The Vev Flip-Flop

Impact of Cosmological Phase Transitions on Dark Matter

Joachim Kopp
SUSY 2017 Conference | TIFR Mumbai | December 11-15, 2017

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Popular DM Production Mechanisms

Thermal Freeze-Out

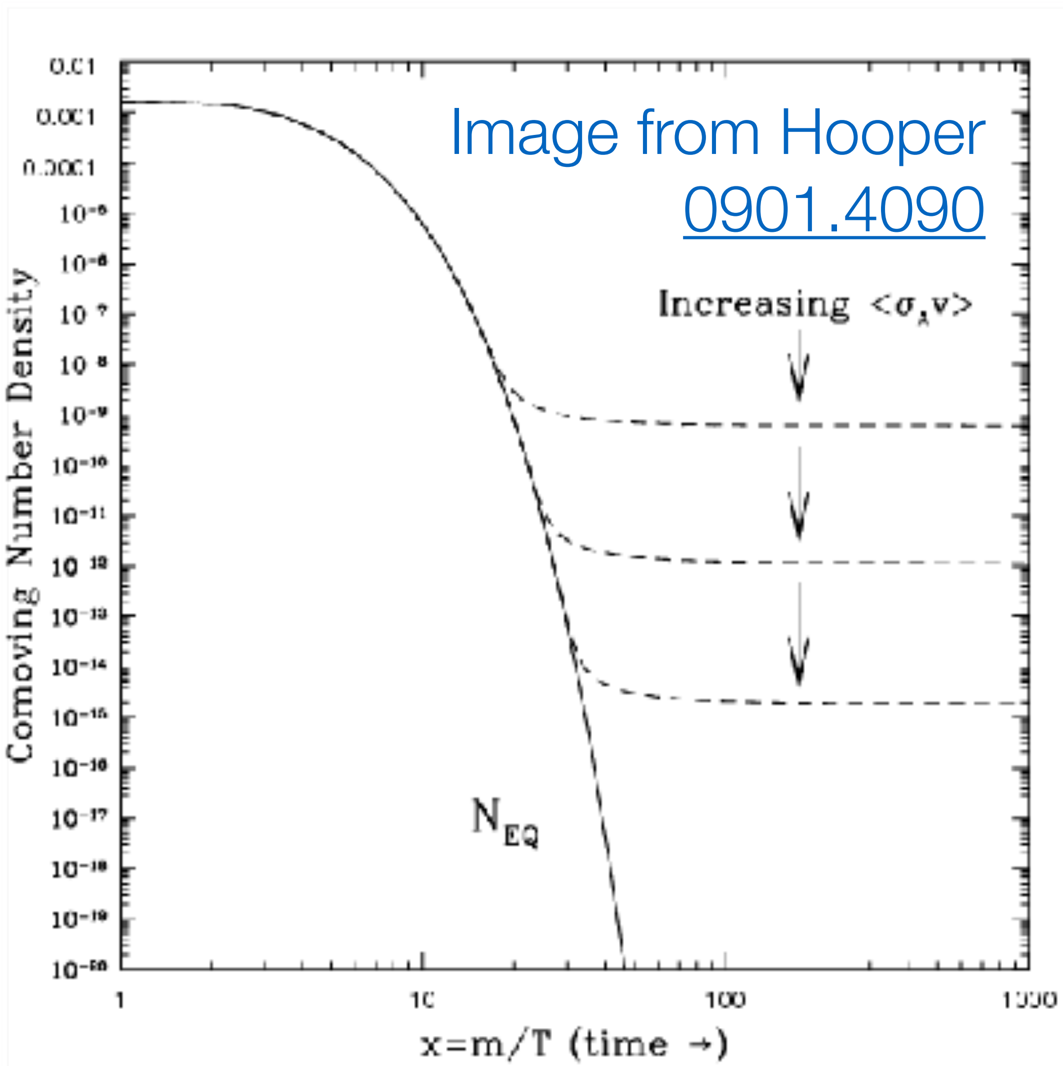

Image from Hooper [0901.4090](0901.4090)

Popular DM Production Mechanisms

Thermal Freeze-Out

- Observed abundance requires

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

- Realized for
  new particles at ~ 100 GeV
  couplings ~ α_{em} ~ 0.01

WIMP Miracle

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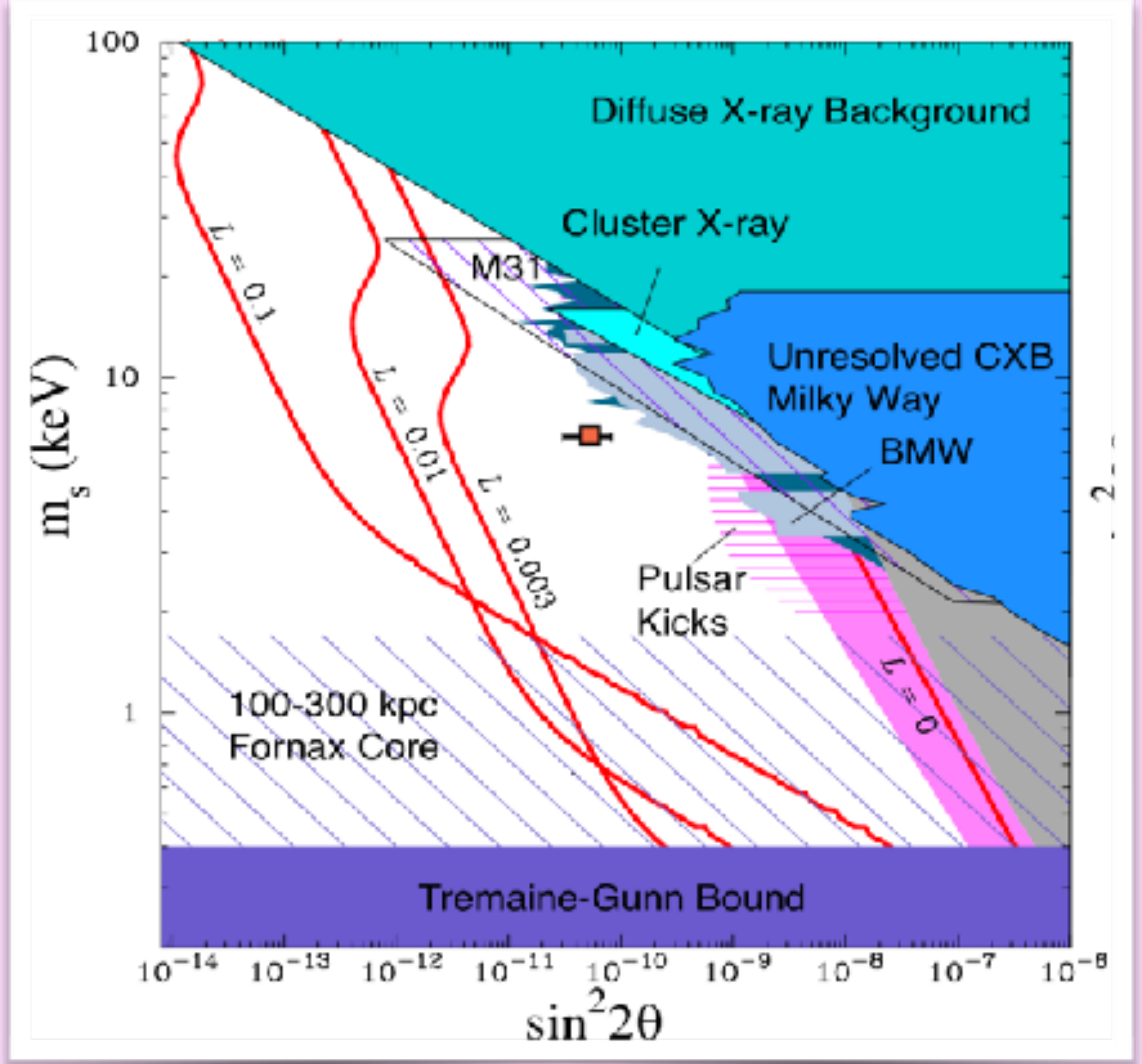
Freeze-In via Oscillation



Bulbul et al. 1402.2301

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Tension with LHC Constraints

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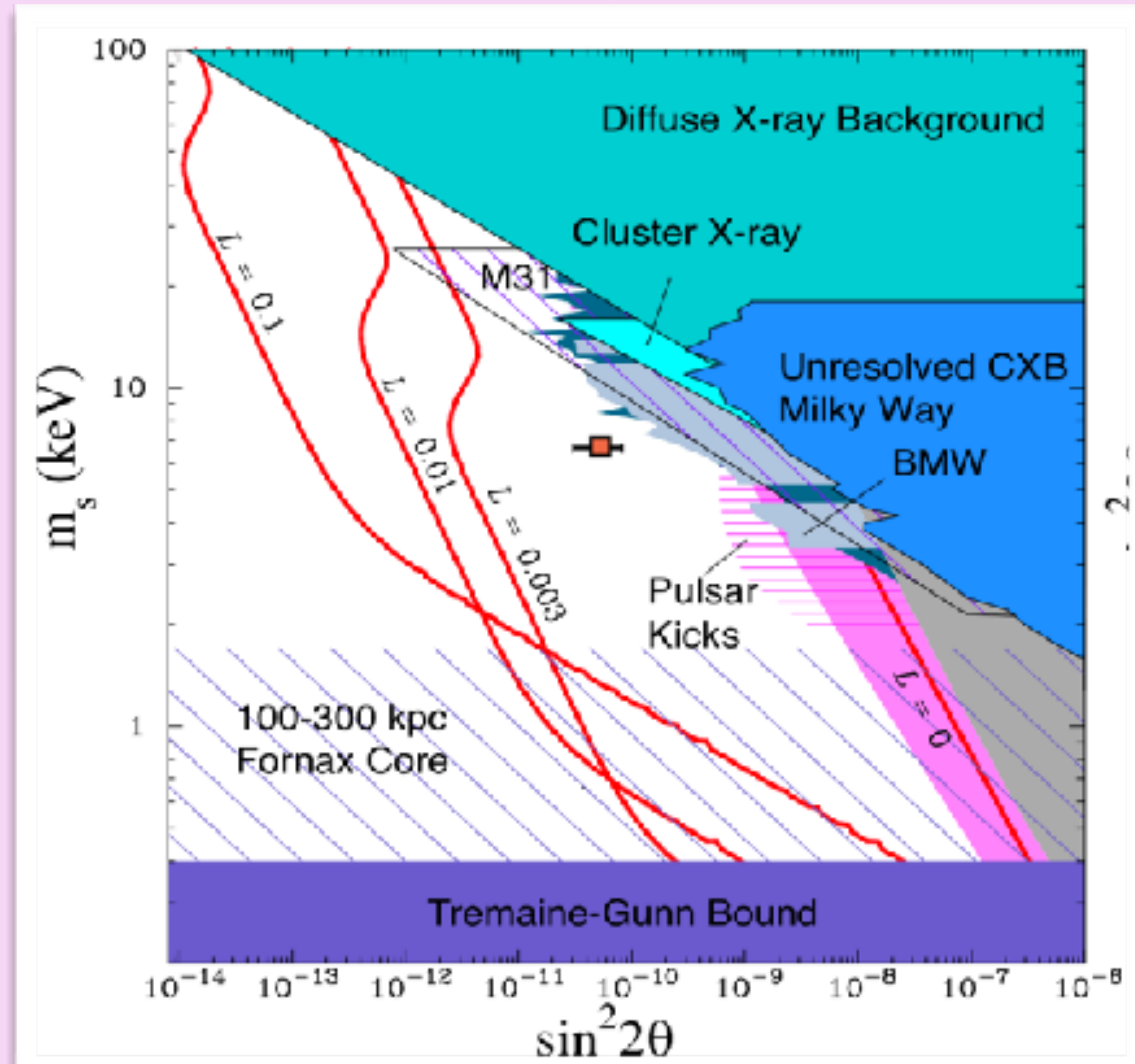

