Minimal Baryogenesis induced Asymmetric Dark Matter

Miguel Escudero Abenza
miguel.escudero@cern.ch

based on: 2511.10731   (today on arxiv!)
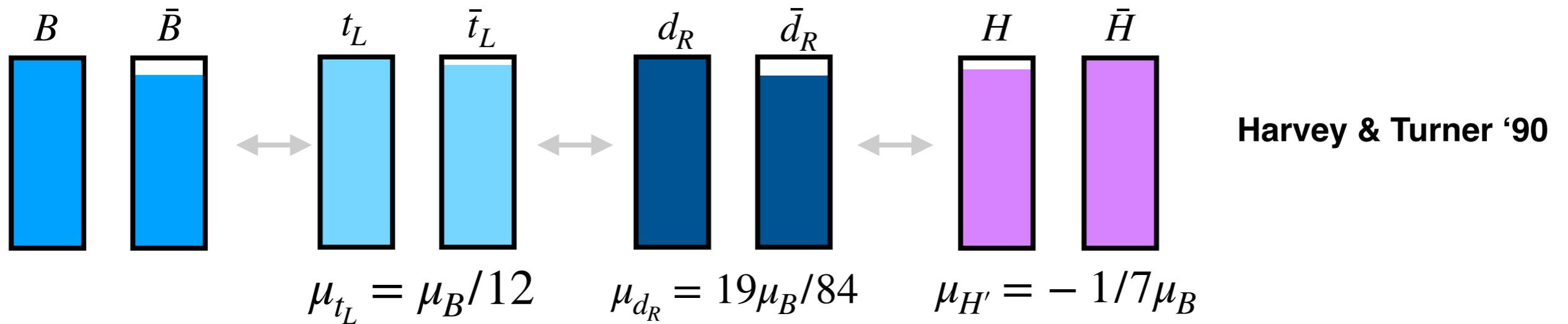
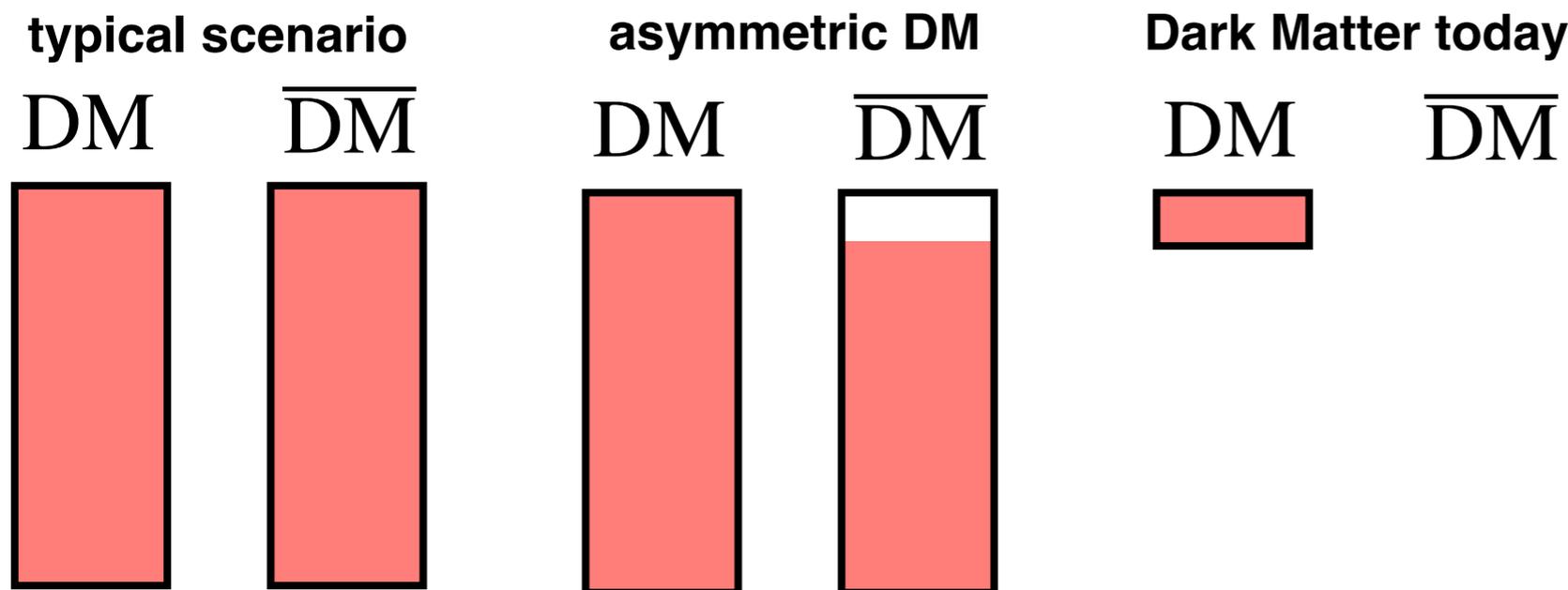with Thomas Hambye and Chandan Hati

CKC workshop, Busan
17-11-2025

We know that if the baryon asymmetry of the Universe was generated before the electroweak phase transition, then all states in the SM but $W^{\pm}$ had different numbers of particles than antiparticles:

B $\bar{B}$ t_L $\bar{t}_L$ d_R $\bar{d}_R$ H $\bar{H}$

Harvey & Turner '90

$$\mu_{t_L} = \mu_B/12 \qquad \mu_{d_R} = 19\mu_B/84 \qquad \mu_{H'} = -1/7\mu_B$$

Can dark matter be asymmetric?

typical scenario

DM $\overline{\mathrm{DM}}$

asymmetric DM

DM $\overline{\mathrm{DM}}$

Dark Matter today

DM $\overline{\mathrm{DM}}$

Early Refs.

Hut & Olive '79
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]

Motivation

Many Asymmetric Dark Matter models have been proposed.

Set one:

Models with a large number of fields needed to engineer an asymmetry in the dark matter

Set two:

Models which relate an existing baryon asymmetry and transfer it to the Dark Matter (which are in most cases based on effective operators)

Kaplan, Luty & Zurek [0901.4117]
Cohen & Zurek [0909.2035]
Ibe, Matsumoto & Yanagida [1110.5452]
Servant & Tullin [1304.3464]
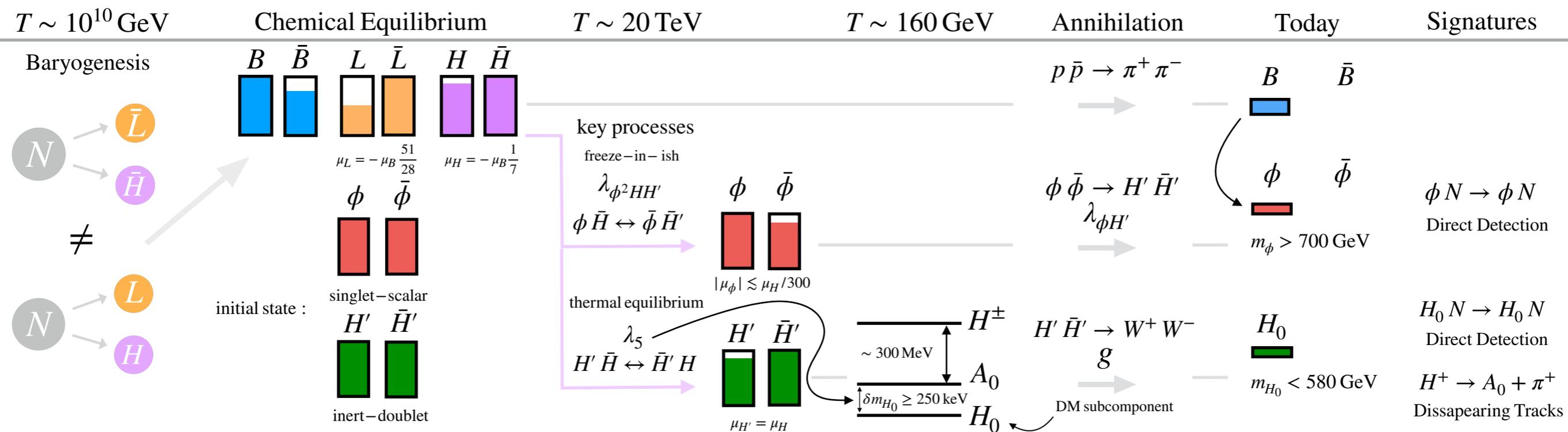Boucenna, Krauss & Nardi [1503.01119]
*Dhen & Hambye [1503.03444]

Goals:

1) Can we do it with a minimal set of elements?

2) Link the Dark Matter abundance to the baryon asymmetry of the Universe

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)

The scenario

Minimal Baryogenesis induced Asymmetric Dark Matter

The rest of the talk:

The elements of the model ϕ **(complex singlet scalar)** $+1$ Z_4
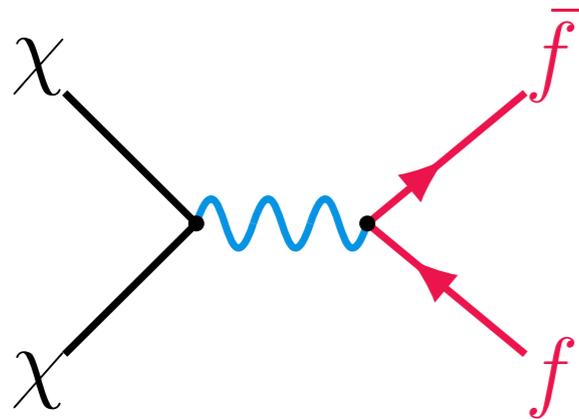H' **(inert Higgs doublet)** -2

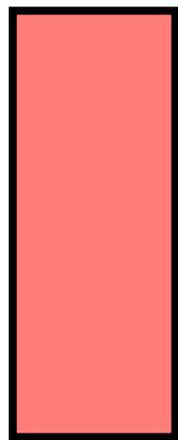**How it avoids issues that are fatal in other scenarios**

