New Scalars as Dark Matter induced by Baryogenesis

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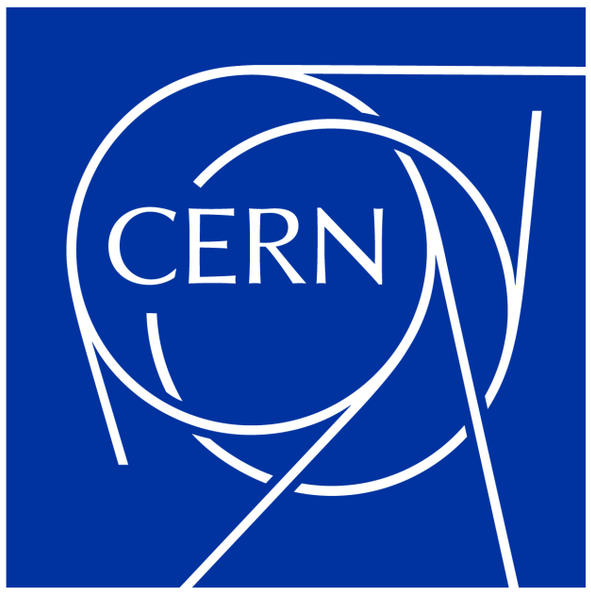
Based on ongoing work with
Thomas Hambye & Chandan Hati



CERN 22-10-2024

Extended Scalar Sectors From All Angles
https://indico.cern.ch/event/1376030/

The Idea

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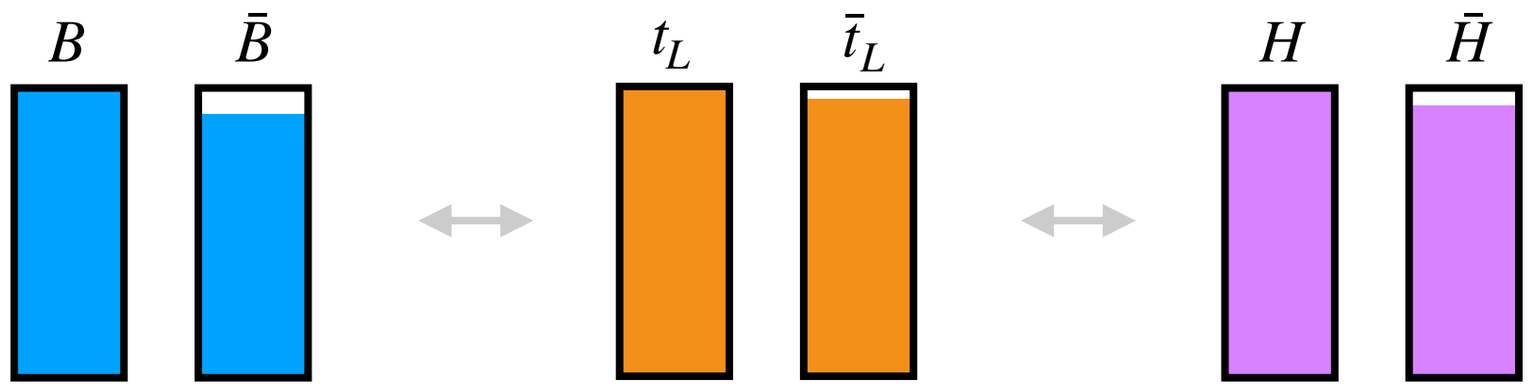

Harvey & Turner ‘90

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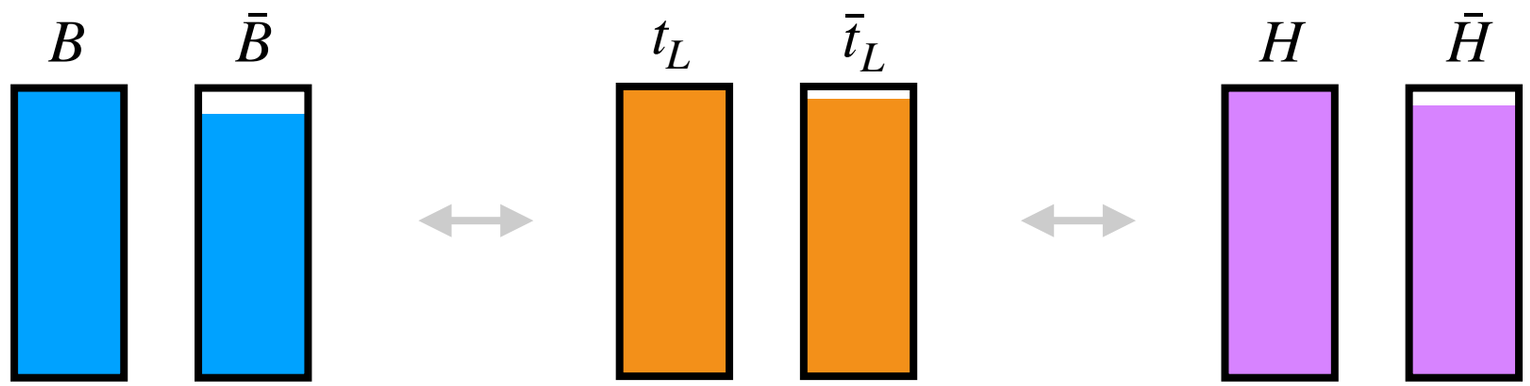

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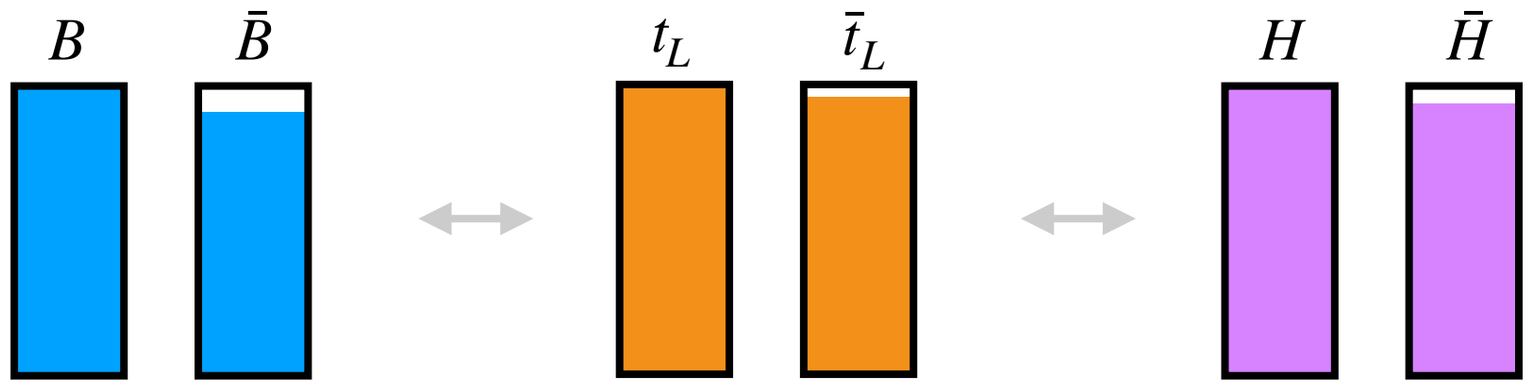