Bulbul et al. 1402.2301

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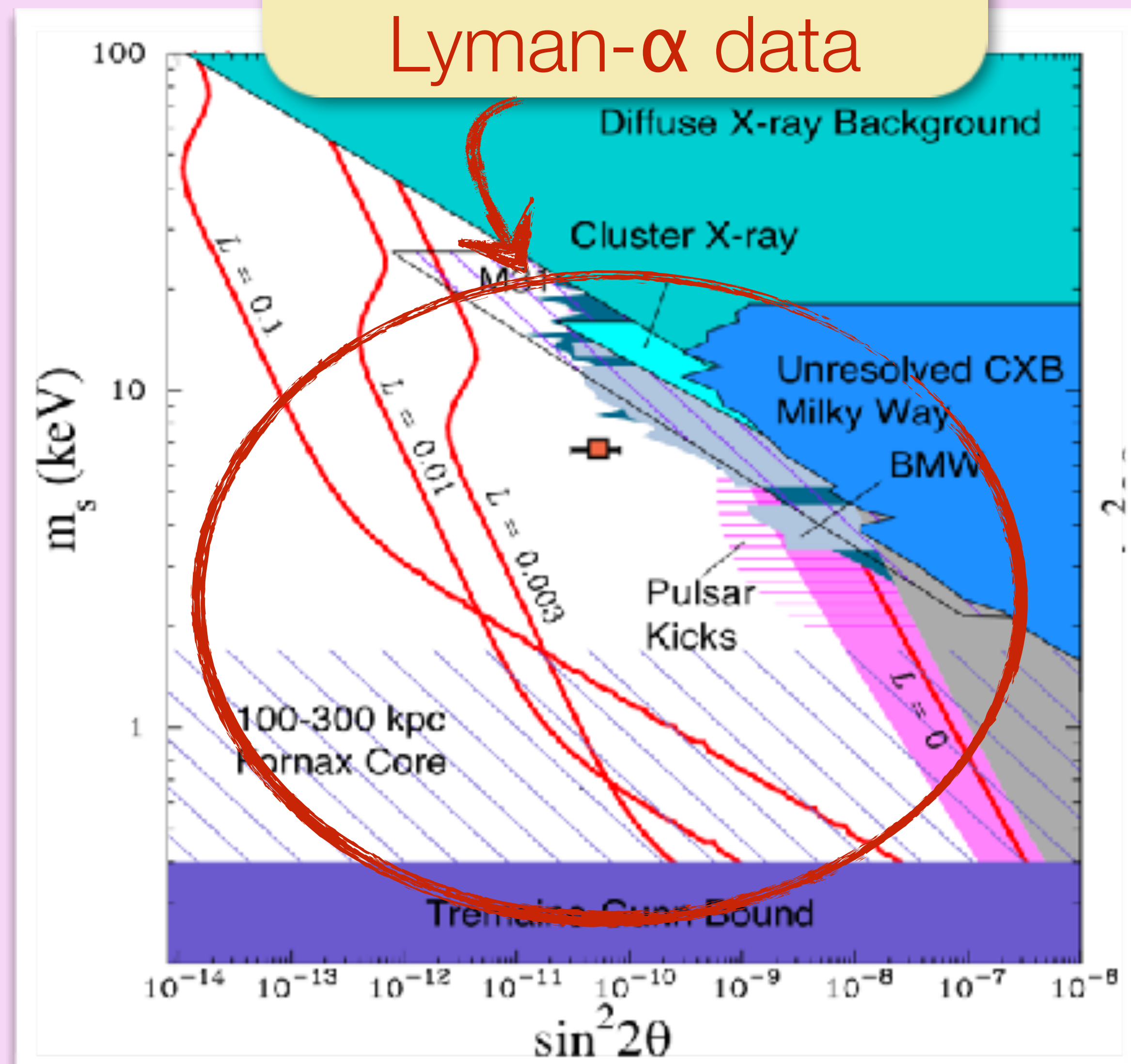
Freeze-In via Oscillation

Tension with X-Ray & Lyman-α data



Bulbul et al. 1402.2301

In this Talk

New Production Mechanisms for Dark Matter:
(controlled by finite temperature effects)

- ☑ Temporarily Unstable Dark Matter
- ☑ Vev-Controlled Freeze-In
- ☑ Outlook

Temporarily Unstable Dark Matter

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: $\langle \bar{q}_L q_R \rangle$

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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
  - second phase transition restores symmetry

The Vev Flip-Flop

- Toy Model: SM + singlet scalar S

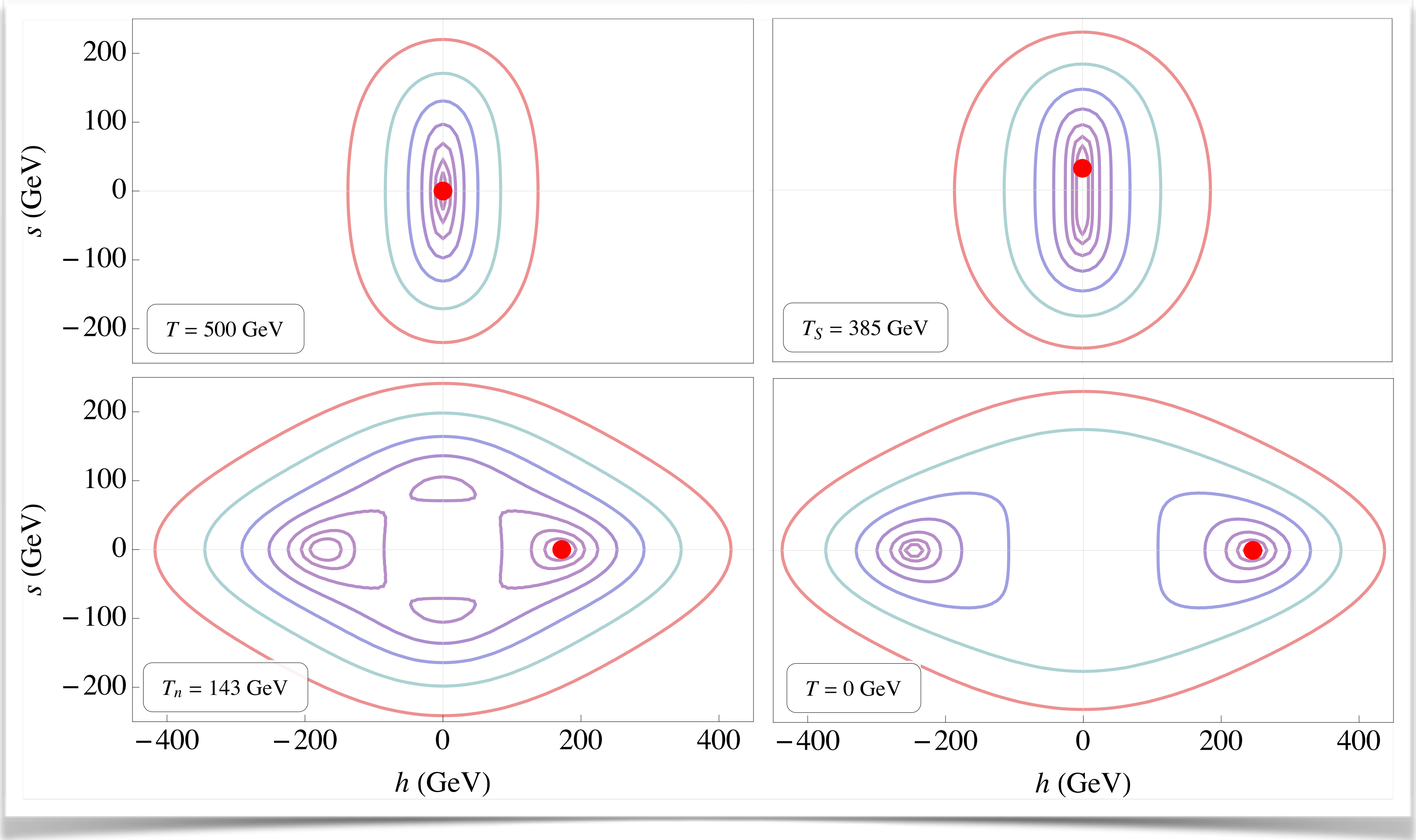
$$V^{\rm tree} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

- 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 $\propto \langle S \rangle$