Early Universe dynamics
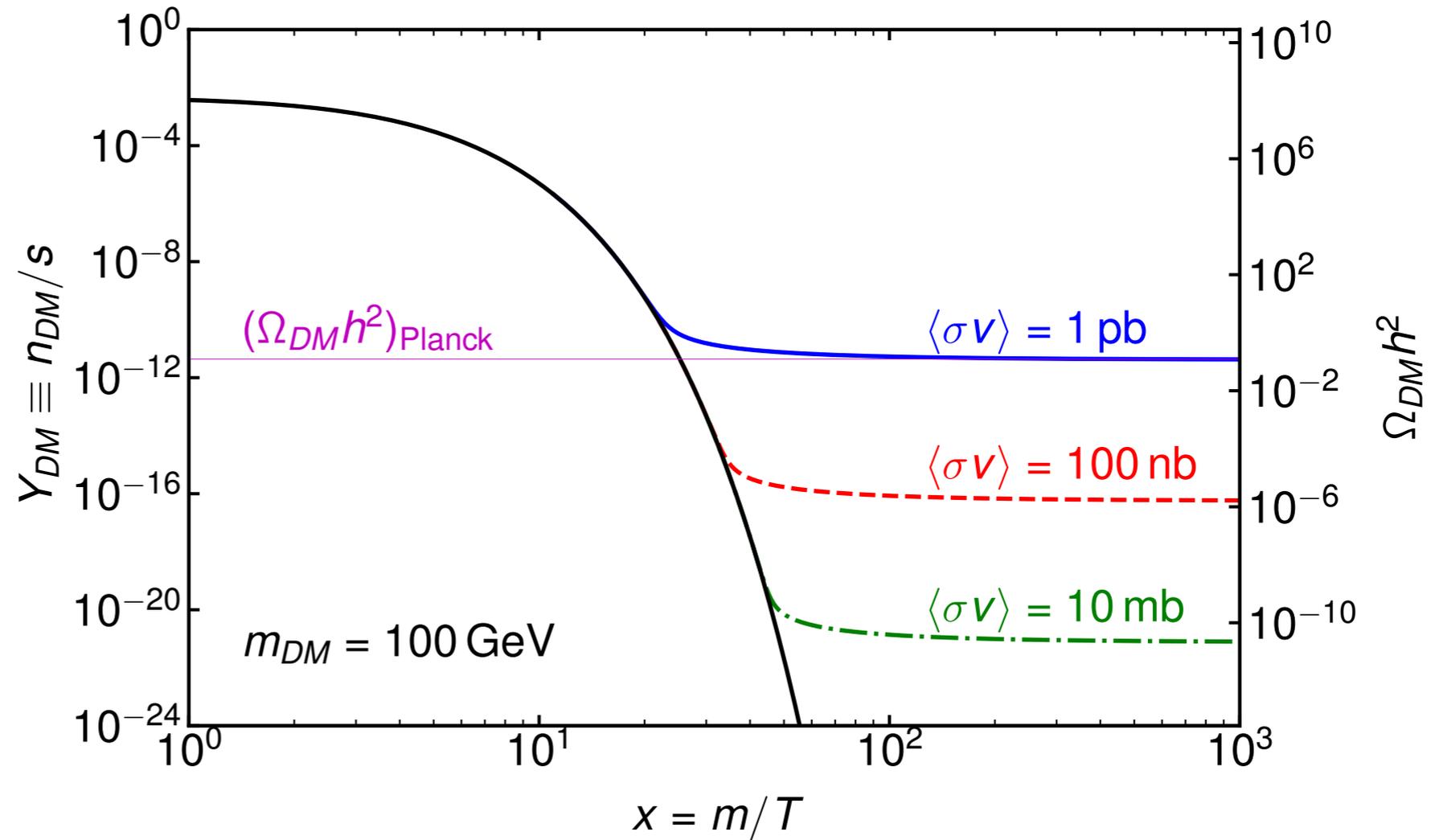
Signatures

Thermal Freeze-out

WIMP freeze-out

Thermal Freeze-out
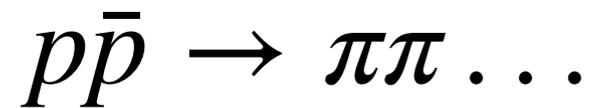
proton-antiproton freeze-out

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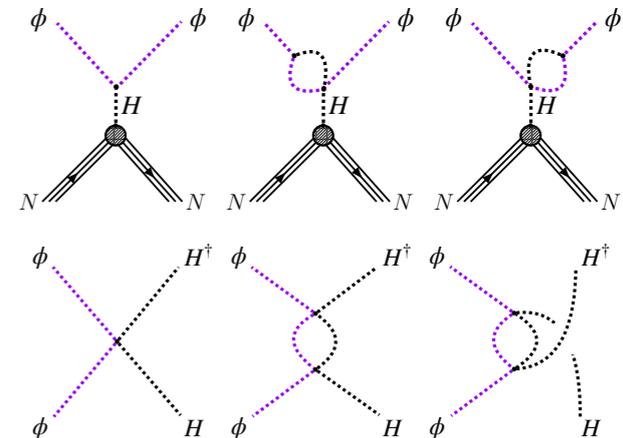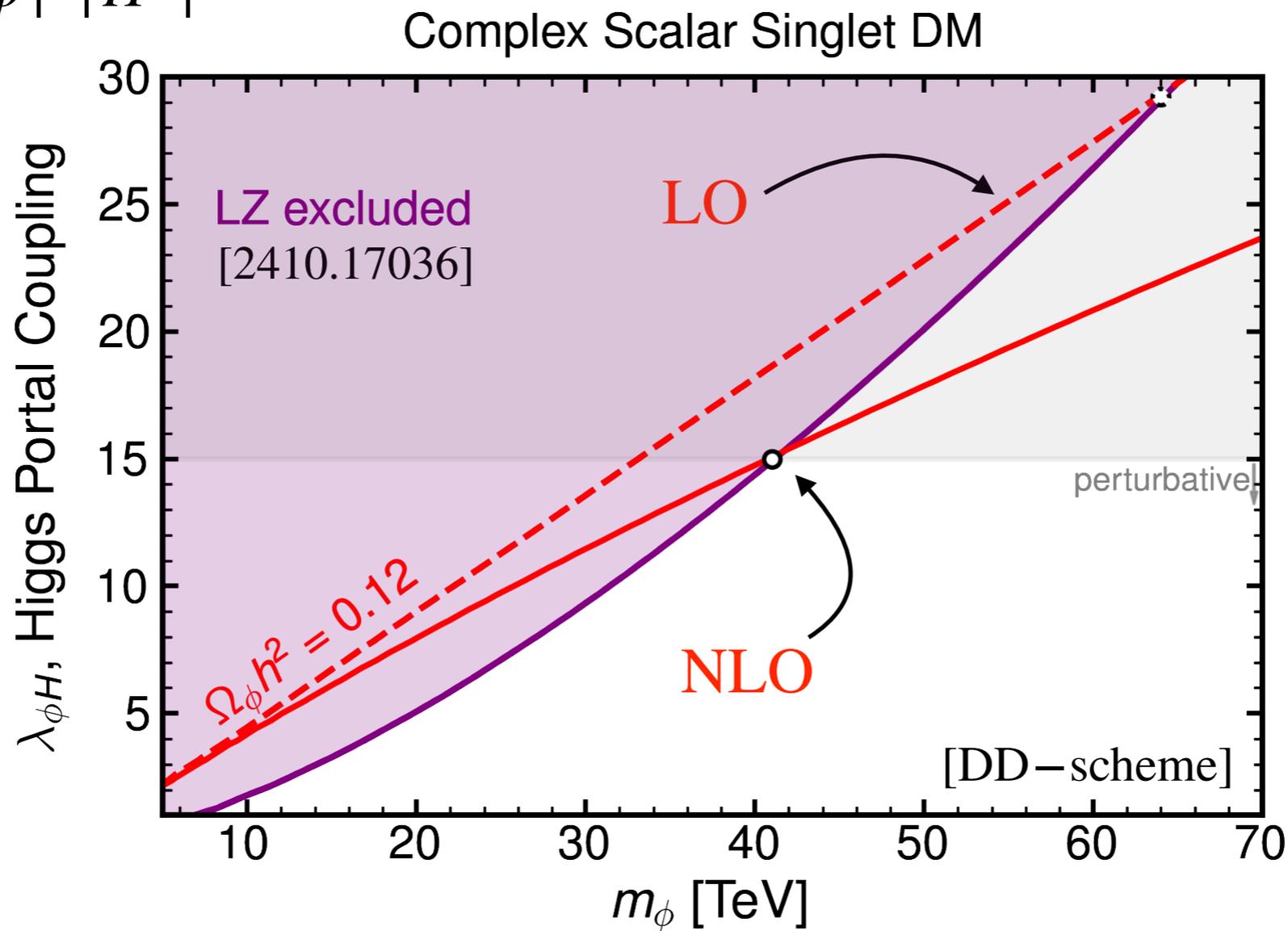

- **No antiparticles today**

- **Key requirement for asymmetric dark matter:**

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

If one wants to make dark matter annihilate efficiently one cannot use Standard Model portals! $\phi\bar{\phi} \to H\bar{H}$ is now excluded by LZ!

$$\mathcal{L} = -\lambda_{\phi H}|\phi|^2|H^2|$$

Complex Scalar Singlet DM

Escudero & Hambye [2505.02408]

We showed that the recent LZ limit (2025) is so strong that it rules out a singlet complex scalar dark matter in the perturbative regime

Asymmetry Transfer

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

does not work:

$$\mathscr{L} = \lambda |\phi|^2 |H|^2$$

$$\phi\bar{\phi} \leftrightarrow H\bar{H}$$

works

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

$$HH \leftrightarrow H'H'$$

Renormalizable operators:

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

Take $\lambda_5 (H^\dagger H')^2$ **if** $\lambda_5 \gtrsim 10^{-5}$ **then there is a thermal dark Higgs Asymmetry**