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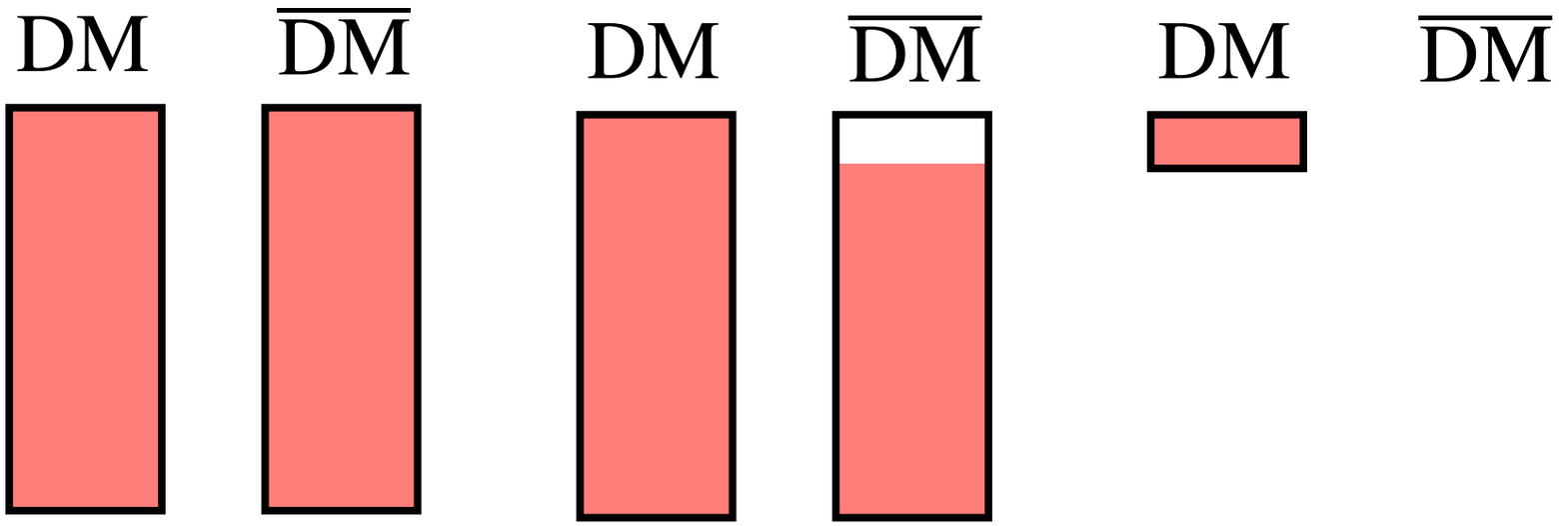

Original Refs.

Nussinov ’85
Barr, Chivukula & Farhi ’90
Kaplan ’92
Dodelson, Greene & Widrow ‘92

Reviews:

Cirelli, Strumia & Zupan [2406.01705]
Petraki & Volkas [1305.4939]
Zurek [1308.0338]

The Issue & the Goals

Asymmetric Dark Matter has been studied in depth but most models in the literature are either effective or rather convoluted

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The Higgs has an asymmetry (2) and since it is a scalar it can allow for renormalizable interactions (1)!

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Why could this be interesting?

Use something that we know should be there (from e.g. Thermal Leptogenesis) and employ mechanisms that we know operate in the early Universe (thermal freeze-out)

Outline

- **Early Universe evolution in the presence of asymmetries**

- **Minimal ingredients for an Asymmetric Dark Matter model**

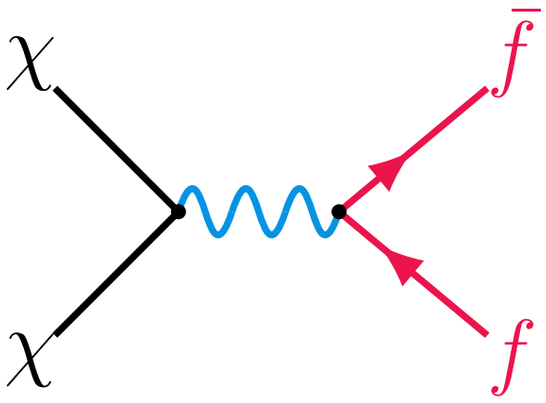
- **A minimal realization with only two new fields BSM**

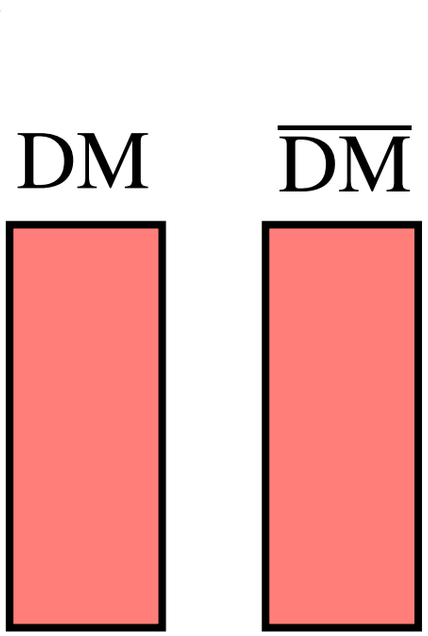
  Z_4 symmetry
  scalar singlet dark matter
  new dark Higgs doublet