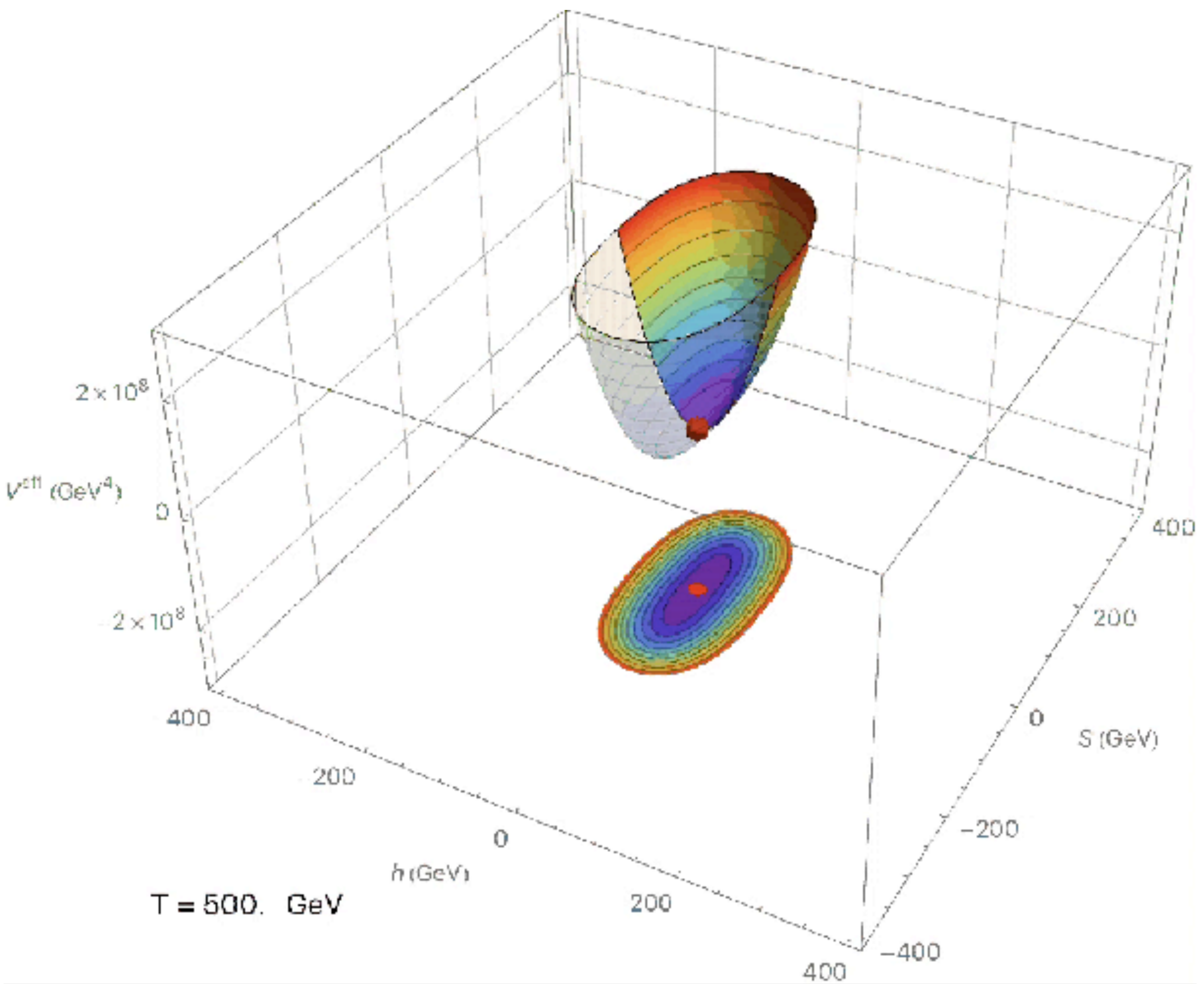
The Vev Flip-Flop



- $T > 400$ 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

The Vev Flip-Flop



Computed using `CosmoTransitions`

Wainwright 1109.4189, Kozaczuk Profumo Haskins Wainwright 1407.4134

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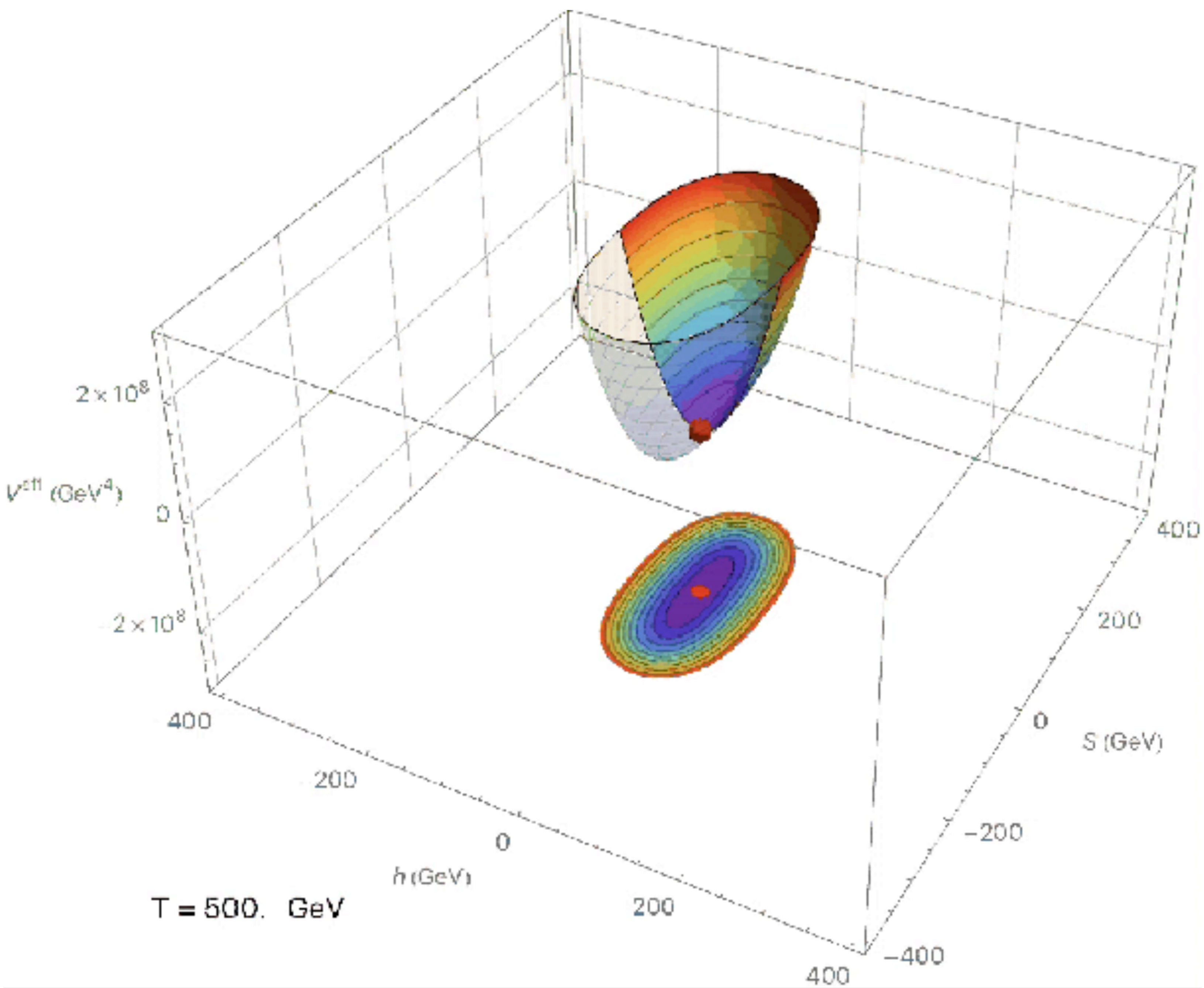

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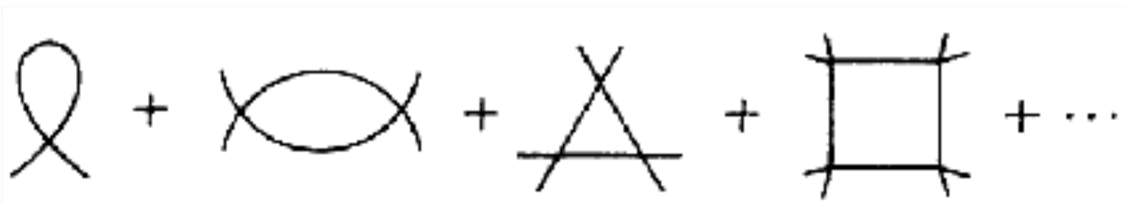
Scalar Potentials at Finite Temperature

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

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

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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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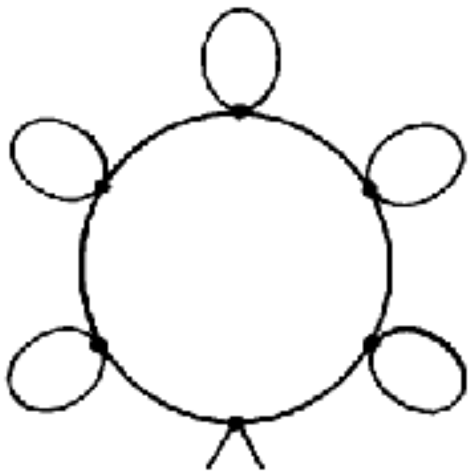
Scalar Potentials at Finite Temperature

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 $\Pi(T)$

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

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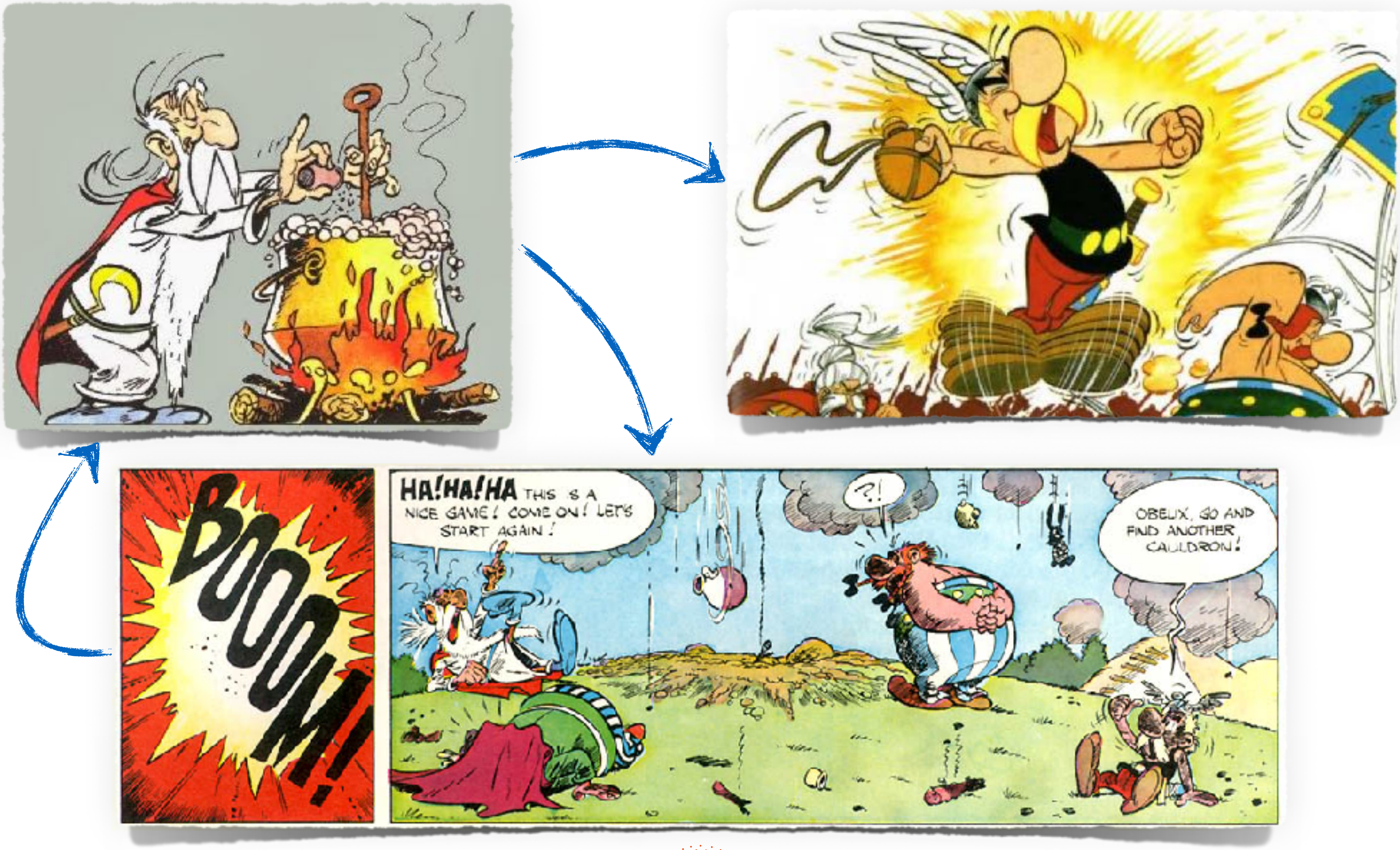
Dark Matter Model Building Flowchart



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
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DM candidate