Cohen & Zurek [0909.2035] $\dfrac{1}{\Lambda^4} X^2 (LH)^2$

Servant & Tullin [1304.3464] $\dfrac{1}{\Lambda} X^2 (H)^2$

Boucenna, Krauss & Nardi [1503.01119] $\dfrac{1}{\Lambda^m} X^2 (H)^n$
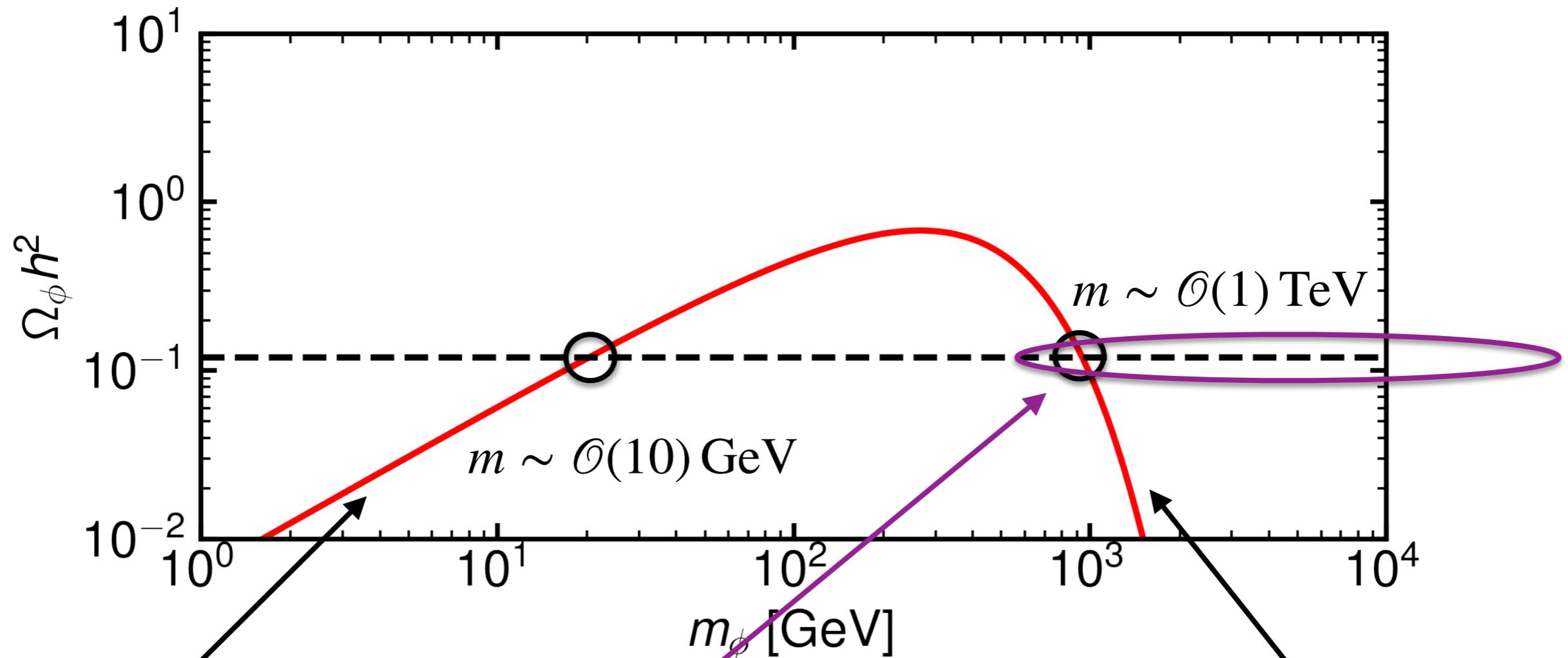
Ibe, Matsumoto & Yanagida [1110.5452] $\dfrac{1}{\Lambda^3} \phi^2 (LH)^2$

*Dhen & Hambye [1503.03444]: $\lambda_5 (HH')^2$

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_{EW}

$m \sim \mathcal{O}(1)\,\text{TeV}$

$m \sim \mathcal{O}(10)\,\text{GeV}$

Linear scaling with mass

Our model works in a sort of freeze-in fashion and the parameter space of interest is $m_\phi > 700\,\text{GeV}$
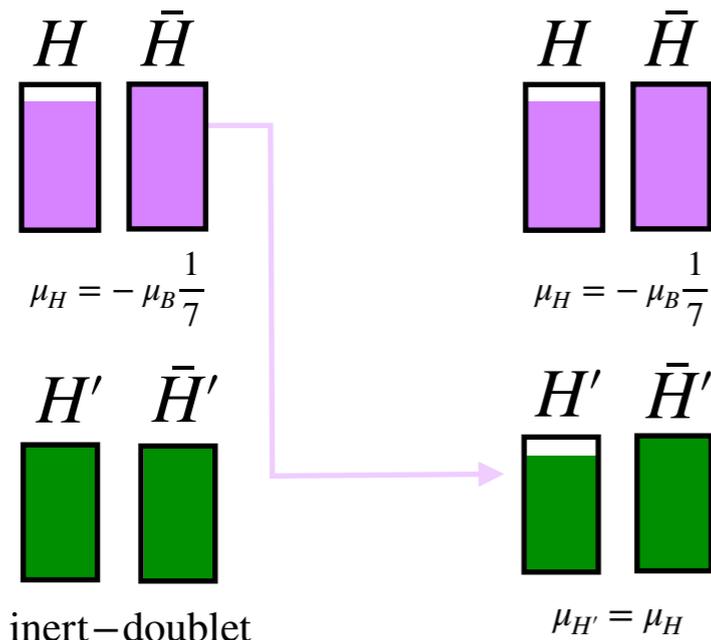
Exponential Boltzmann suppression

Our Model

Our model: Z_4 $[\phi] = 1$ **dominant Asymmetric DM**

$[H'] = -2$ **subdominant symmetric DM**

$m_\phi > m_{H'}$

Comments: **usual Z_2 symmetries for WIMPs have issues:** $m_\phi^2 \phi^2 + m_{\bar\phi}^2 \bar\phi^2$

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

$U(1)_X$ **global (killed by star cooling (axion))**

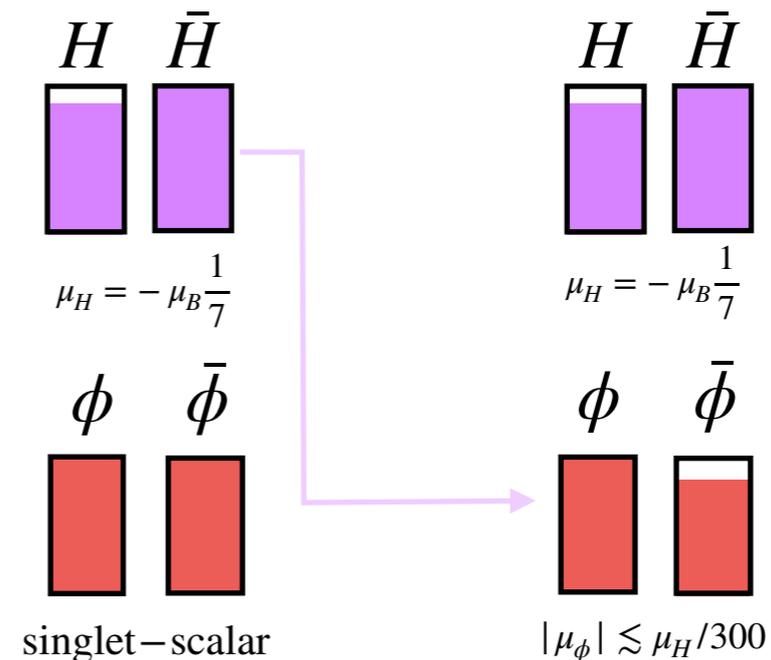## This symmetry structure allows for two particle asymmetry portals:

$$V = \lambda_5 (H^\dagger H')^2 + \mathrm{h.c.}$$

$$\mathrm{e.g.} \quad HH \leftrightarrow H'H'$$

$$V = \lambda_{\phi^2 HH'} \phi^2 H^\dagger H' + \mathrm{h.c.}$$

$$\mathrm{e.g.} \quad H\bar{H}' \to \phi\phi$$

H $\bar{H}$

$\mu_H = -\mu_B \frac{1}{7}$

H $\bar{H}$

$\mu_H = -\mu_B \frac{1}{7}$

H' $\bar{H}'$

inert−doublet

H' $\bar{H}'$

$\mu_{H'} = \mu_H$

H $\bar{H}$

$\mu_H = -\mu_B \frac{1}{7}$

H $\bar{H}$

$\mu_H = -\mu_B \frac{1}{7}$

ϕ $\bar{\phi}$

singlet−scalar

ϕ $\bar{\phi}$

$|\mu_\phi| \lesssim \mu_H/300$
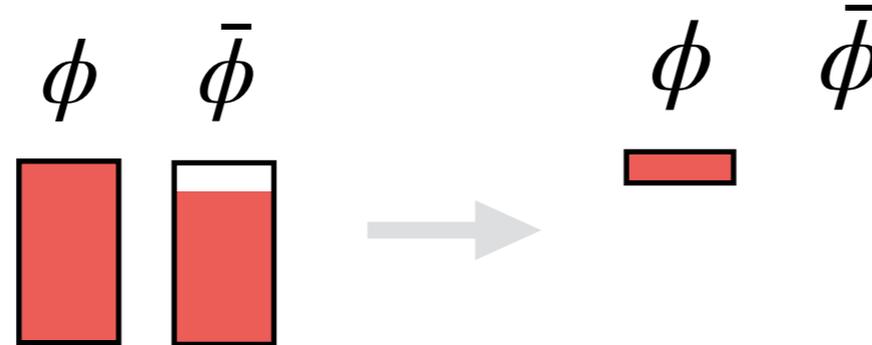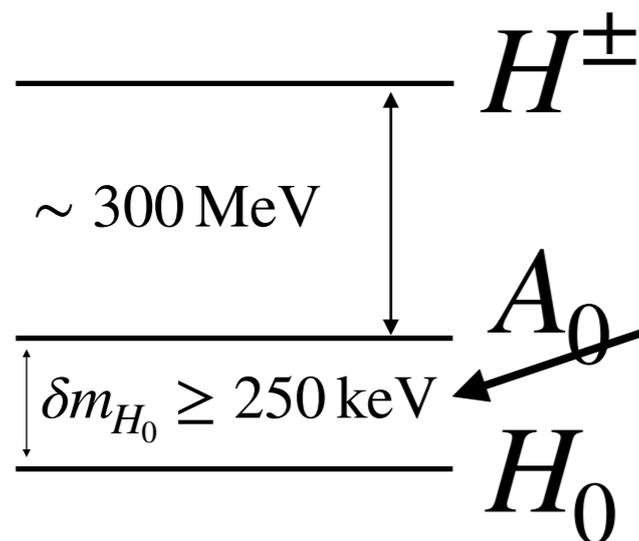
Our Model

3) How do we ensure that the dark matter annihilates completely and its abundance is dictated by an asymmetry?