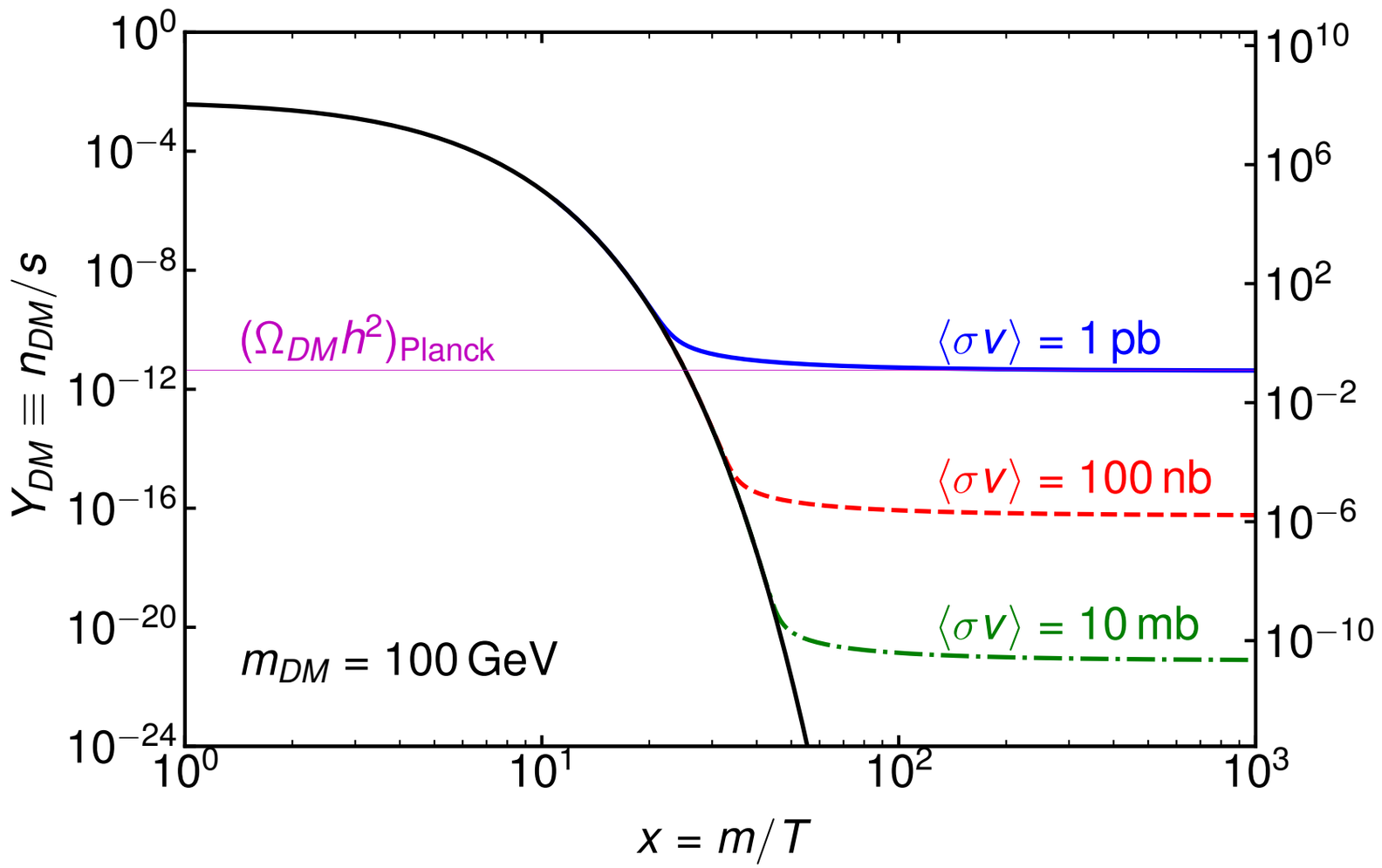
- **Its phenomenology in 2 slides**

Thermal Freeze-out

WIMP freeze-out



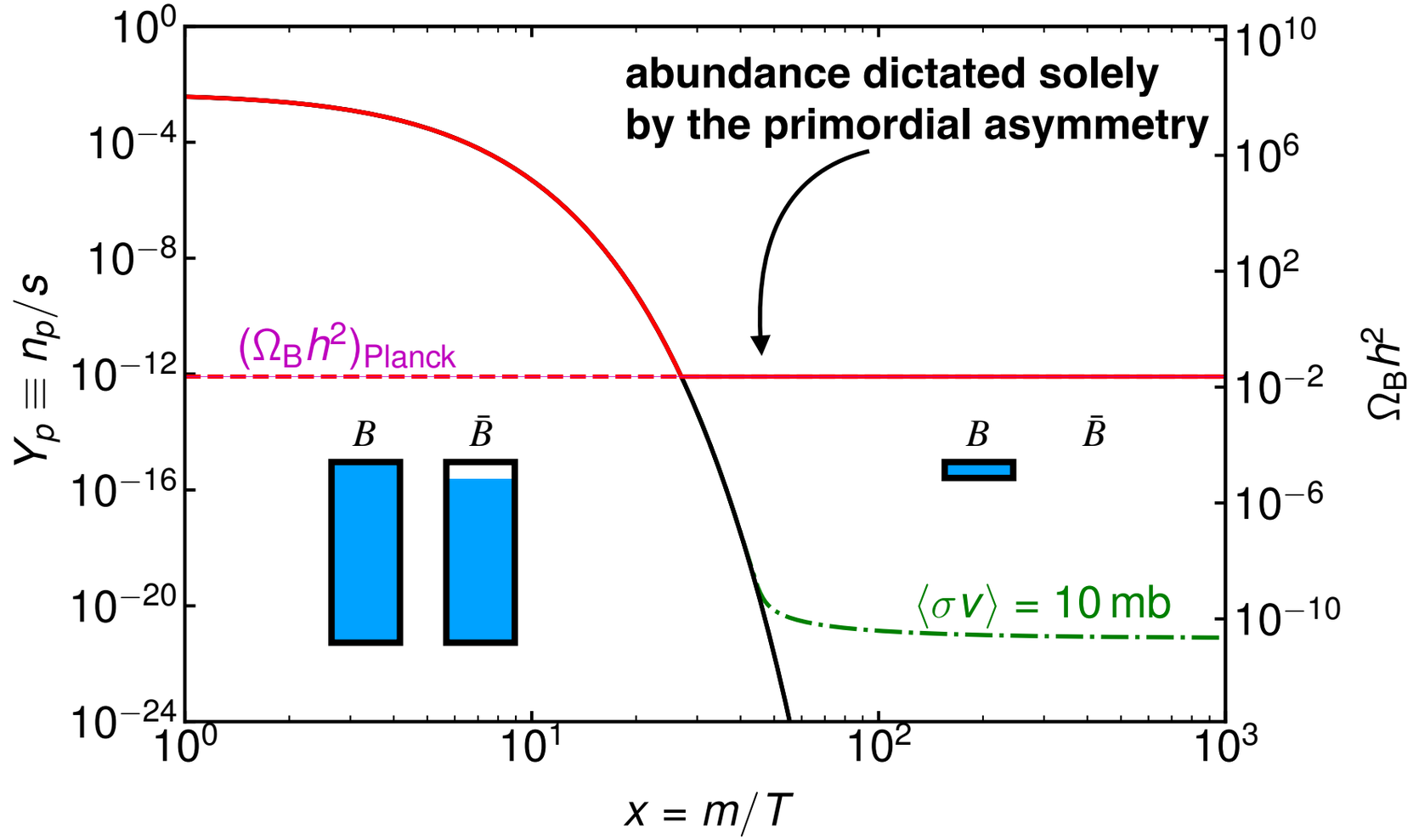




Thermal Freeze-out

proton-antiproton freeze-out

$$p\bar{p} \to \pi\pi \ldots$$



- No antiparticles today

- Key requirement for dark matter:

Annihilation cross section larger than for a WIMP $\langle \sigma v \rangle > \langle \sigma v \rangle^{\text{WIMP}}$

Asymmetry Transfer

One needs to connect the Standard Model asymmetries to the dark sector

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Renormalizable operators:

$$\begin{aligned}
L &: LH'N,\ L\phi\psi_d, LH'\Sigma\,, \\
l &: l\phi N, lH'\psi_d\,, \\
H &: H\psi_d N, HH'\phi, HH'\Delta, HH'\phi\phi', HH'H''H''', HH'\Delta\phi\,, HH'\Delta\Delta'\,, H\psi_d\Sigma\,, \\
HH &: HHH'H'',\ HH\Delta\phi,\ HH\Delta\Delta'\,,
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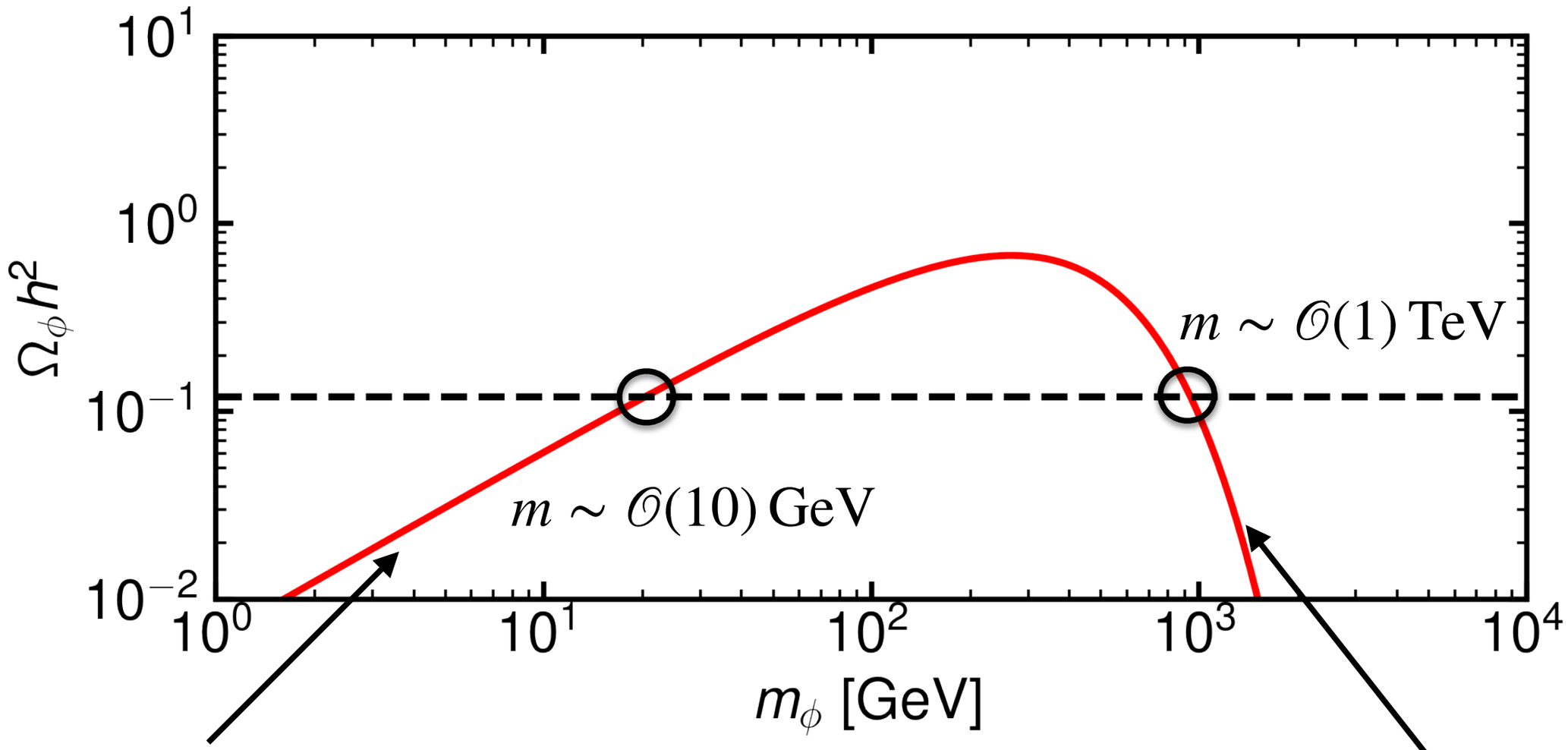
\end{aligned}$$

Take $\lambda_5 (H^\dagger H')^2$

if $\lambda_5 \gtrsim 10^{-5}$ then there is a thermal dark Higgs Asymmetry

Typical Dark Matter Abundance

Take a dark matter particle that couples in a non-self conjugated way to the Higgs and remains in thermal equilibrium with it until $T_{\rm EW}$



Linear scaling with mass

Exponential Boltzmann suppression

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Our model: **DM:** $[\phi] = i$ $\mathscr{L} = \lambda\phi\phi H^\dagger H' + \lambda_5 (H^\dagger H')^2$

Z_4 $[H'] = -1$

$U(1)_X$ **local (killed by DD as there is tree level mass mixing)**
$U(1)_X$ **global (killed by star cooling (axion))**

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Our model: $\mathscr{L} = \lambda_P |\phi|^2 |H|^2$ **The good old Higgs portal**

$\phi\bar{\phi} \to H\bar{H}$

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Relevant processes in the EU

$$\frac{d\Delta_{H'}}{dx} = -\frac{s}{Hx}\Big[\left\langle\sigma v(H'H' \to HH)\right\rangle Y_{H'}^{\rm eq} Y_{H'}^{\rm eq}\left[\frac{Y_{H'}}{Y_{H'}^{\rm eq}}\frac{Y_{H'}}{Y_{H'}^{\rm eq}} - \frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}}\frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}} + \frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}}\frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}} - \frac{Y_{H}}{Y_{H}^{\rm eq}}\frac{Y_{H}}{Y_{H}^{\rm eq}}\right]$$

$$+\left\langle\sigma v(H'\bar{H} \to \bar{H}'H)\right\rangle Y_{H'}^{\rm eq} Y_{H}^{\rm eq}\left[\frac{Y_{H'}}{Y_{H'}^{\rm eq}}\frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}} - \frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}}\frac{Y_{H}}{Y_{H}^{\rm eq}} + \frac{Y_{H'}}{Y_{H'}^{\rm eq}}\frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}} - \frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}}\frac{Y_{H}}{Y_{H}^{\rm eq}}\right]$$

$$H'H' \leftrightarrow HH\,, \quad \bar{H}'\bar{H}' \leftrightarrow \bar{H}\bar{H}$$
$$H'\bar{H} \leftrightarrow \bar{H}'H\,, \quad \bar{H}'H \leftrightarrow H'\bar{H}$$

$H^\dagger H'$ interaction will be the following:

$$\phi\phi \leftrightarrow H\bar{H}'\,, \quad \bar{\phi}\bar{\phi} \leftrightarrow \bar{H}H'$$
$$\phi\bar{H} \leftrightarrow \bar{\phi}\bar{H}'\,, \quad \bar{\phi}H \leftrightarrow \phi H'$$
$$H' \leftrightarrow \bar{\phi}\bar{\phi}H$$

$$-\left\langle\sigma v(\bar{\phi}\bar{\phi} \to \bar{H}H')\right\rangle Y_{\phi}^{\rm eq} Y_{\phi}^{\rm eq}\left[\frac{Y_{\bar{\phi}}}{Y_{\phi}^{\rm eq}}\frac{Y_{\bar{\phi}}}{Y_{\phi}^{\rm eq}} - \frac{Y_{\phi}}{Y_{\phi}^{\rm eq}}\frac{Y_{\phi}}{Y_{\phi}^{\rm eq}} + \frac{Y_{H}}{Y_{H}^{\rm eq}}\frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}} - \frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}}\frac{Y_{H'}}{Y_{H'}^{\rm eq}}\right]$$

$$-\left\langle\sigma v(\bar{\phi}H \to \phi H')\right\rangle Y_{\phi}^{\rm eq} Y_{H}^{\rm eq}\left[\frac{Y_{\bar{\phi}}}{Y_{\phi}^{\rm eq}}\frac{Y_{H}}{Y_{H}^{\rm eq}} - \frac{Y_{\phi}}{Y_{\phi}^{\rm eq}}\frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}} + \frac{Y_{\bar{\phi}}}{Y_{\phi}^{\rm eq}}\frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}} - \frac{Y_{\phi}}{Y_{\phi}^{\rm eq}}\frac{Y_{H'}}{Y_{H'}^{\rm eq}}\right]$$