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A Toy Model

stabilizes DM

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DM candidate

DM decay products

Baker JK 1608.07578

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

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A Toy Model

stabilizes DM

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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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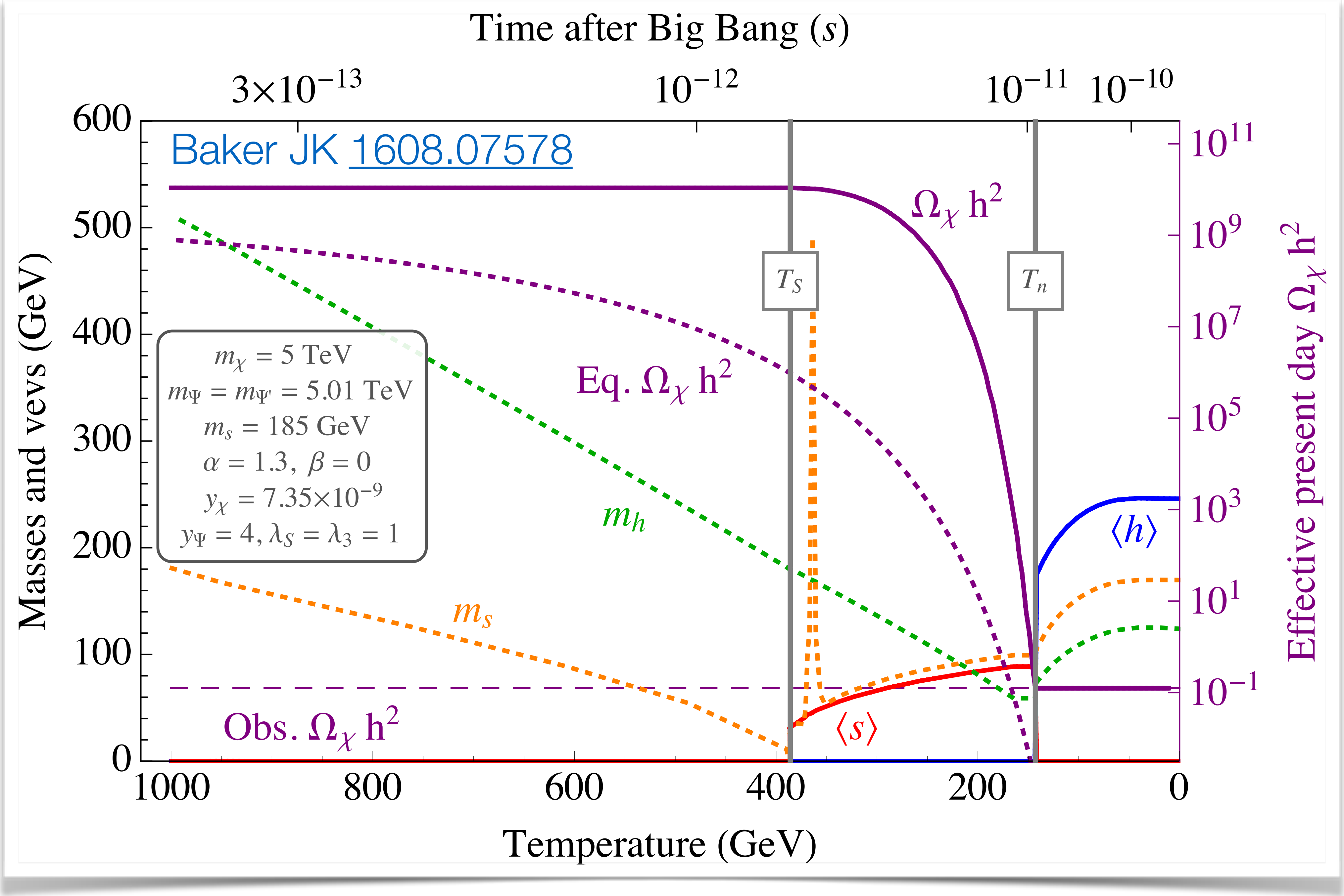
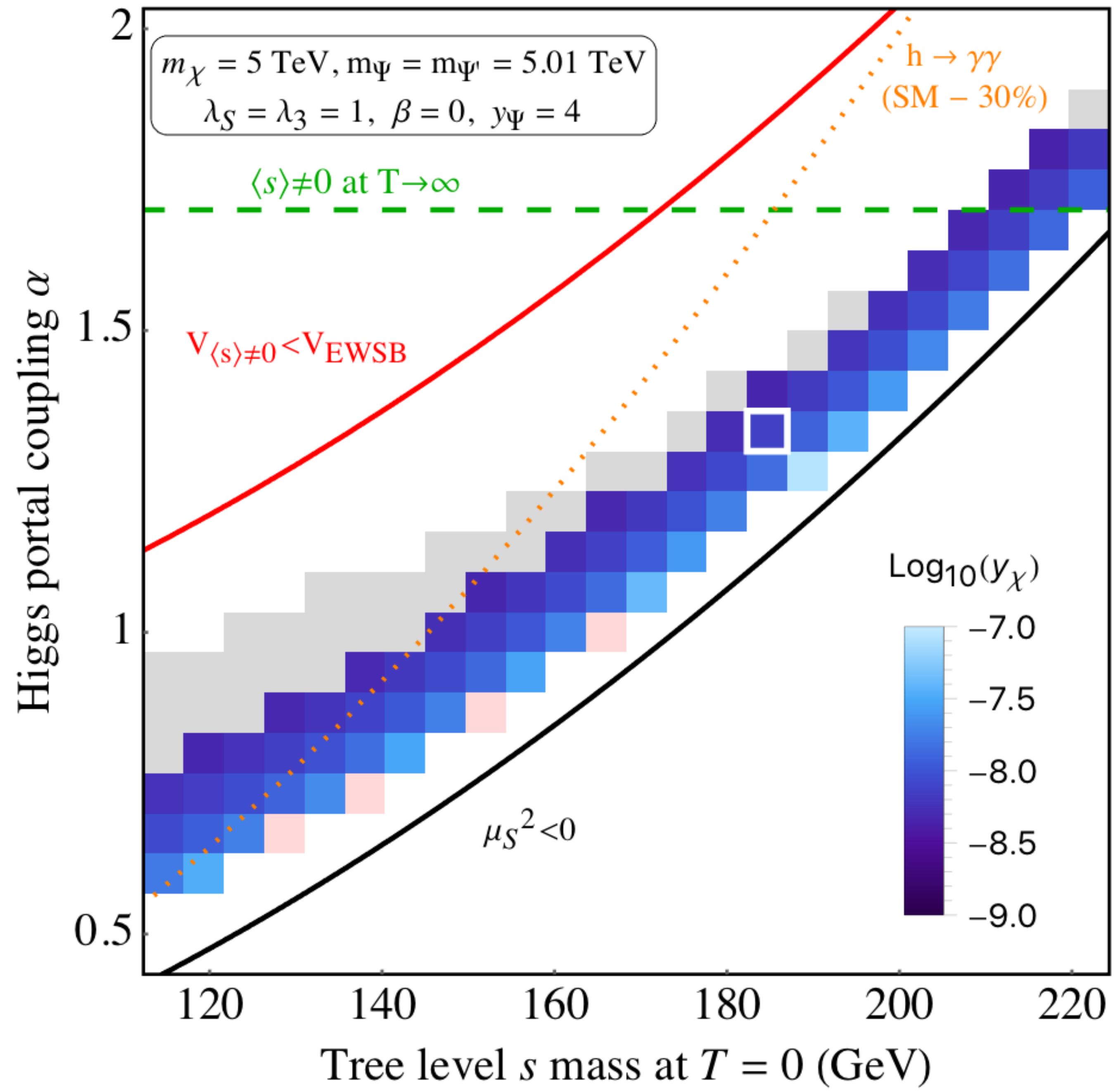
Cosmological Evolution



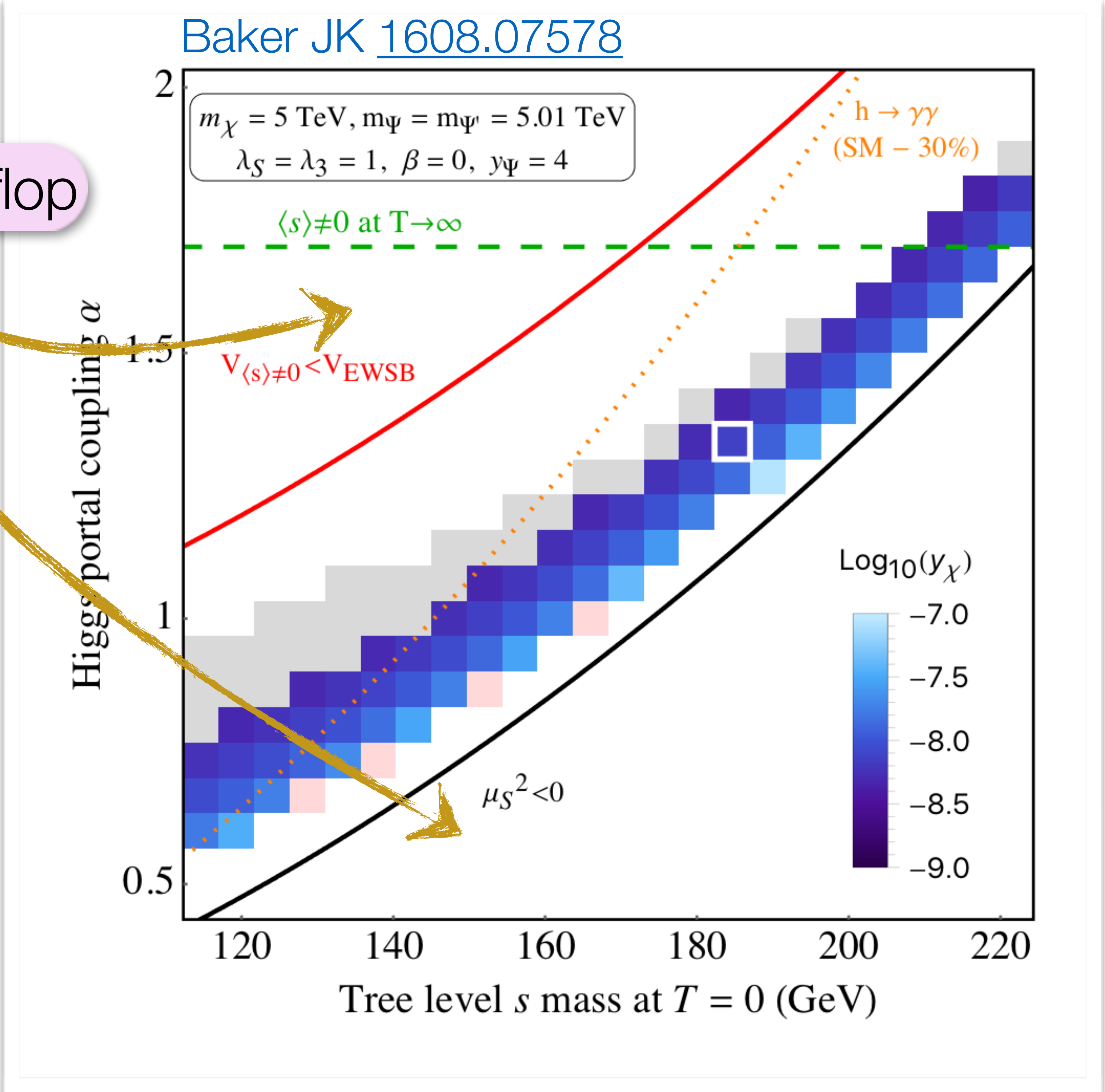
Parameter Space

Baker JK [1608.07578](1608.07578)