$$V = \lambda_{\phi H'} |\phi|^2 |H'|^2 \qquad \phi\bar\phi \to H'\bar H'$$

This prevents stringent direct detection constraints

$$\phi \quad \bar\phi \qquad\qquad \phi \quad \bar\phi$$

H₀ or A₀ end up being a subcomponent of Dark Matter: $\quad \Omega_{H_0} h^2 = 0.12 \left(\dfrac{m_{H'}}{580\,\text{GeV}}\right)^2$

4) We have a Higgs doublet as DM fraction and it talks with the Z boson:

$$H^\pm$$

$$\sim 300\,\text{MeV}$$

$$A_0$$

$$\delta m_{H_0} \geq 250\,\text{keV}$$

$$H_0$$

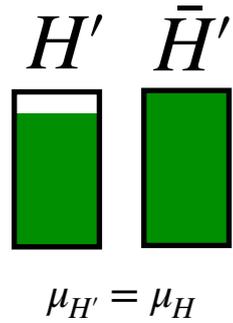$$V = \lambda_5/2 (H^\dagger H')^2 + \text{h.c.}$$

the same λ_5 interaction provides the mass splitting which avoids being ruled out by direct detection

Relevant processes in the EU

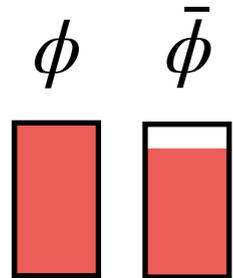**Relevant processes:**

$$H'H' \leftrightarrow HH\,, \quad \bar{H}'\bar{H}' \leftrightarrow \bar{H}\bar{H}\,, \quad H'\bar{H} \leftrightarrow \bar{H}'H\,, \quad \bar{H}'H \leftrightarrow H'\bar{H} \quad \text{(induced by } \lambda_5\text{)}$$

$$\phi\phi \leftrightarrow H\bar{H}'\,, \quad \bar{\phi}\bar{\phi} \leftrightarrow \bar{H}H'\,, \quad \phi\bar{H} \leftrightarrow \bar{\phi}\bar{H}'\,, \quad \bar{\phi}H \leftrightarrow \phi H' \quad \text{(induced by } \lambda_{\phi^2 HH'}\text{)}$$
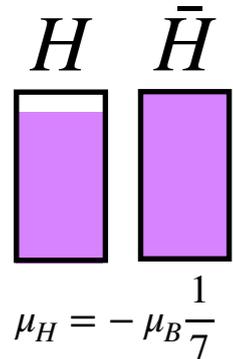
Boltzmann equations:

$H' \quad \bar{H}'$

$\mu_{H'} = \mu_H$

$$\frac{d\Delta_{H'}}{dx} = -\frac{s}{Hx}\left\{ + 2\big(\langle\sigma v(H'H' \to HH)\rangle + \langle\sigma v(H'\bar{H} \to \bar{H}'H)\rangle\big)Y_{H'}^{\text{eq}}\left[\Delta H' - \frac{Y_{H'}^{\text{eq}}}{Y_H^{\text{eq}}}\Delta H\right]\right.$$

$$\left. + \big(\frac{1}{2}\langle\sigma v(\phi\phi \to H\bar{H}')\rangle Y_\phi^{\text{eq}} + 2\langle\sigma v(\phi\bar{H} \to \bar{\phi}\bar{H}')\rangle Y_H^{\text{eq}}\big)\left[2\Delta\phi + \frac{Y_\phi^{\text{eq}}}{Y_{H'}^{\text{eq}}}\Delta H' - \frac{Y_\phi^{\text{eq}}}{Y_H^{\text{eq}}}\Delta H\right]\right\}$$

$\phi \quad \bar{\phi}$
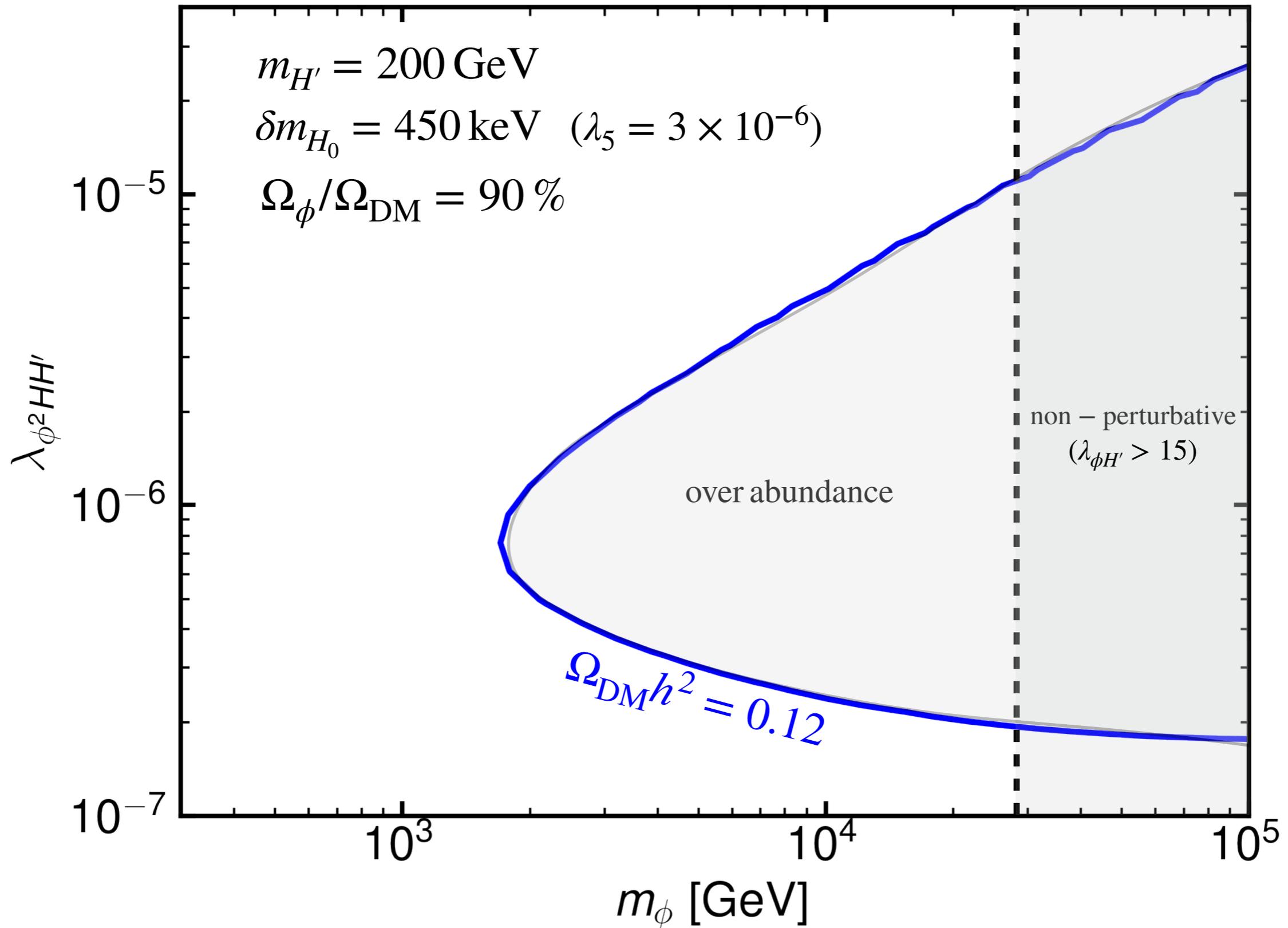
$$\frac{d\Delta_\phi}{dx} = -\frac{s}{Hx}\left\{ + \big(2\langle\sigma v(\phi\bar{H} \to \bar{\phi}\bar{H}')\rangle Y_H^{\text{eq}} + \langle\sigma v(\phi\phi \to H\bar{H}')\rangle Y_\phi^{\text{eq}}\big)\left[2\Delta\phi + \frac{Y_\phi^{\text{eq}}}{Y_{H'}^{\text{eq}}}\Delta H' - \frac{Y_\phi^{\text{eq}}}{Y_H^{\text{eq}}}\Delta H\right]\right\}$$
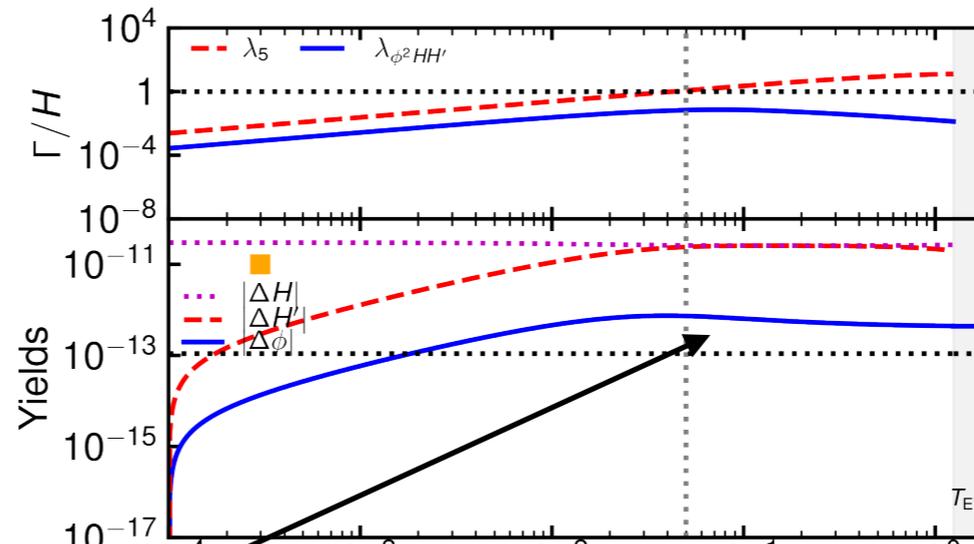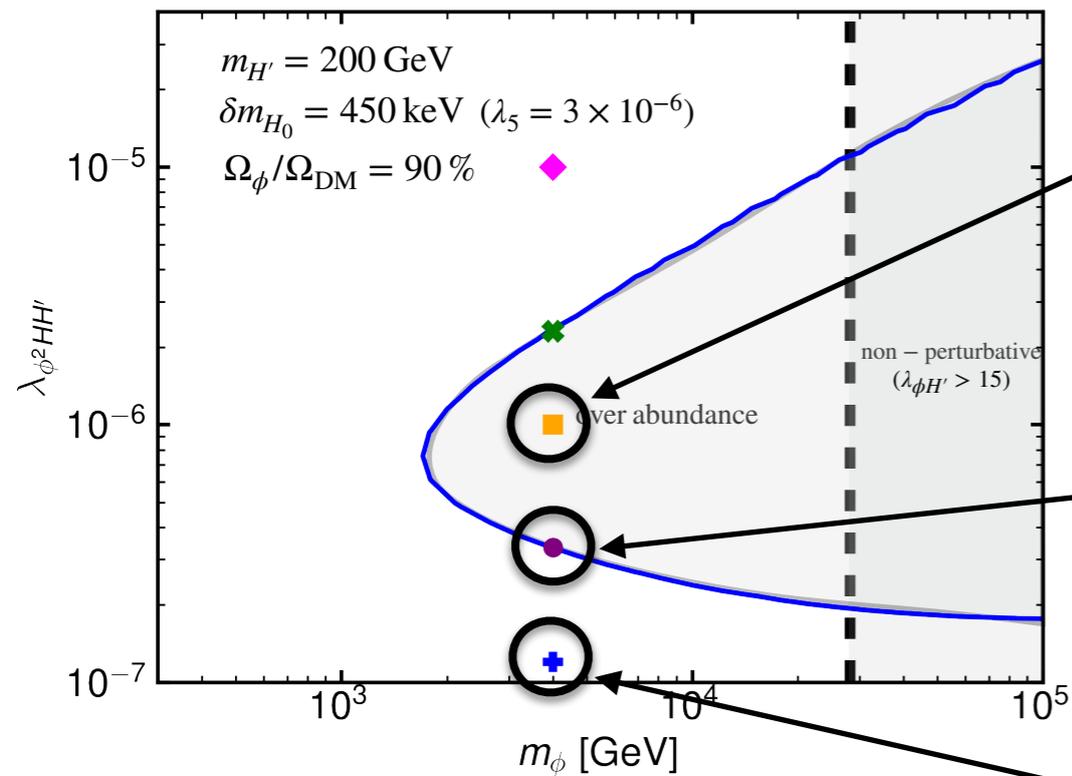
$H \quad \bar{H}$