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$$-\frac{\langle\Gamma(H' \to \phi\phi H)\rangle}{Hx} Y_{H'}^{\rm eq}\left[\frac{Y_{H'}}{Y_{H'}^{\rm eq}} - \frac{Y_{\bar{H}'}}{Y_{H'}^{\rm eq}} + \frac{Y_{\bar{\phi}}}{Y_{\phi}^{\rm eq}}\frac{Y_{\bar{\phi}}}{Y_{\phi}^{\rm eq}}\frac{Y_{\bar{H}}}{Y_{H}^{\rm eq}} - \frac{Y_{\phi}}{Y_{\phi}^{\rm eq}}\frac{Y_{\phi}}{Y_{\phi}^{\rm eq}}\frac{Y_{H}}{Y_{H}^{\rm eq}}\right]$$

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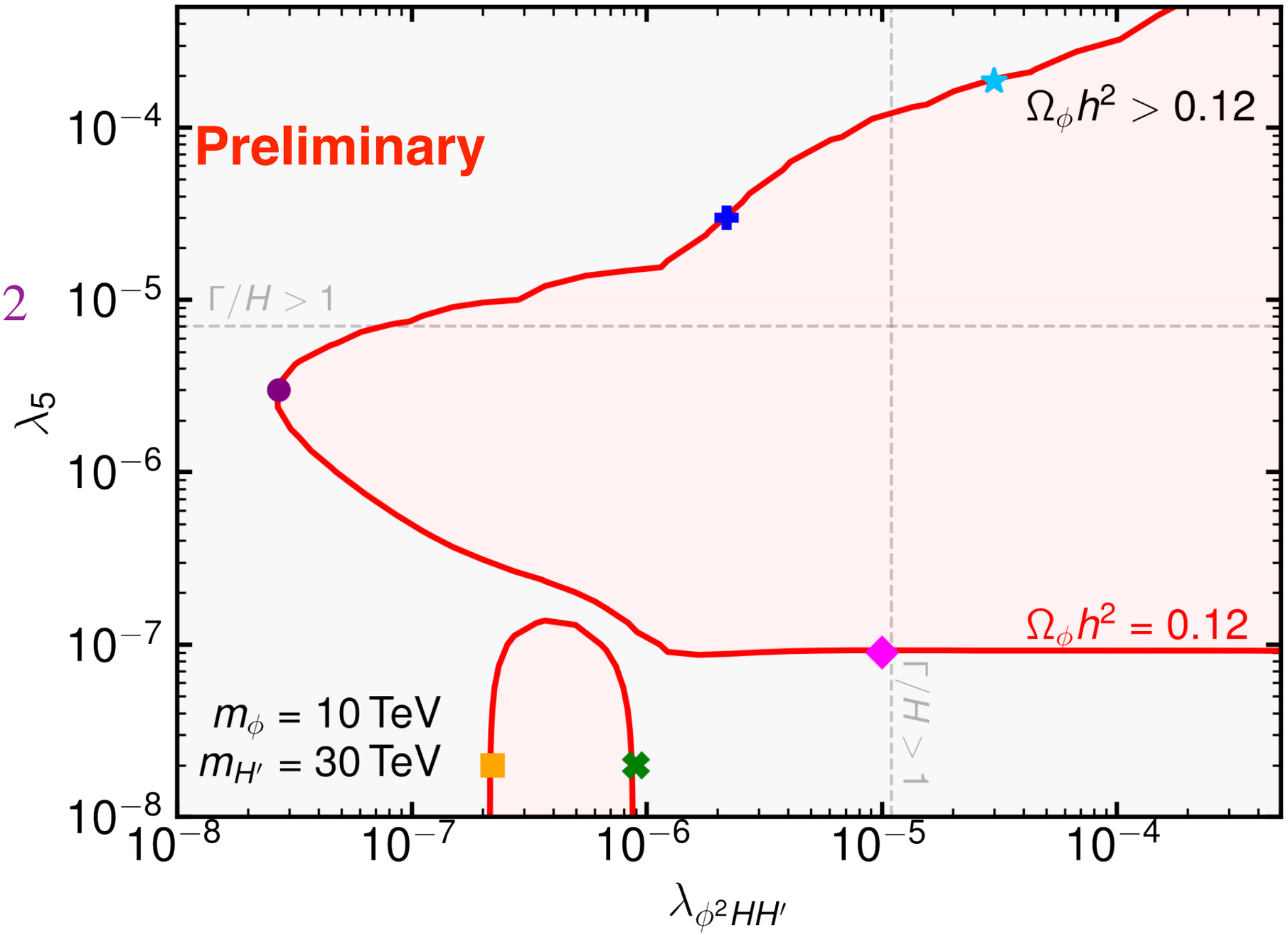
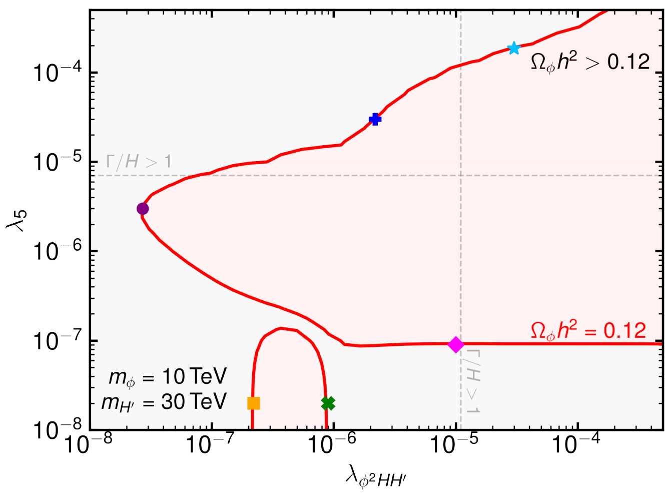
Parameter Space