Parameter Space

no vev flip-flop



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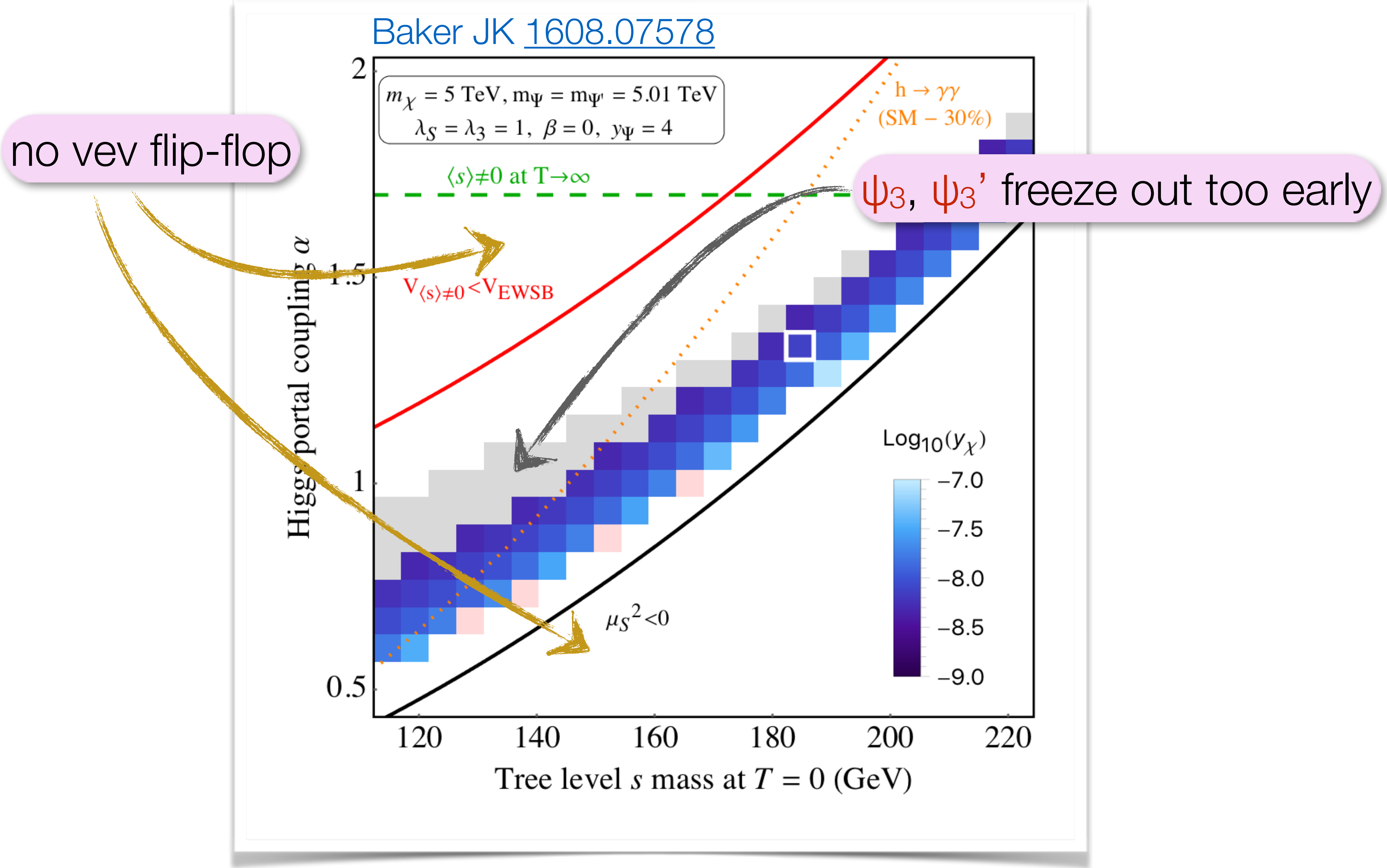

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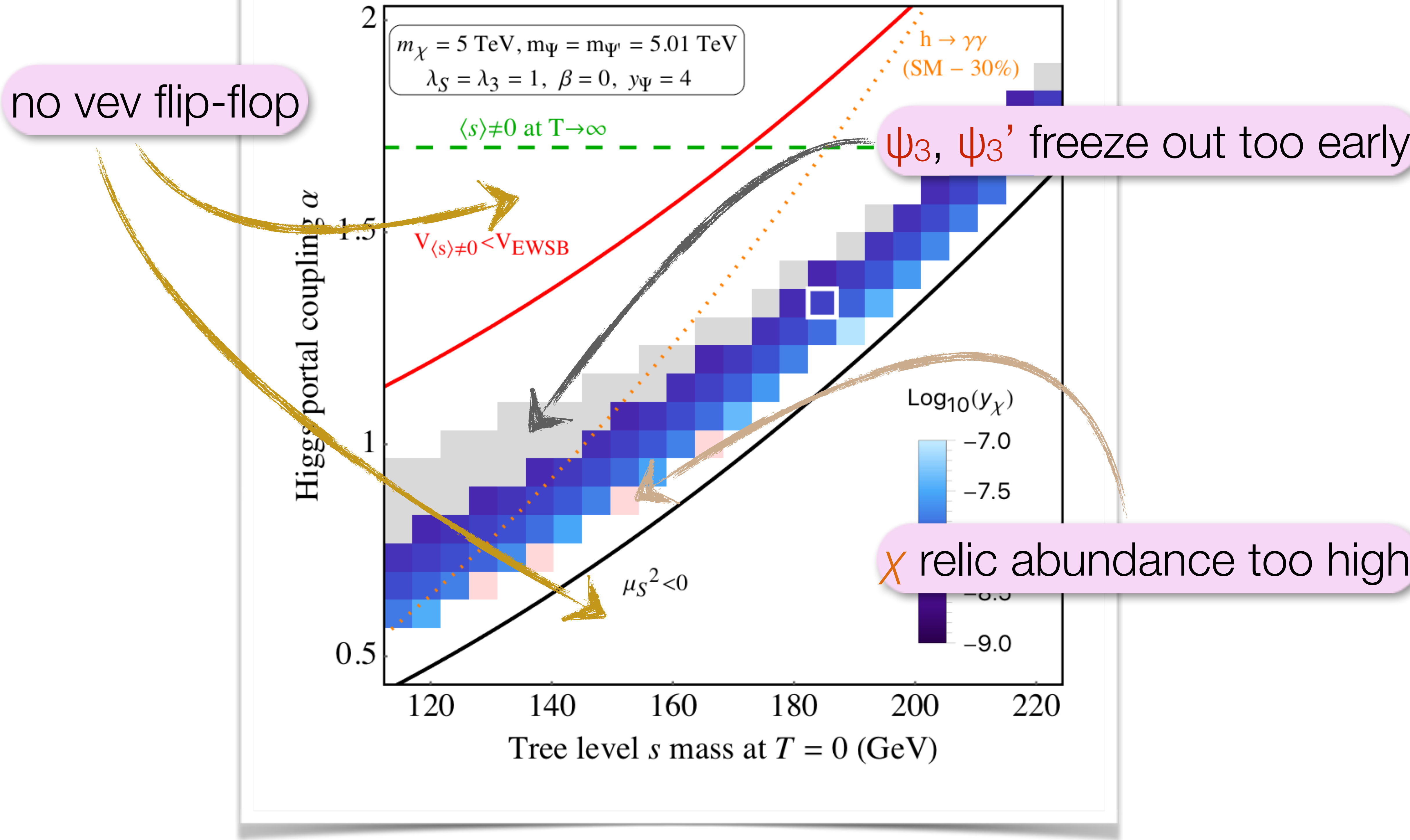

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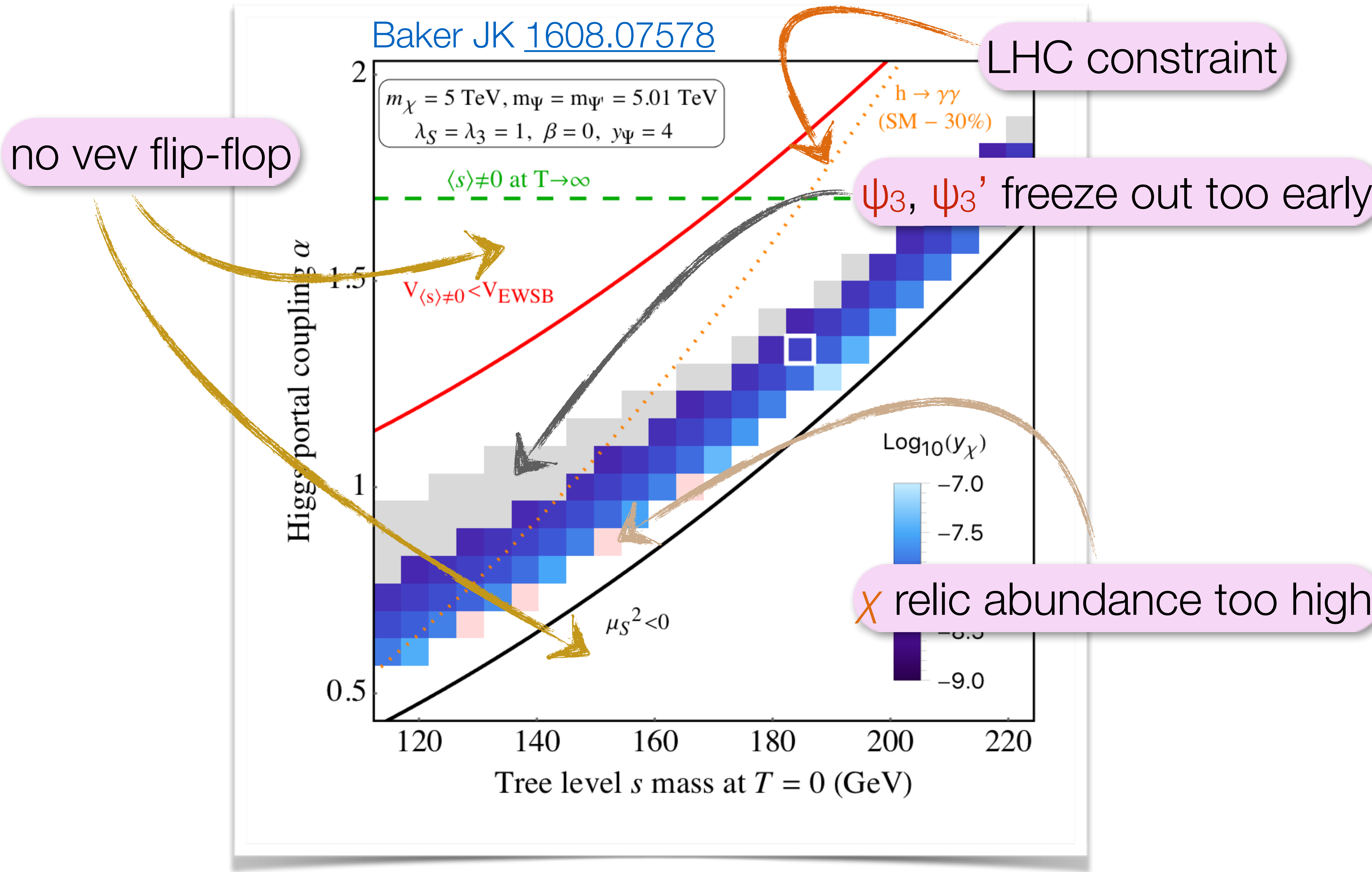

Vev-Controlled Freeze-In

Vev-Controlled Freeze-In

- **Idea:** DM production rate depends on a vev
- **Toy Model:** Fermionic Higgs Portal
  SM + fermionic DM χ + singlet scalar S

$$\mathcal{L} \supset y_\chi S \bar{\chi}\chi - V^{\text{tree}}$$

- **Scalar Potential** (same as before)

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

- If $m_S < 2\, m_\chi$, main production channels are $H^\dagger H$, $SS \rightarrow \bar{\chi}\chi$
- Only open when $\langle S \rangle \neq 0$