$\mu_H = -\mu_B \frac{1}{7}$

$$\frac{d\Delta_H}{dx} = -\frac{13}{79}\frac{d\Delta_{H'}}{dx}\,. \quad (B-L \text{ and } Q \text{ conservation and all SM interactions active})$$
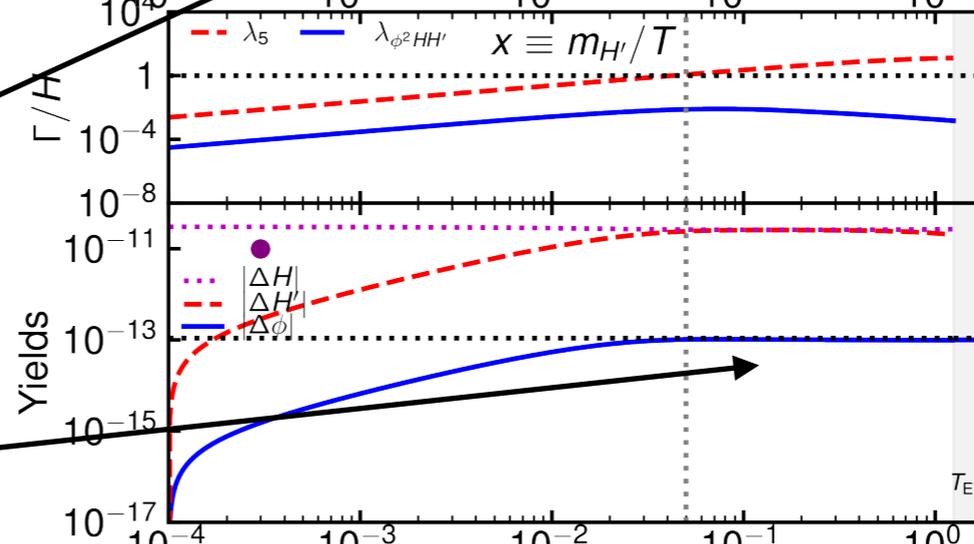
$m_{H'} = 200\,\text{GeV}$
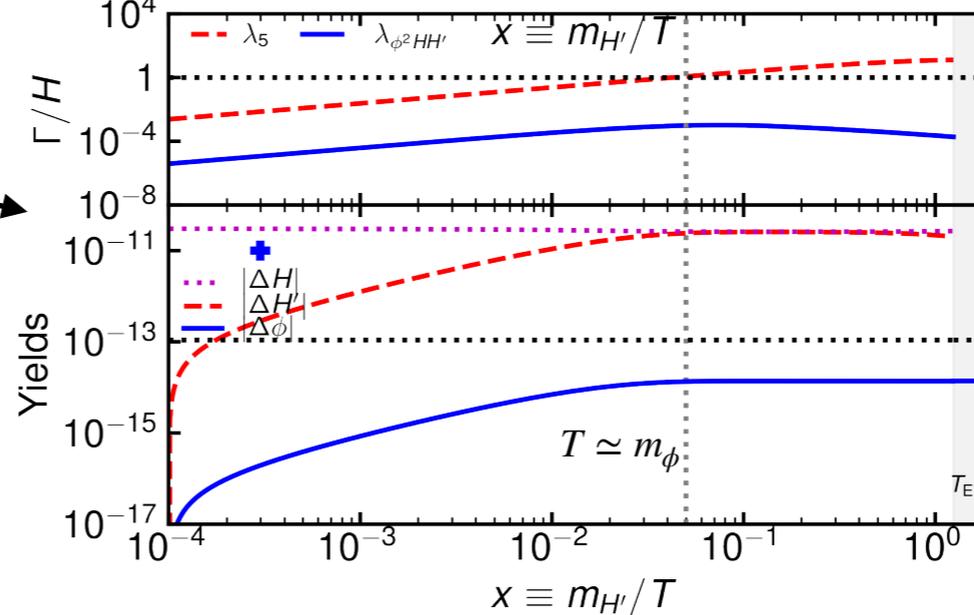
$\delta m_{H_0} = 450\,\text{keV} \quad (\lambda_5 = 3 \times 10^{-6})$

$\Omega_\phi/\Omega_{\text{DM}} = 90\,\%$

non $-$ perturbative $(\lambda_{\phi H'} > 15)$

over abundance

$\Omega_{\text{DM}} h^2 = 0.12$

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

m_ϕ [GeV]

Some examples

$m_{H'} = 200\,\mathrm{GeV}$

$\delta m_{H_0} = 450\,\mathrm{keV}$ $(\lambda_5 = 3 \times 10^{-6})$

$\Omega_\phi / \Omega_{\mathrm{DM}} = 90\,\%$

over abundance

non − perturbative $(\lambda_{\phi H'} > 15)$

λ_5 $\lambda_{\phi^2 HH'}$

Γ/H

Yields

$|\Delta H|$
$|\Delta H'|$
$|\Delta \phi|$

$x \equiv m_{H'}/T$

$T \simeq m_\phi$

T_{EW}

too much freeze-in + a bit of damping from H' thermalization

freeze-in + a bit of damping from H' thermalization

freeze-in (too little)

Some examples

$m_{H'} = 200\,\text{GeV}$

$\delta m_{H_0} = 450\,\text{keV}$ $(\lambda_5 = 3 \times 10^{-6})$

$\Omega_\phi/\Omega_{\text{DM}} = 90\,\%$

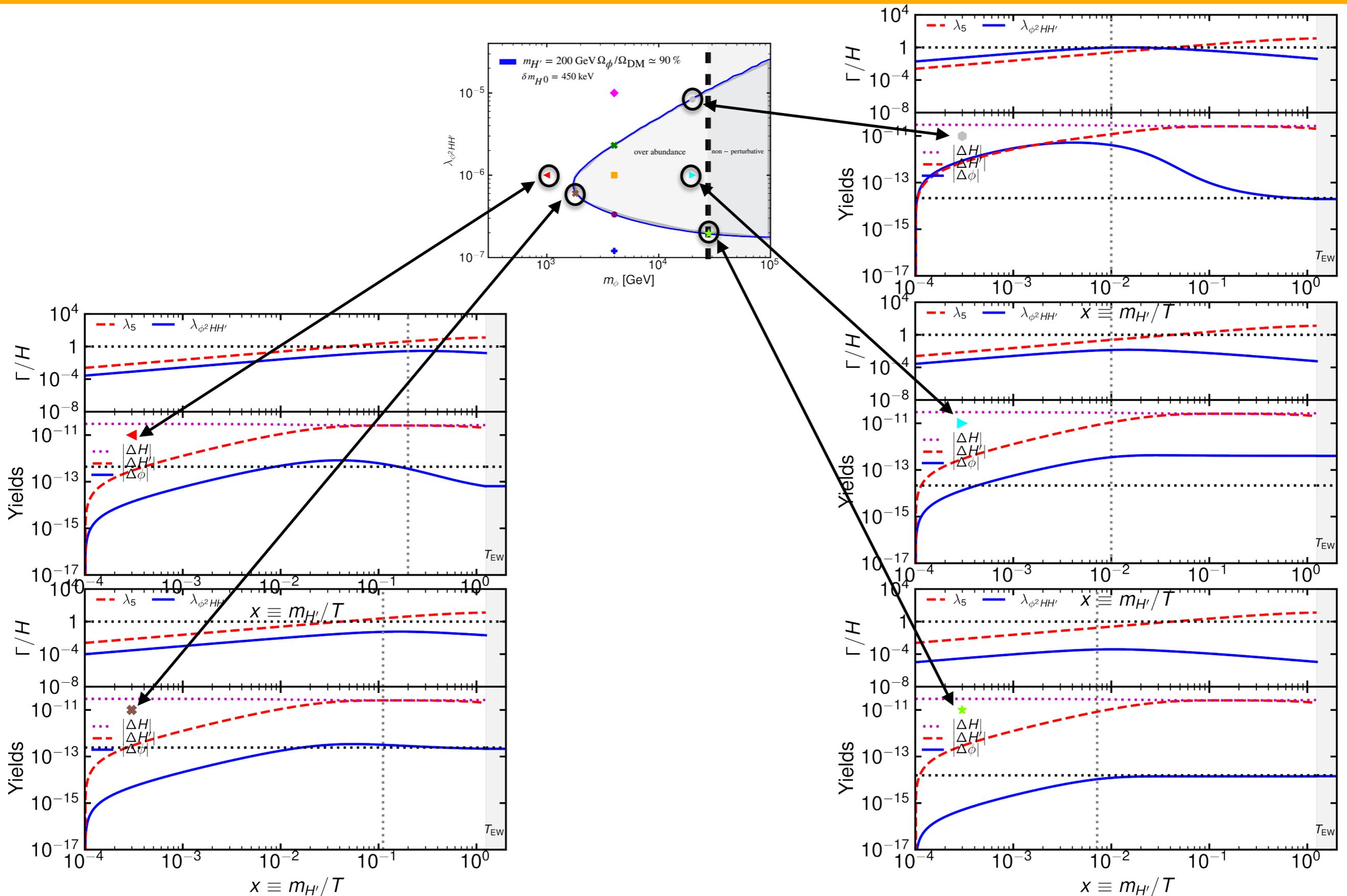non − perturbative ($\lambda_{\phi H'} > 15$)