$\lambda_5 (H^\dagger H')^2$

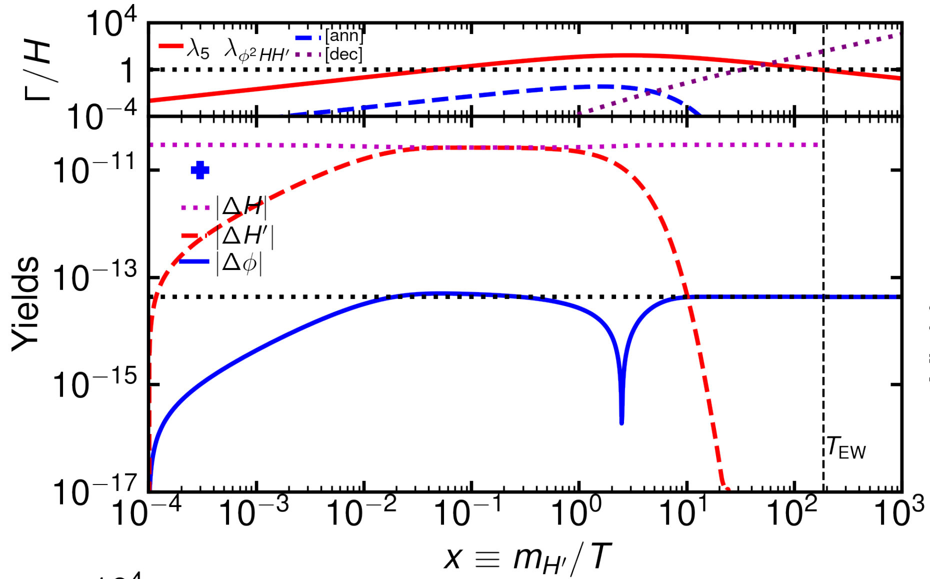


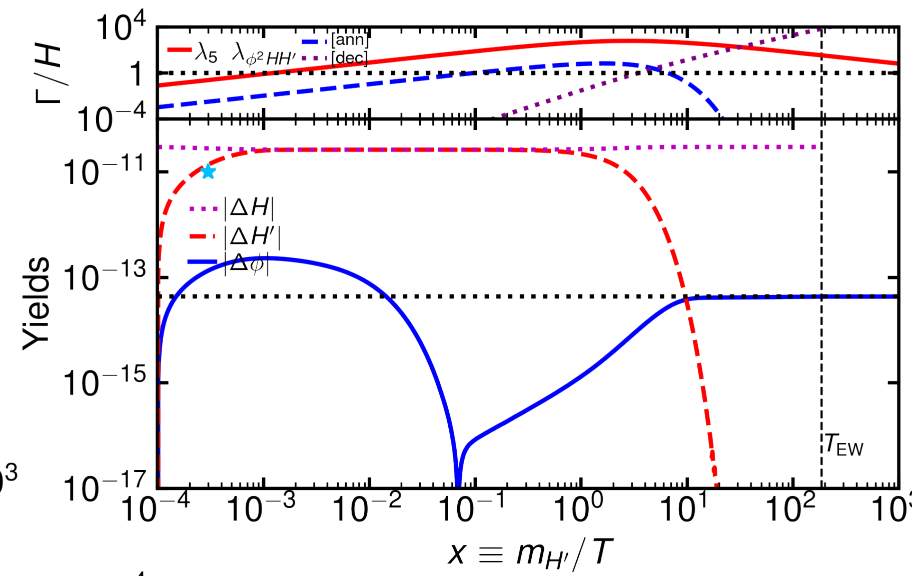
$\lambda_{\phi^2 HH'} \phi\phi H^\dagger H'$