Baker Breitbach JK Mittnacht, in preparation

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Vev-Controlled Freeze-In

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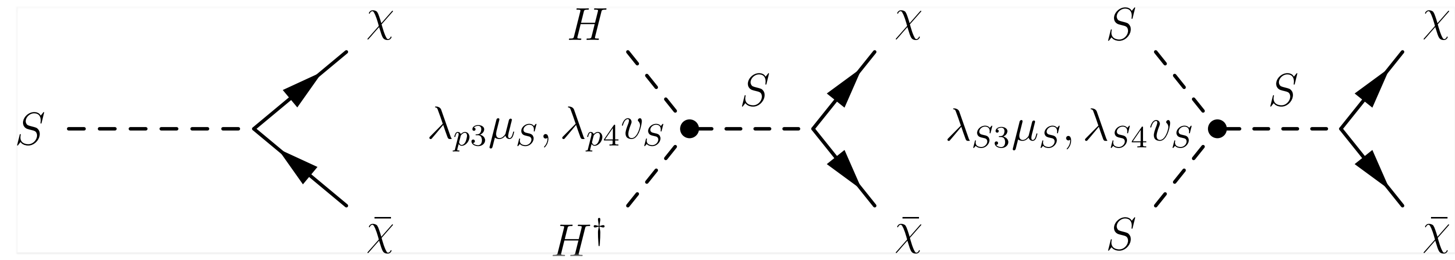

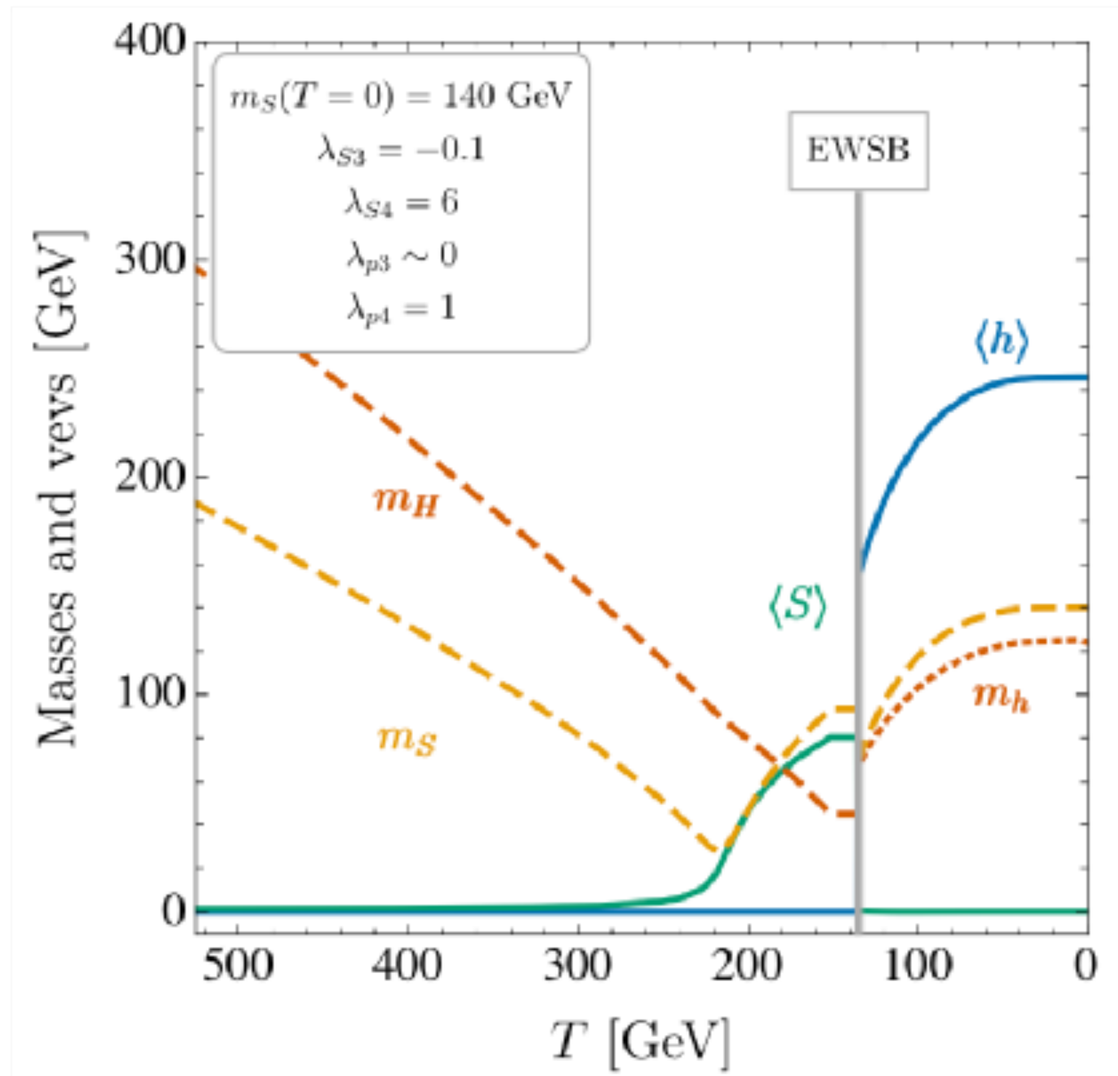

Baker Breitbach
JK Mittnacht,(in preparation)

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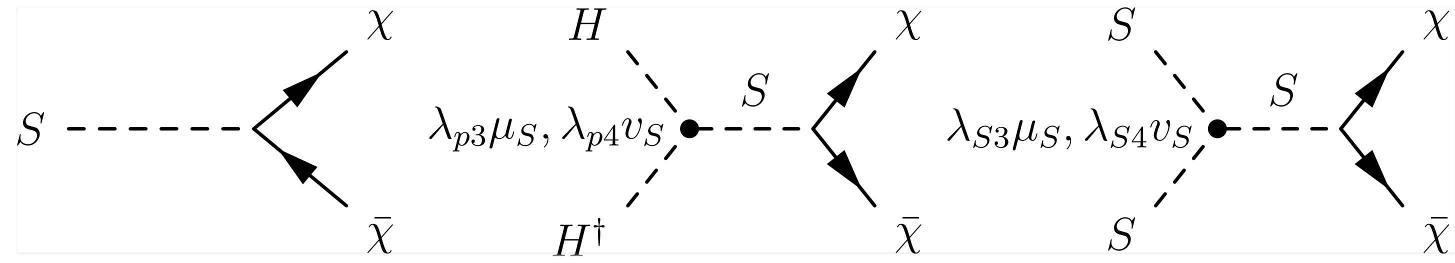

