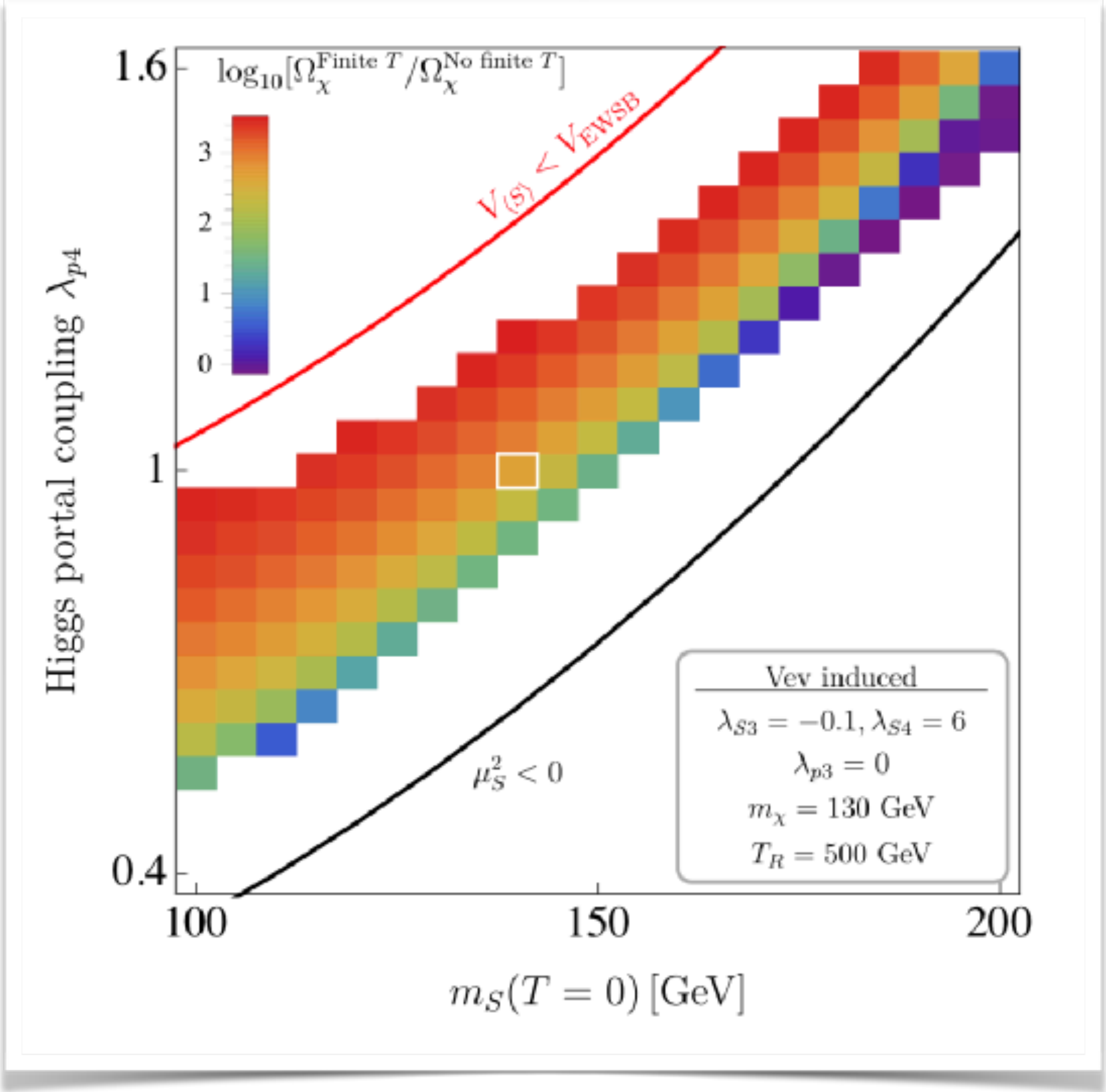
Scalar Masses and Vevs, DM Freeze-In







Impact of Finite-T Effects: Parameter Scan



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Summary

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Thermal Effects in the Early Universe

- ☑ can (temporarily) affect DM stability via phase transitions
- ☑ can affect kinematics of freeze-in
- ☑ can open/close production channels in phase transitions

➥ DM abundance may crucially depend on thermal effects

Summary

Thermal Effects in the Early Universe

- ☑ can (temporarily) affect DM stability via phase transitions
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➡ DM abundance may crucially depend on thermal effects

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Moritz Breitbach

Lukas Mittnacht

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Thank you!