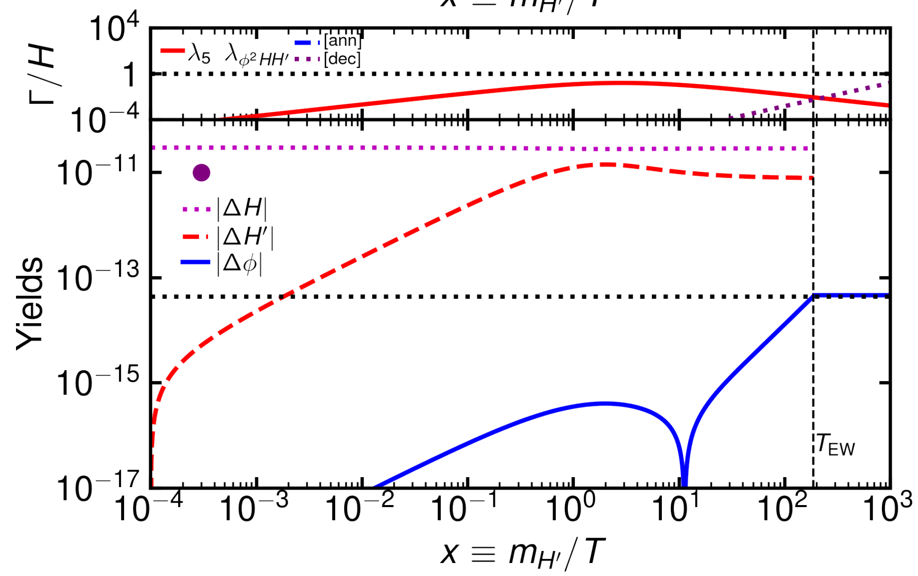
Examples

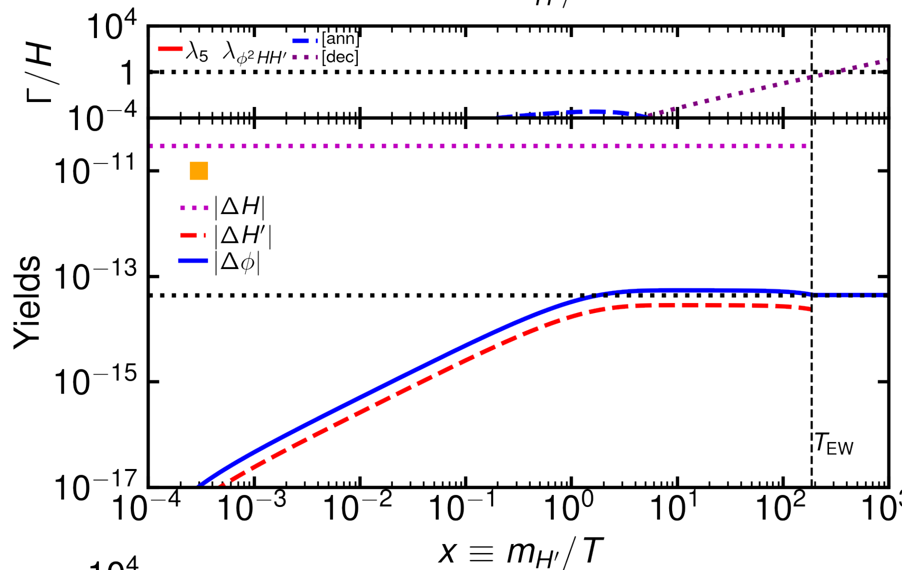


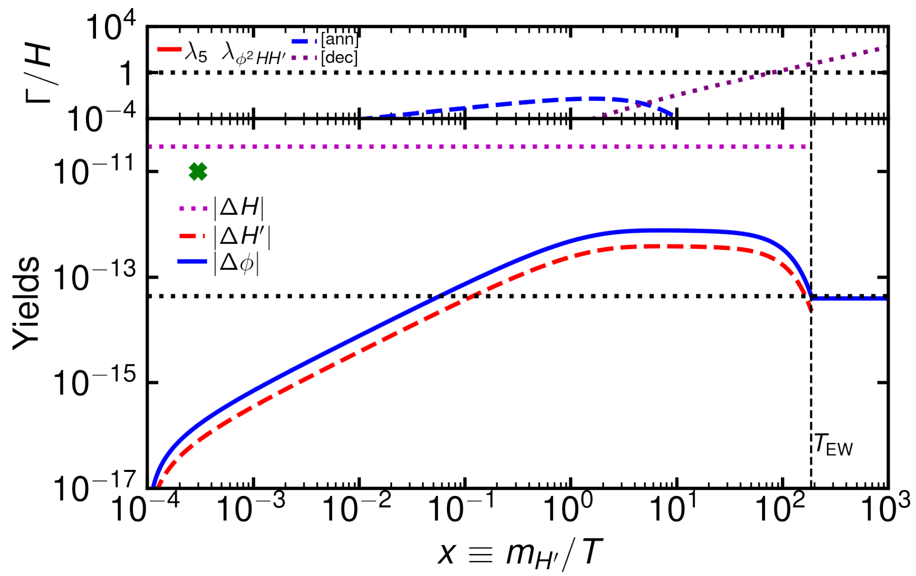
Preliminary

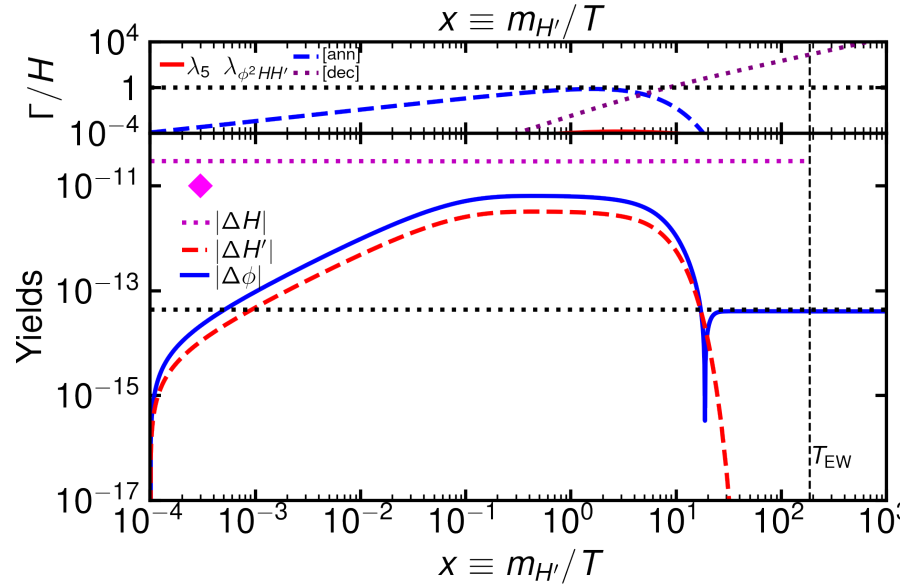




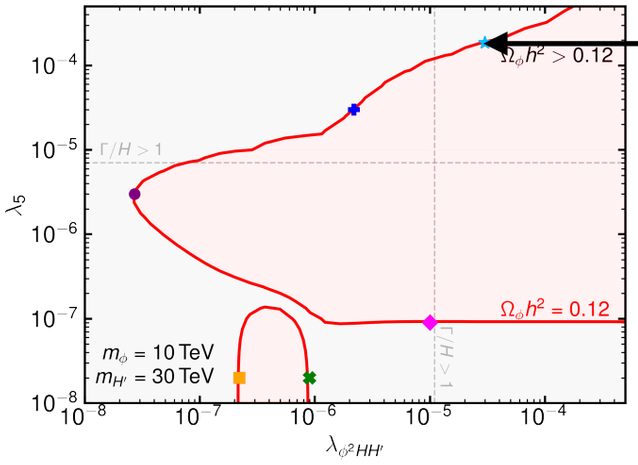








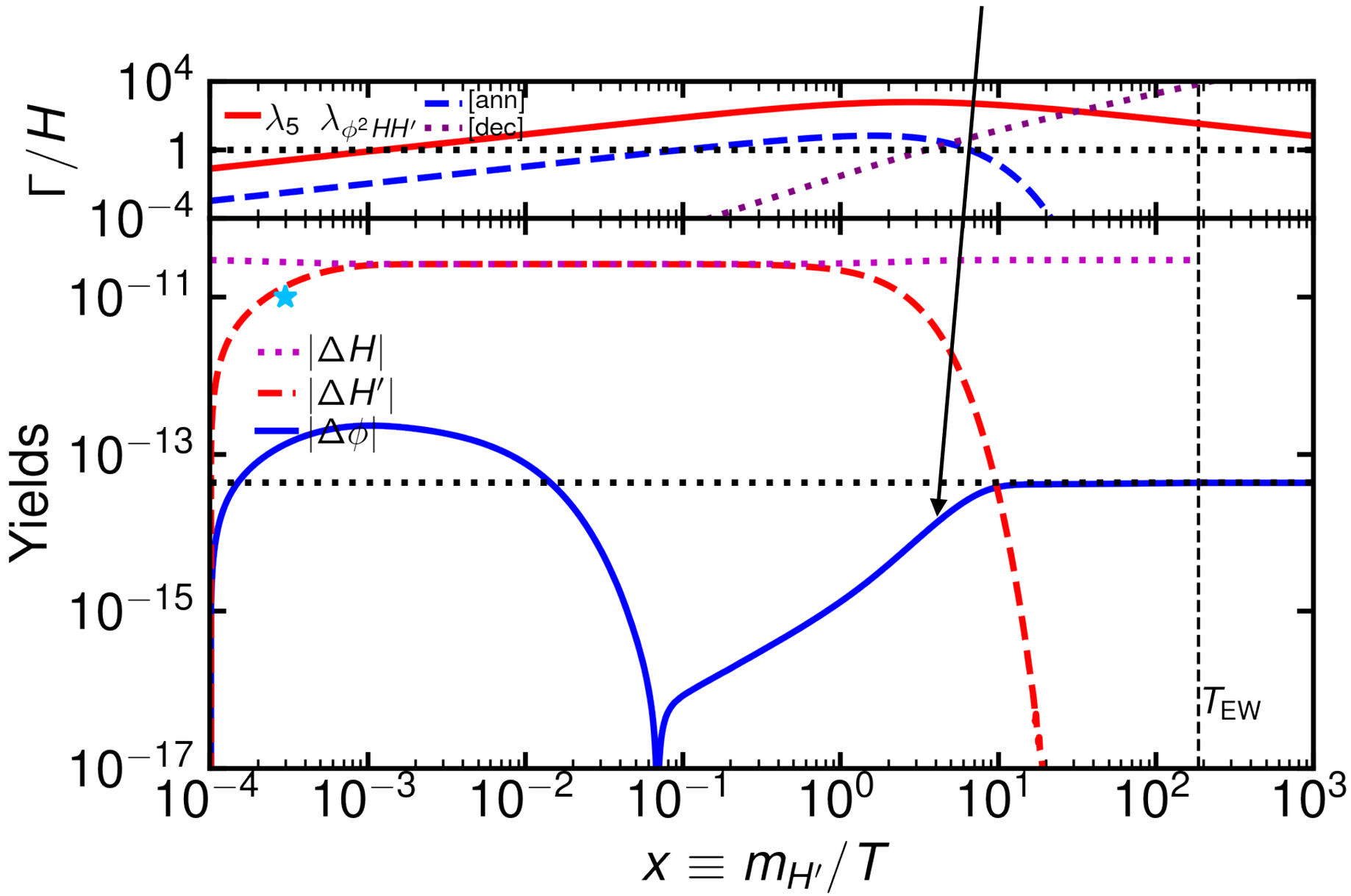
Dark Matter from imperfect TE



Deep into thermal equilibrium