over abundance

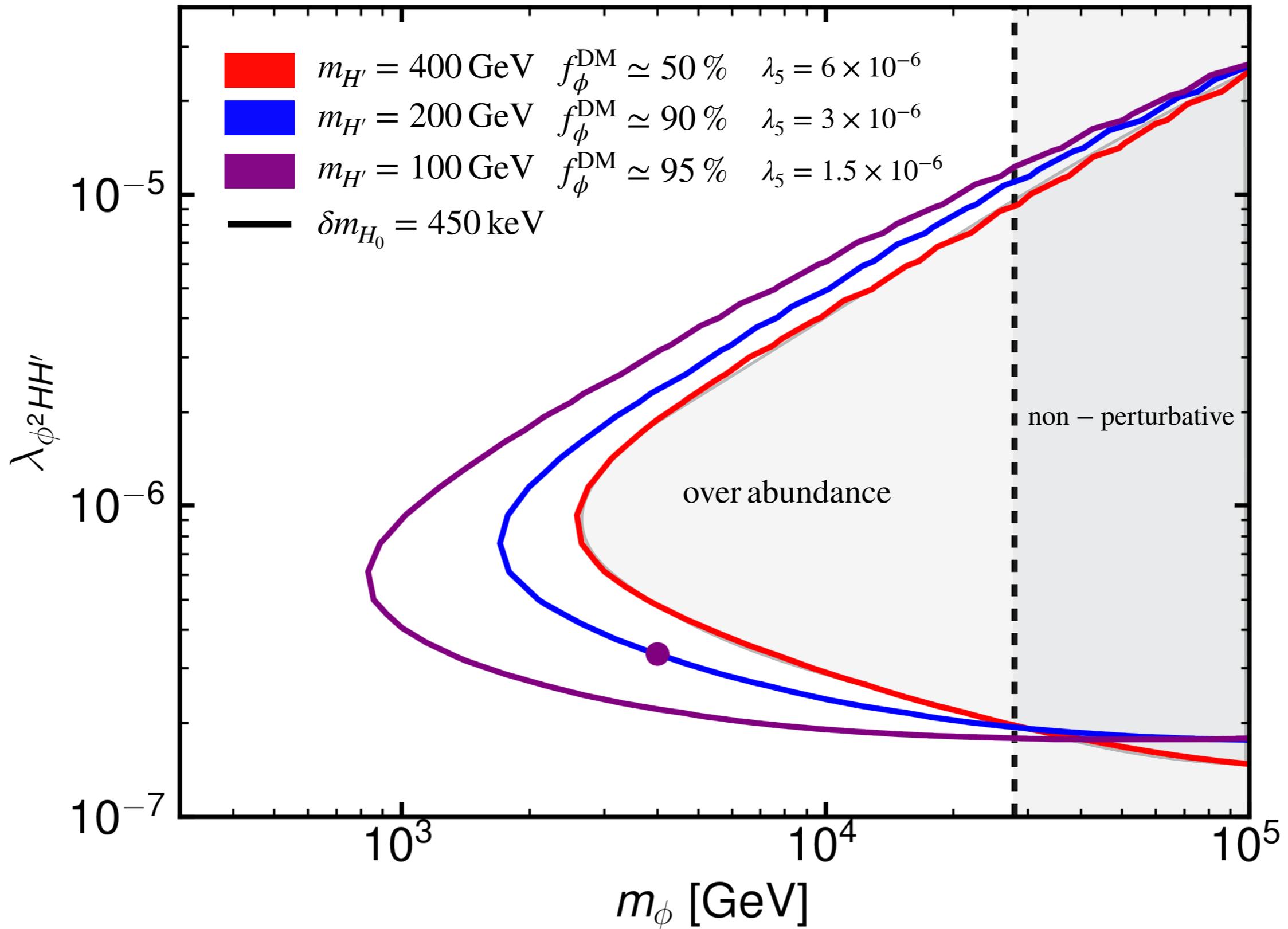**Thermal equilibrium of both rates make the phi asymmetry 0!**

freeze-in with the right damping from H' thermalization

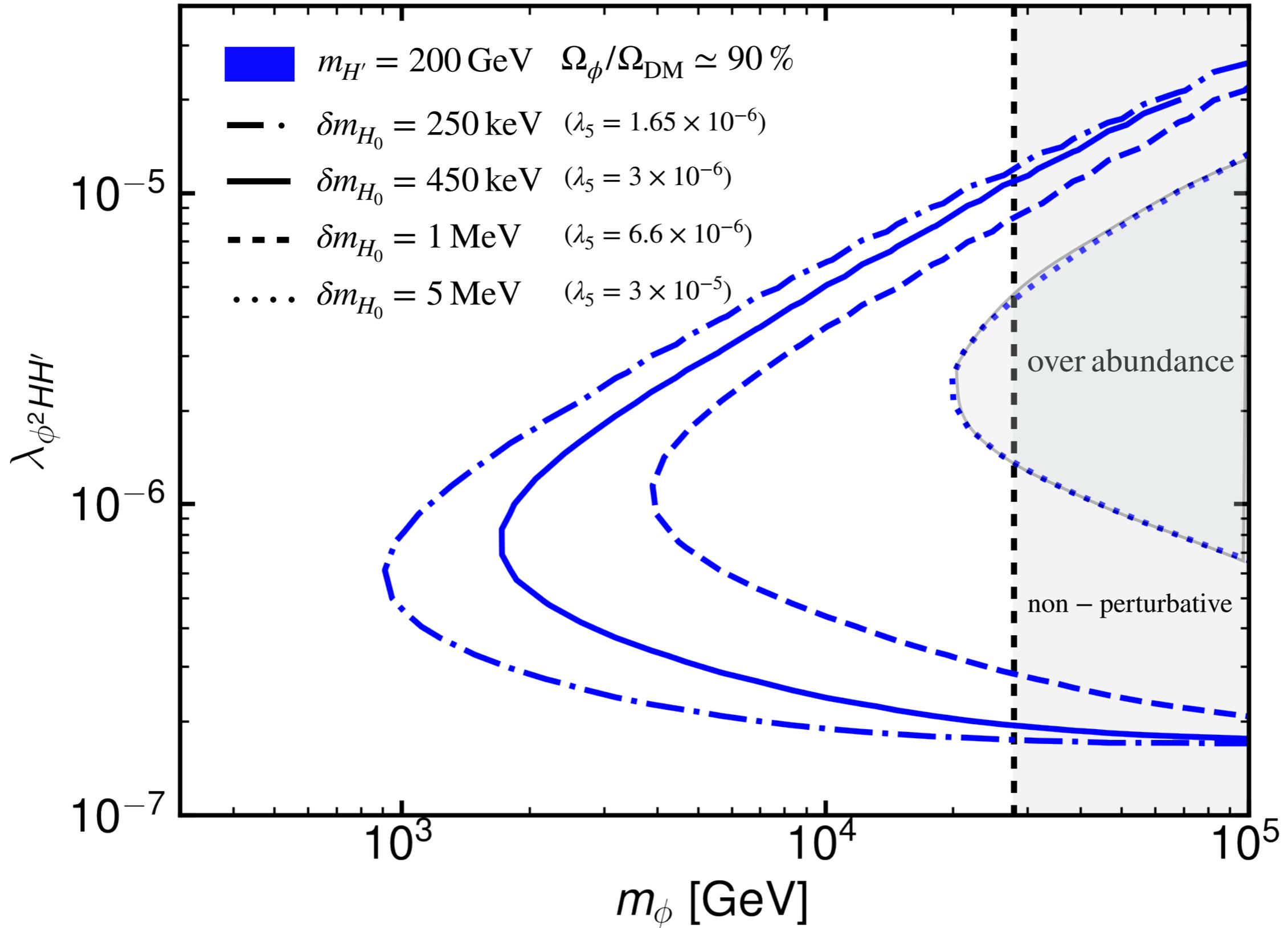**too much freeze-in + a bit of damping from H' thermalization**

Parameter Space

Parameter Space

Parameter Space

The mass is too light and the ϕ asymmetry would be too small

$$700\,\text{GeV} \lesssim m_\phi \lesssim 30\,\text{TeV}$$

symmetric annihilations non-perturbative

LEP

$$70\,\text{GeV} \lesssim m_{H'} < 580\,\text{GeV}$$

overabundance

$$\Omega_{H_0} h^2 = 0.12 \left(\frac{m_{H'}}{580\,\text{GeV}} \right)^2$$

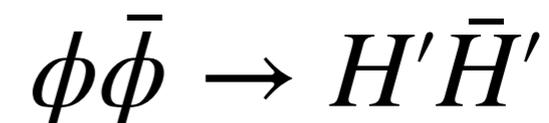**The lighter H' the more asymmetric dark matter is**