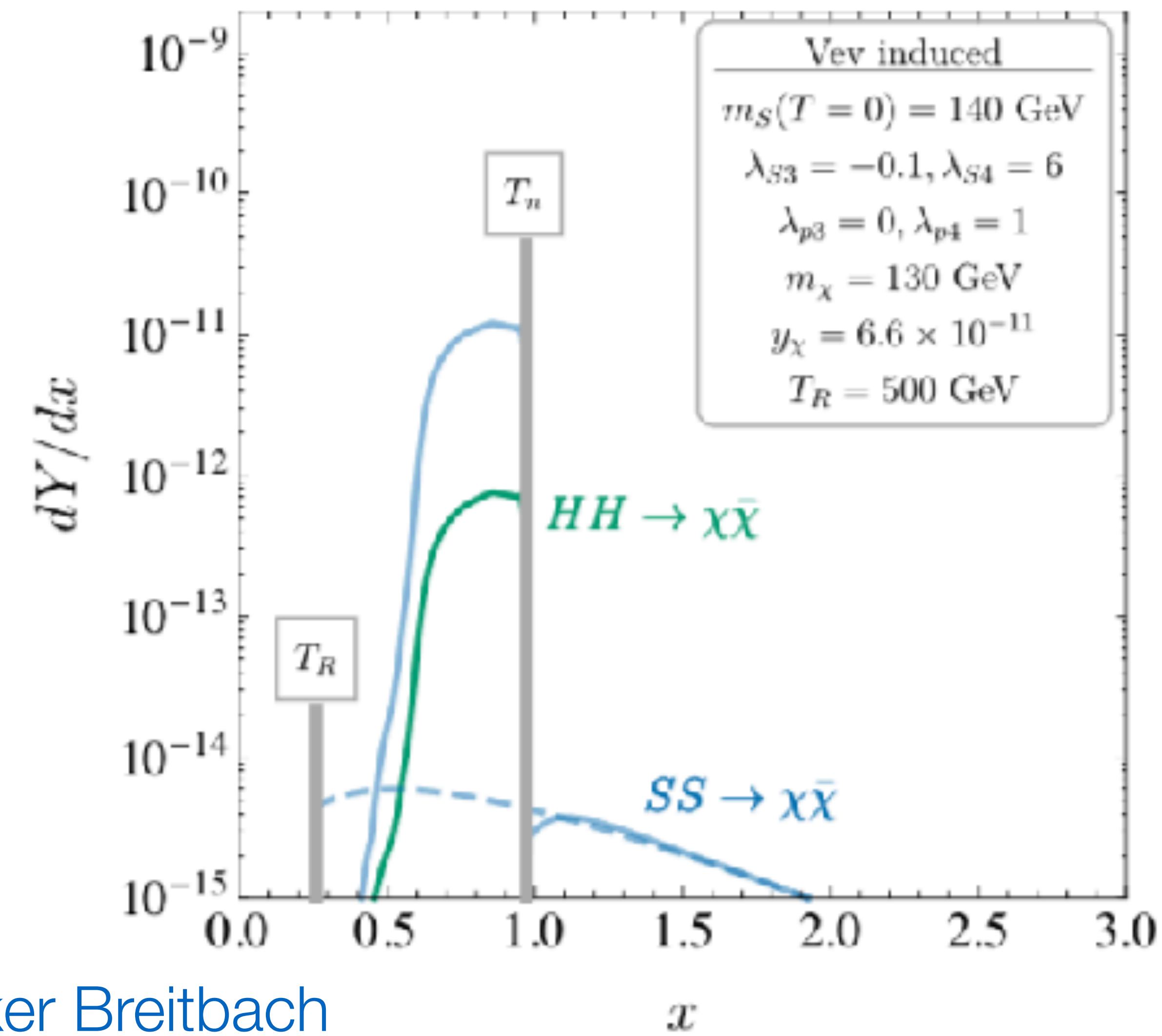

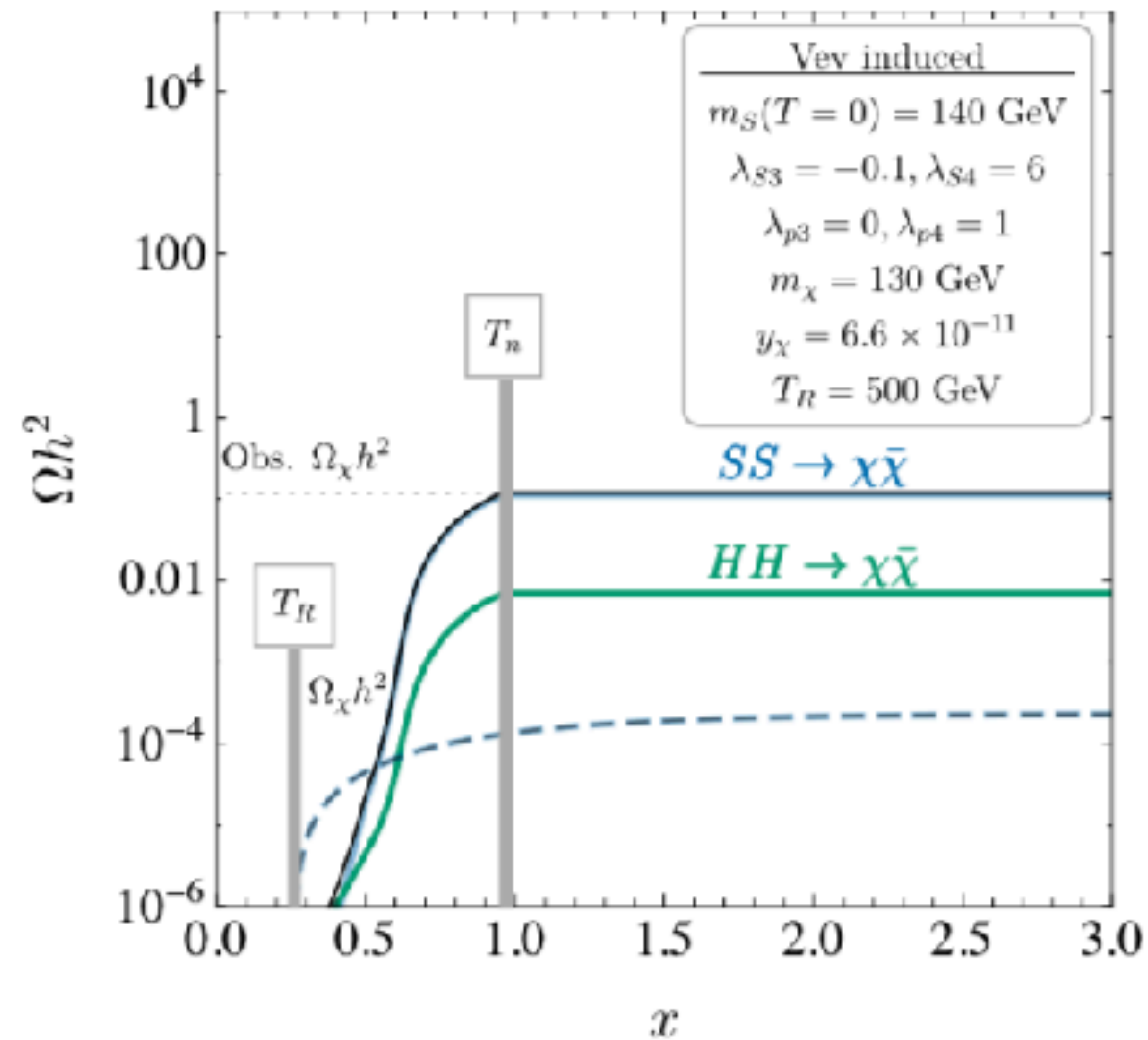

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JK Mittnacht,(in preparation)

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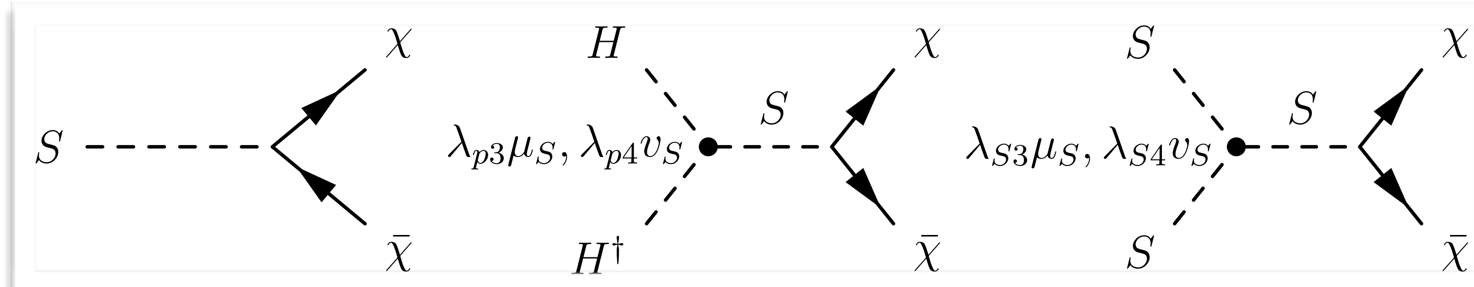
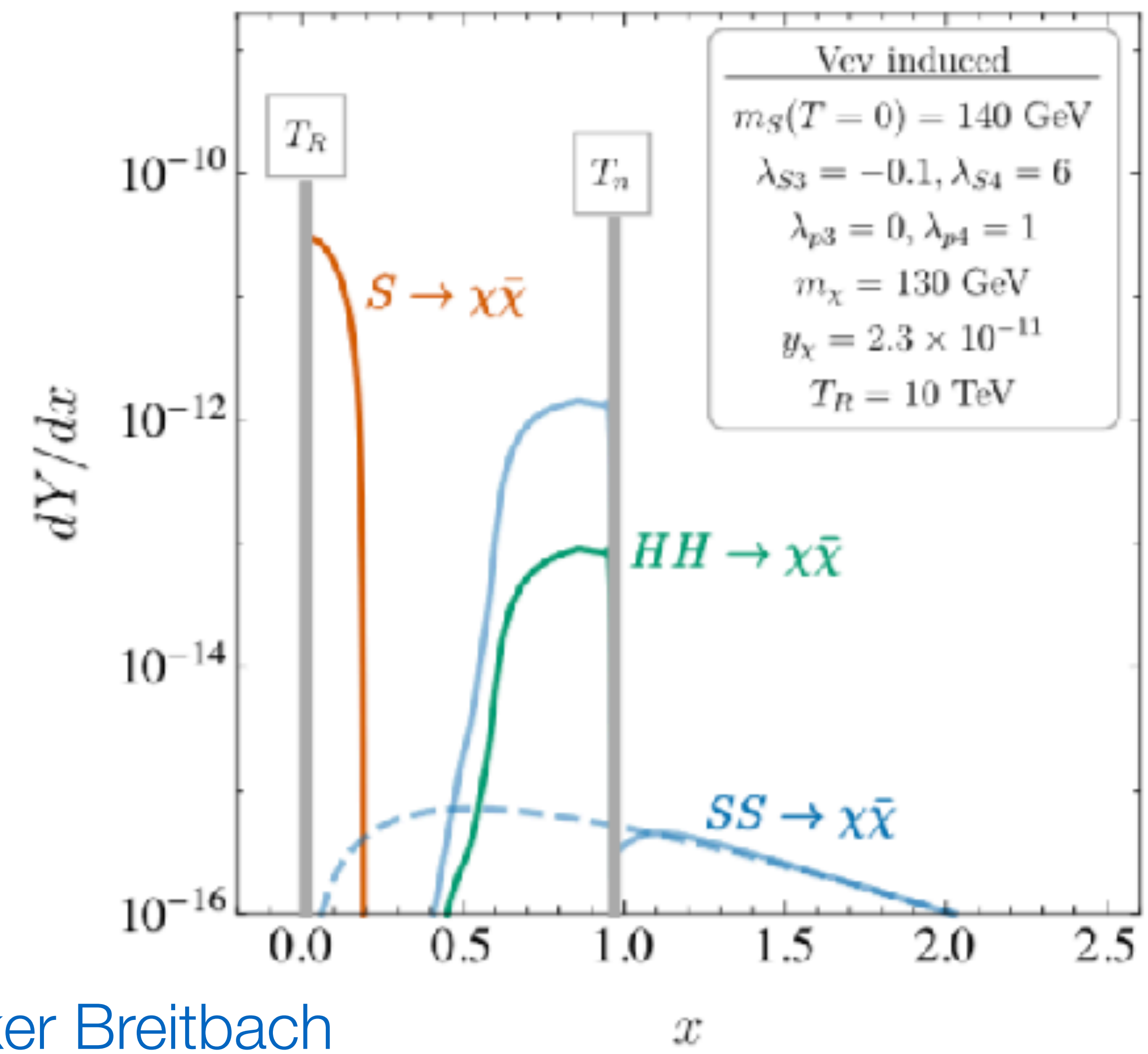
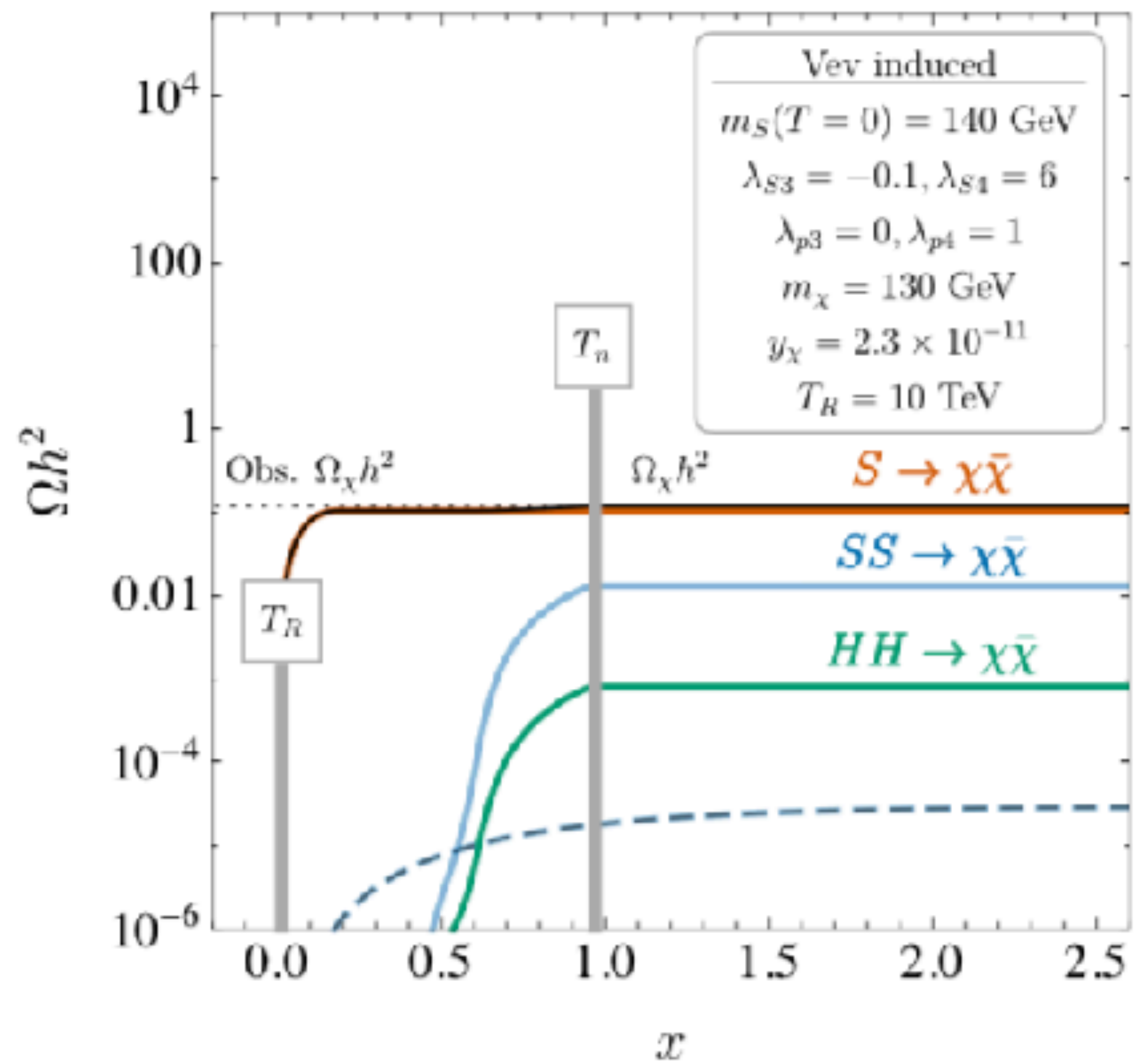
Vev-Controlled Freeze-In

$$\mathcal{L} \supset y_\chi S \bar{\chi}\chi - V^{\text{tree}}$$







Baker Breitbach
JK Mittnacht,(in preparation)