$$\mathscr{L} = \lambda\phi\phi H^\dagger H' + \lambda_5 (H^\dagger H')^2$$

Resulting asymmetry arises from small departures from thermal equilibrium



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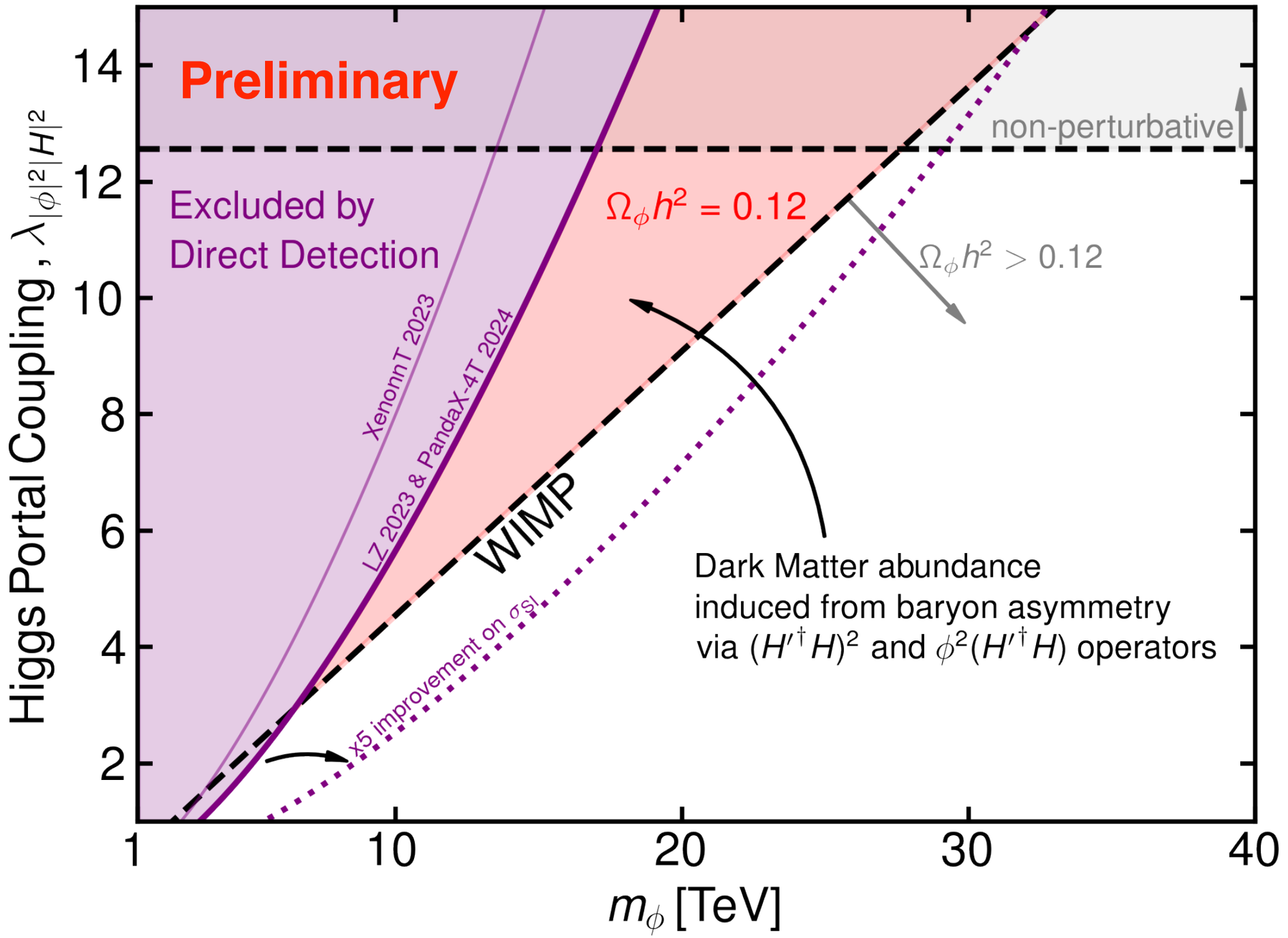

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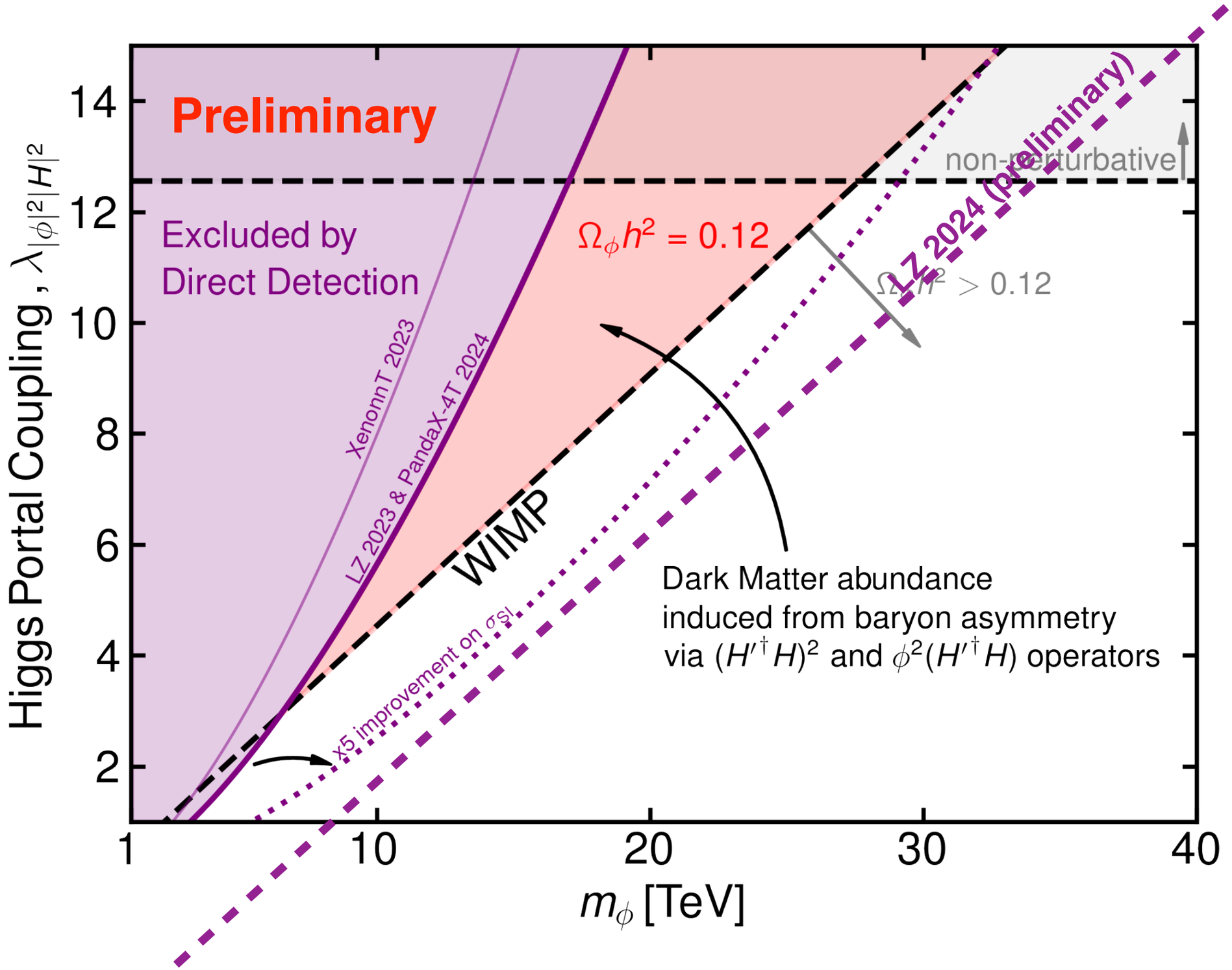

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