Z-induced DD

$$250\,\text{keV} \lesssim \delta m_{H_0} \lesssim 5\,\text{MeV}$$

too much chemical equilibrium and the mechanism is not efficient

$$\overline{}\ A_0$$

$\updownarrow \delta m_{H_0} \geq 250\,\text{keV}$

$$\overline{}\ H_0$$

$$\lambda_{\phi H'} > \frac{m_\phi}{2\,\text{TeV}}$$

Required for the annihilation of dark matter in the early Universe

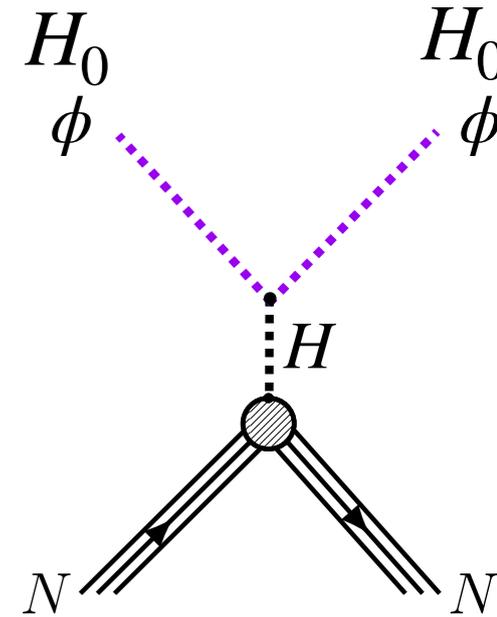$$\phi\bar{\phi} \to H'\bar{H}'$$

Signals

The model allows for the Direct Detection of the two dark matter components via the various Higgs portal couplings:

$$V(H, H', \phi) \in + \lambda_{\phi H} |\phi|^2 |H|^2 + \lambda_{\phi H'} |\phi|^2 |H'|^2$$

$$V(H, H', \phi) \in + \lambda_3 |H|^2 |H'|^2 + \lambda_4 |H^\dagger H'|^2$$

LZ [2025] limit:

$$|\lambda_{Sh}| < 0.057 \left(\frac{m_S}{\text{TeV}} \right)^{3/2} \sqrt{\frac{1}{f_S}}$$

f_S **is number density fraction**

Interestingly, λ_4 also controls the charged-neutral mass splitting and tells us:

EW corrections:

$\sim 300\,\text{MeV}$

$H^\pm$

A_0 / H_0

$$|m_{H^\pm} - m_{H_0}| \simeq \frac{\lambda_4 v_H^2}{4 m_H} \lesssim 700\,\text{MeV}$$
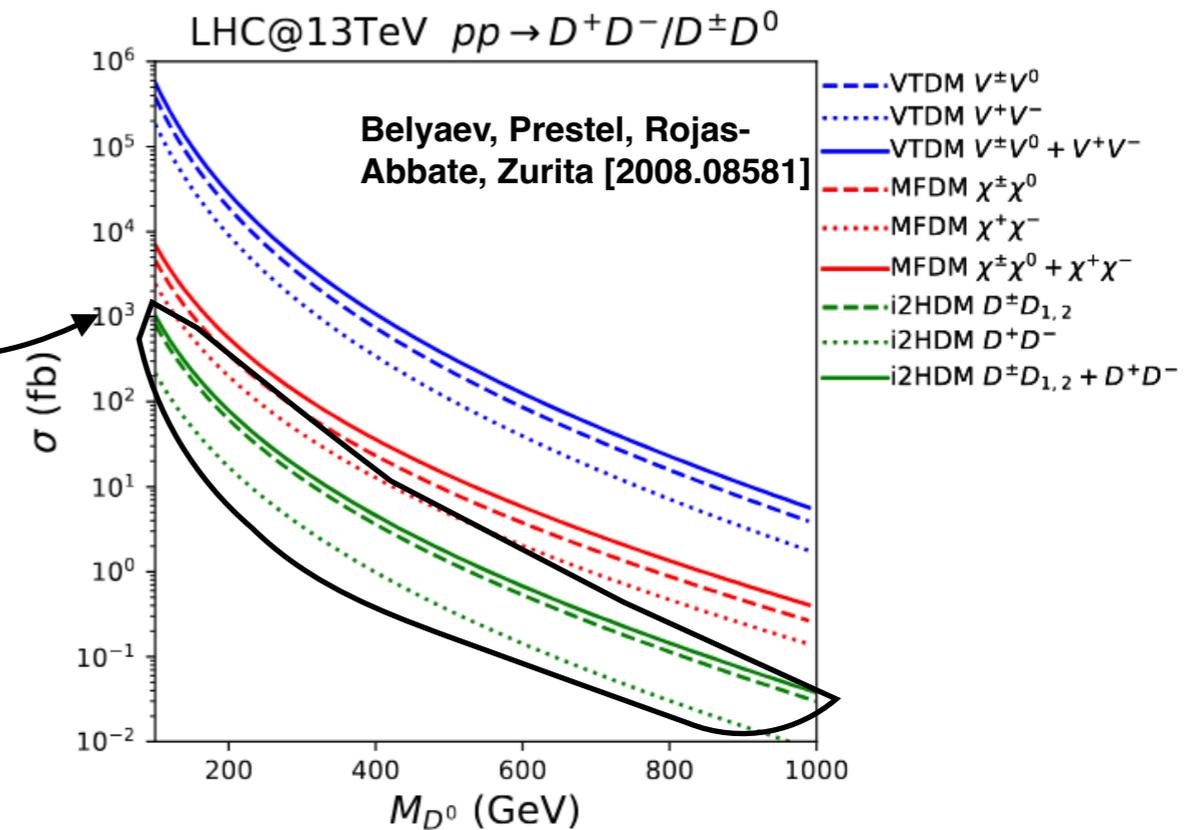
Factor of ~10 expected improvement in DD rates in the upcoming years with XLZD and PandaX-xT

Can a Higgs so light be allowed?

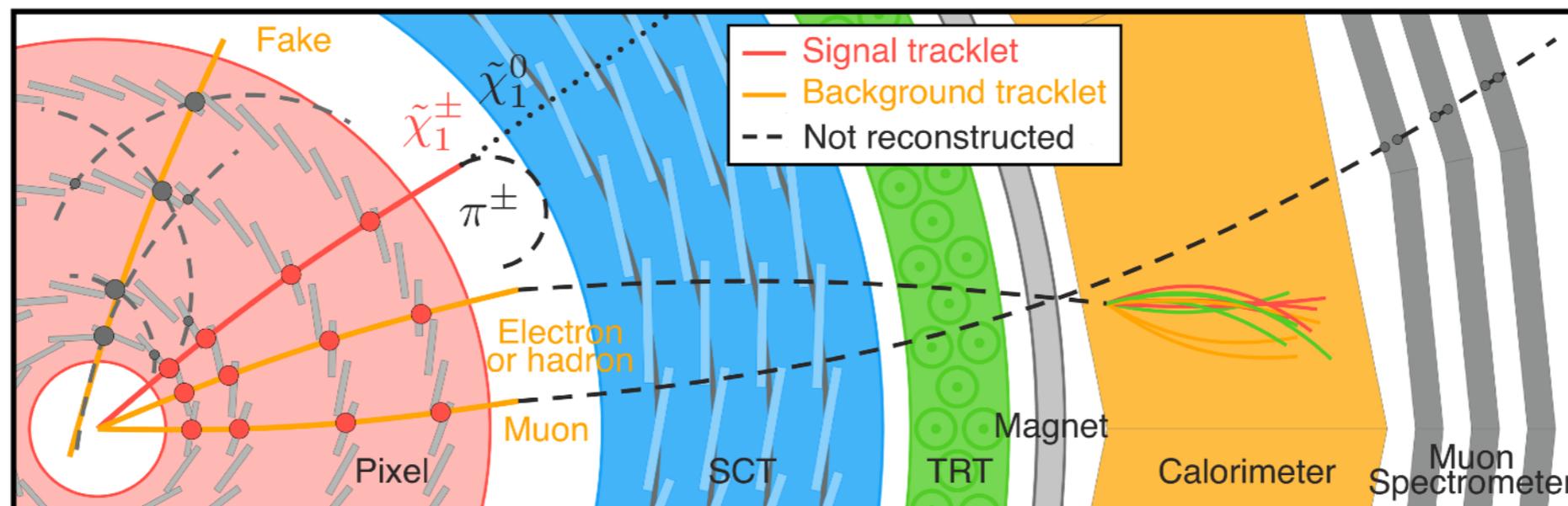The inert Higgs doublet only interacts electroweakly and its production cross section at the LHC is not that large:

30 smaller x-sec than the Wino
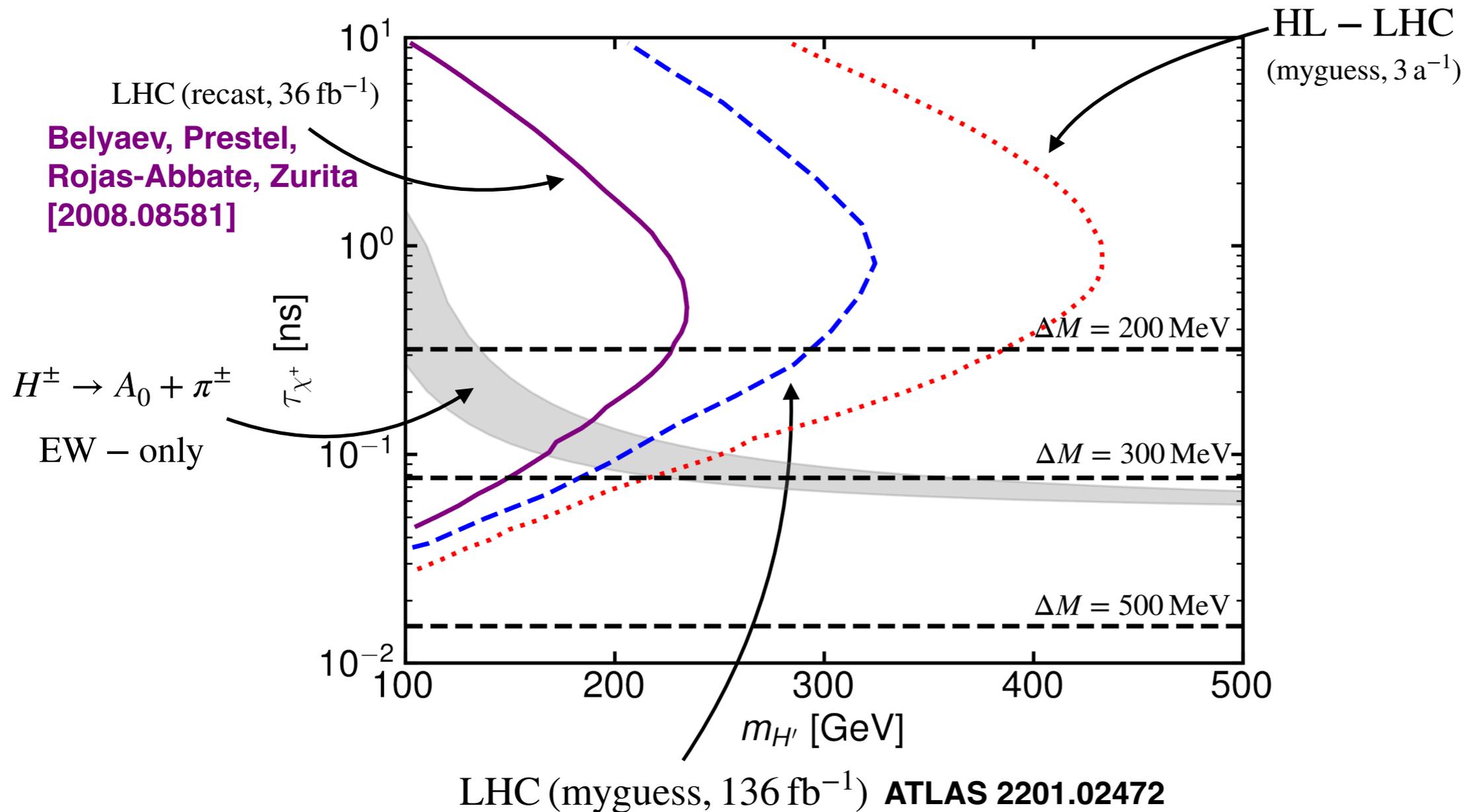
8 smaller x-sec than the Higgsino