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Outlook

Future Directions

Related Mechanisms

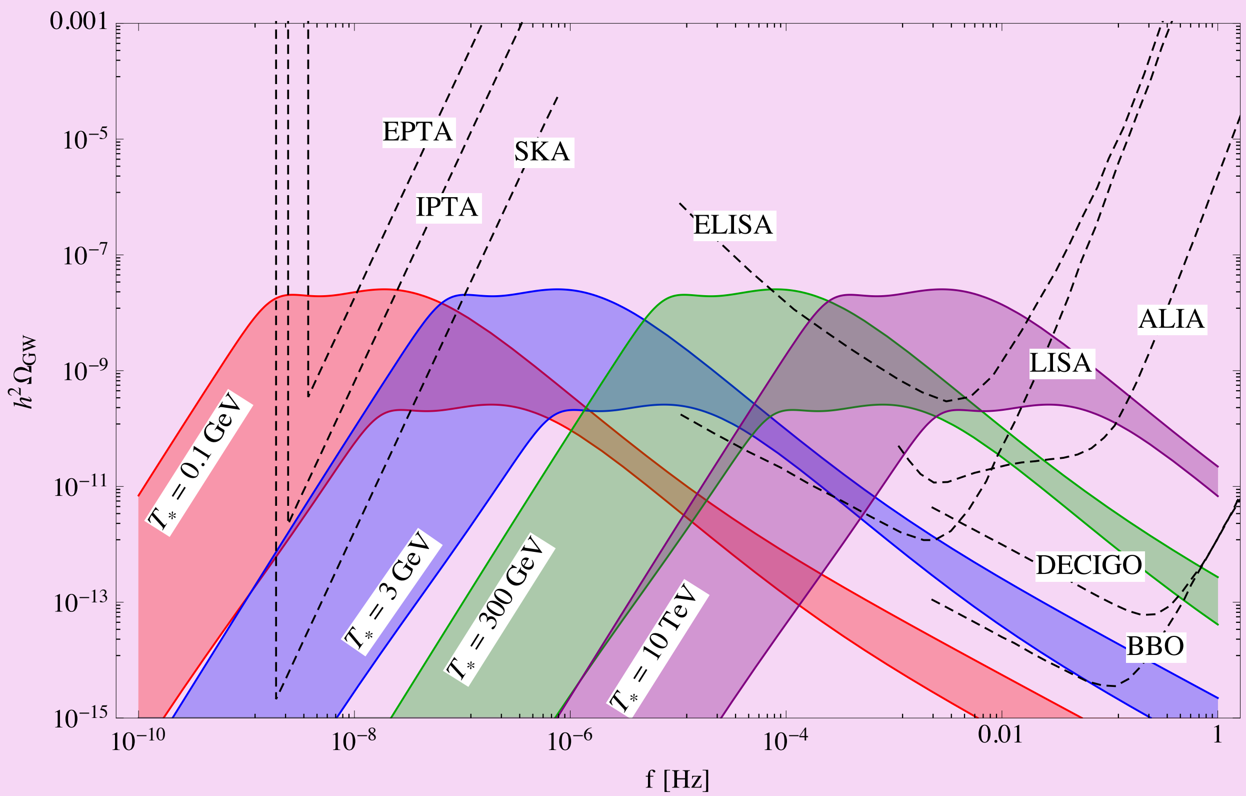
- ☑ *T*-dependence of masses opens/closes DM production channels
- ☑ *T*-dependent vev allows DM to temporarily mix with strongly coupled particles

Baker Breitbach JK Mittnacht (in preparation)

Gravitational Waves

phase transitions in vev flip-flop

often 1st order ➠ GW signals

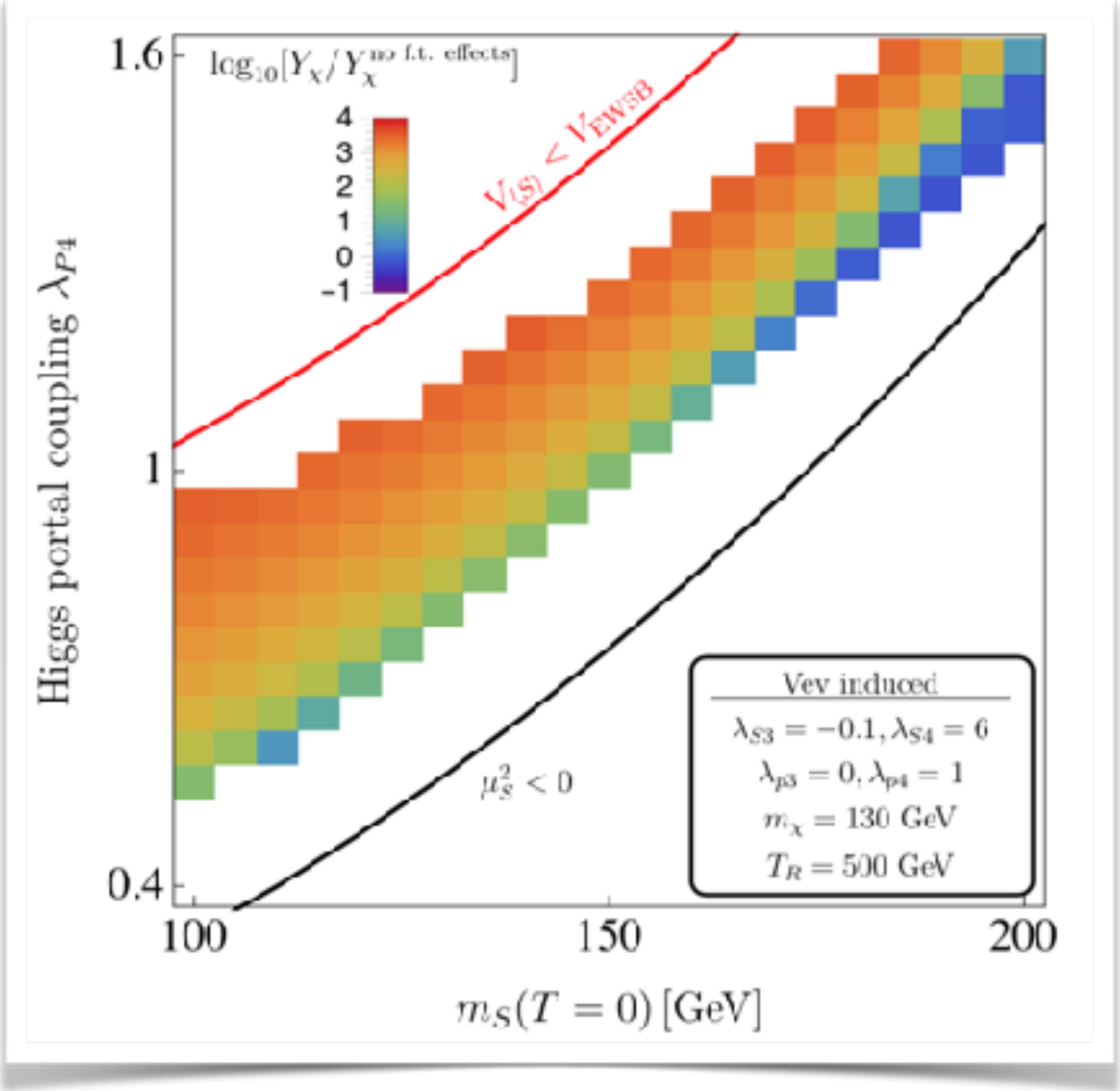


Witten 1984, Schwaller 1504.07263

Summary

Take Home Message

- Thermal effects may be crucial to understand DM production
  - affect DM stability
  - open/close production channel



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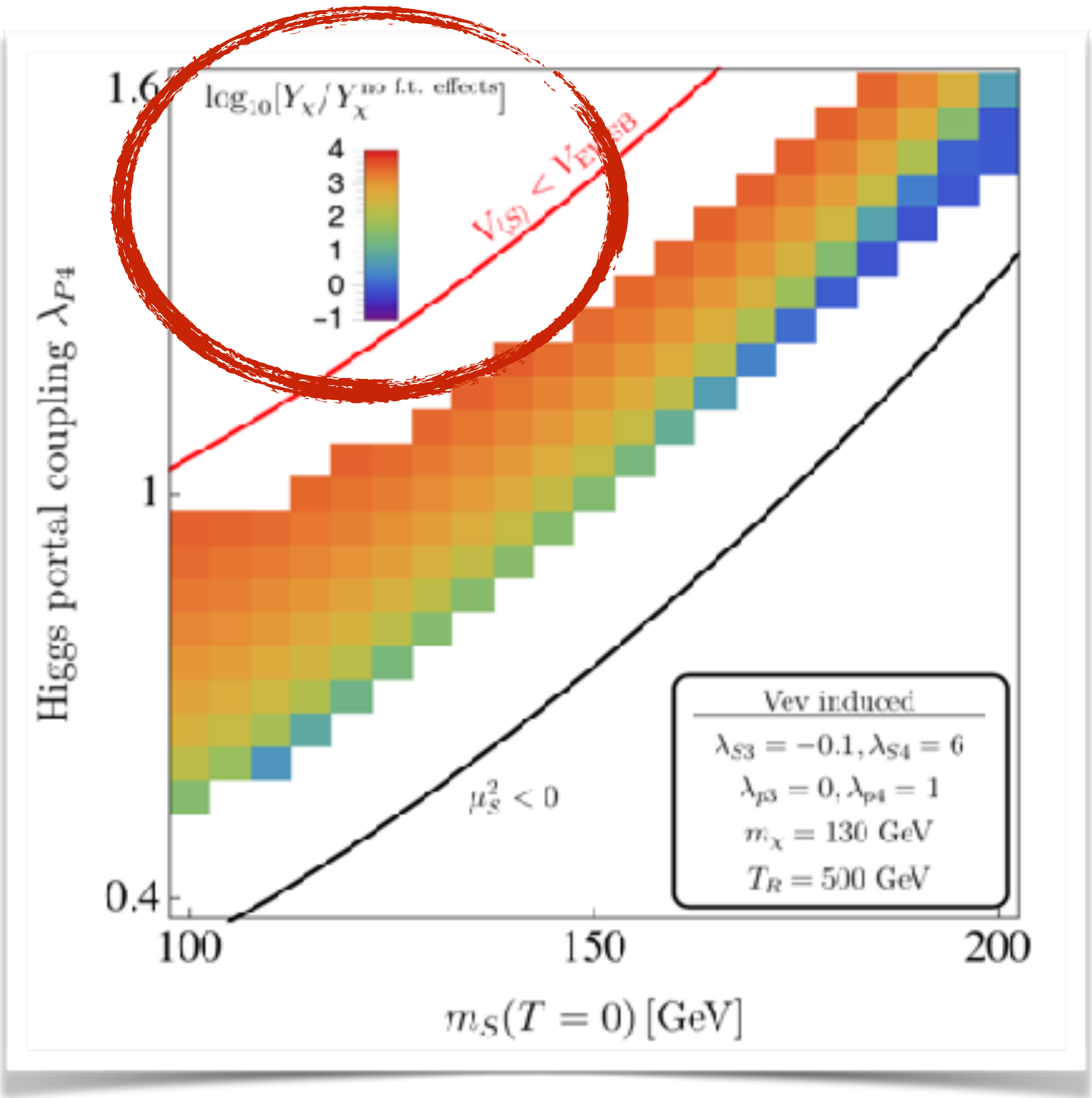

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Thank you!

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