LHC@13TeV $pp \rightarrow D^+D^-/D^\pm D^0$

Belyaev, Prestel, Rojas-Abbate, Zurita [2008.08581]

It mainly leads to missing energy as the $H^\pm$ readily decays into $A_0 + \pi^\pm$

Most striking signature are disappearing charged tracks

ATLAS-CONF-2021-015

All in all
$$m_{H'} \gtrsim 160\,\text{GeV}$$ **if mass splitting comes only from EW corrections**

$$m_{H'} \gtrsim 70\,\text{GeV}$$ **even with only +200 MeV in the mass splitting**

HL-LHC sensitivity: $m_{H'} \sim 250\,\text{GeV}$ **if mass splitting comes only from EW corrections**

Summary

Proposed what we think may be the simplest Baryogenesis induced Asymmetric Dark Matter model

Only two new BSM fields: ϕ **(complex singlet scalar)** $+1$ Z_4
H' **(inert Higgs doublet)** -2

Multicomponent dark matter ϕ $\bar{\phi}$ H_0

We can relate the dark matter abundance to the baryon asymmetry of the Universe, as generated by e.g. Leptogenesis

Signals:

Direct detection for both dark matter components

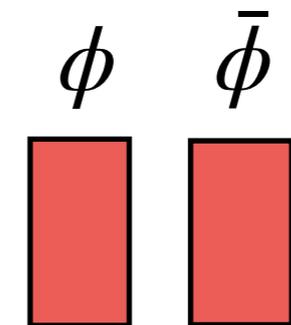**Collider searches for the H' (disappearing tracks)**

The interaction Lagrangian:

$$\phi\bar\phi \to H'\bar H'$$

$$\gtrsim 1$$

$$V(H, H', \phi) = m^2|\phi|^2 + m_{H'}^2|H'|^2 + \lambda_{\phi H}|\phi|^2|H|^2 \quad (2) \quad \text{DD}$$

$$+ \lambda_{\phi H'}|\phi|^2|H'|^2 + \lambda_3|H|^2|H'|^2 + \lambda_4|H^\dagger H'|^2 \quad \lesssim 0.1$$

$$+ \left(\frac{\lambda_{\phi^2 HH'}}{2}\phi^2 H^\dagger H' + h.c.\right) + \frac{\lambda_5}{2}\left((H^\dagger H')^2 + h.c.\right).$$

$$\lambda_{\phi 4}\phi^4$$

$$\sim 10^{-5} \qquad \sim 10^{-5} \qquad \sim 10^{-6}$$

$$HH \leftrightarrow H'H' \qquad H\bar H' \to \phi\phi$$

Hierarchy of couplings. Can one find a theoretical reason as to why?

Our model works in a sort of interesting asymmetric freeze-in-ish regime

Having a renormalizable model not only makes it simple but allows us to highlight that CP is a good symmetry. The CP violating effects are tiny because the couplings are tiny!

$$\phi \qquad \bar\phi$$

the same is not true for symmetric freeze-in!

Acknowledgements

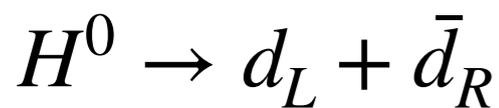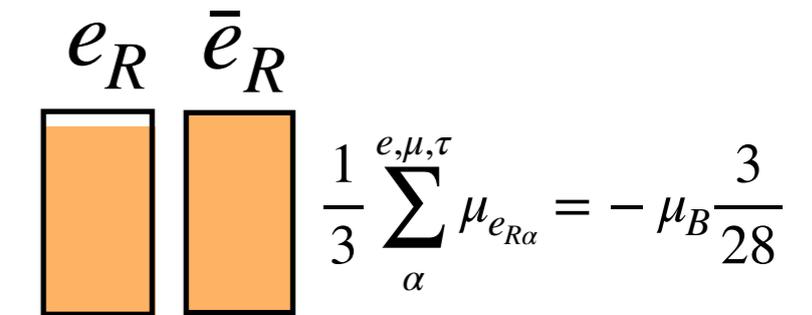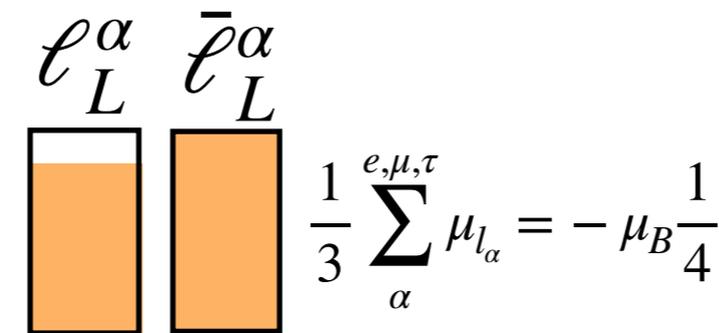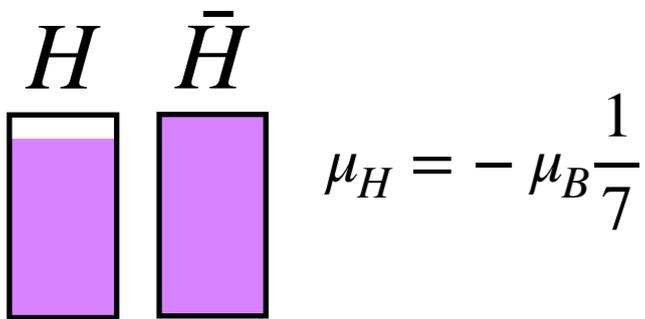**Great thanks to my outstanding collaborators!**

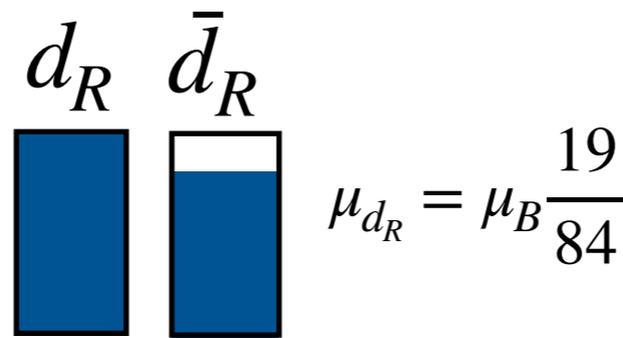**Thomas Hambye**   **Chandan Hati**
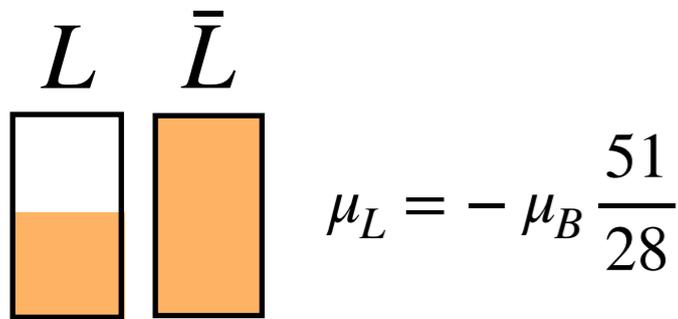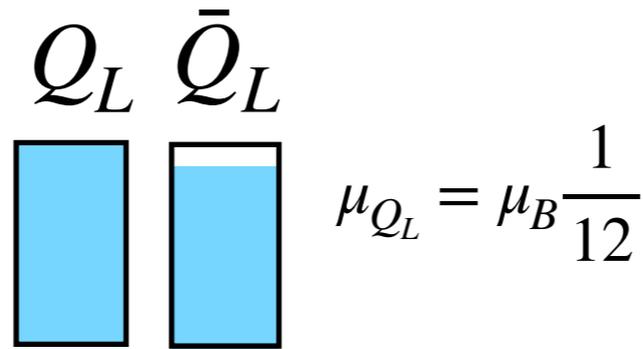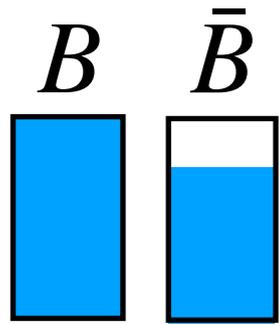

Thanks for your attention!

Questions, comments and criticism are most welcome

Chemical relations in the SM

B $\bar{B}$

Q_L $\bar{Q}_L$

$$\mu_{Q_L} = \mu_B \frac{1}{12}$$

L $\bar{L}$

$$\mu_L = - \mu_B \frac{51}{28}$$

d_R $\bar{d}_R$

$$\mu_{d_R} = \mu_B \frac{19}{84}$$

u_R $\bar{u}_R$

$$\mu_{u_R} = - \mu_B \frac{4}{84}$$

H $\bar{H}$

$$\mu_H = - \mu_B \frac{1}{7}$$

$$H^0 \rightarrow d_L + \bar{d}_R$$

ℓ_L^α $\bar{\ell}_L^\alpha$

$$\frac{1}{3} \sum_{\alpha}^{e,\mu,\tau} \mu_{l_\alpha} = - \mu_B \frac{1}{4}$$

e_R $\bar{e}_R$

$$\frac{1}{3} \sum_{\alpha}^{e,\mu,\tau} \mu_{e_{R\alpha}} = - \mu_B \frac{3}{28}$$

Note that this ends up being multiplied by two as we have also the neutrinos!

all components in the doublets have the same chemical potential due to the fact that muW = 0.