Title: (Dark) Baryogenesis through Asymmetric Reheating in the Mirror Twin Higgs.

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Abstract: We present the ??MTH, a Mirror Twin Higgs (MTH) model realizing asymmetric reheating, baryogenesis and twin-baryogenesis through the out-of-equilibrium decay of a right-handed neutrino without any hard Z2 breaking. The MTH is the simplest Neutral Naturalness solution to the little hierarchy problem and predicts the existence of a twin dark sector related to the Standard Model (SM) by a Z2 symmetry that is only softly broken by a higher twin Higgs vacuum expectation value. The asymmetric reheating cools the twin sector compared to the visible one, thus evading cosmological bounds on ?Neff. The addition of (twin-)colored scalars allows for the generation of the visible baryon asymmetry and, by the virtue of the Z2 symmetry, also results in the generation of a twin baryon asymmetry. We identify a unique scenario with top-philic couplings for the new scalars that can satisfy all cosmological, proton decay and LHC constraints; yield the observed SM baryon asymmetry; and generate a wide range of possible twin baryon DM fractions, from negligible to unity. Implications of predicted atomic DM fractions will be discussed, as well as model-independent asymmetric reheating implications on the abundance of twin helium. These results motivate the search for the rich cosmological and astrophysical signatures of twin baryons, and atomic dark matter more generally, at cosmological, galactic and stellar scales.

(Dark) Baryogenesis through Asymmetric Reheating in the Mirror Twin Higgs

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Based on work 2311.06341 with Gonzalo Alonso Alvarez, David Curtin and Zhihan (Linda) Yuan

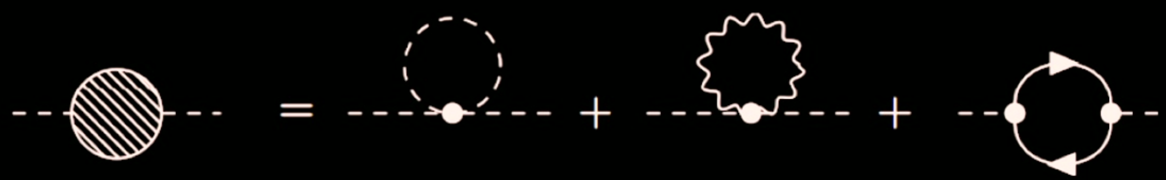
Overview

- Hierarchy Problem and Mirror Twin Higgs (MTH).
- ΔN_{eff} constraints on MTH and asymmetric reheating.
- Twin Baryons and Atomic Dark Matter
- Definition of $\nu\phi$MTH
- Predictions for atomic dark matter abundances
- Conclusions

Hierarchy Problem and Mirror Twin Higgs

- Little Hierarchy Problem – quadratic sensitivity of the Higgs mass to *new physics.*
- In the SM, Higgs mass gets corrections:

$\delta\mu^2 =$



Physical scale where there must be new degrees of freedom, to explain breakdown of low-energy effective theory.

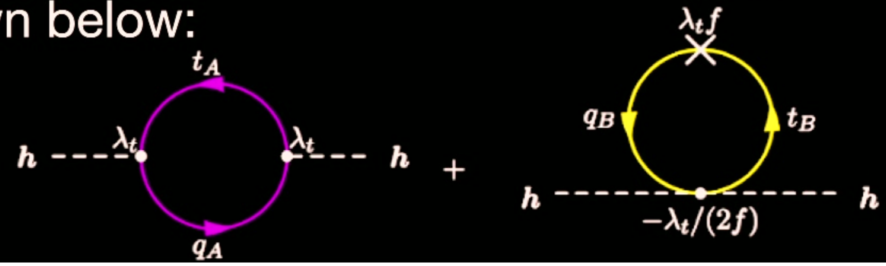
$$= \frac{\Lambda^2}{32\pi^2}\left[-6y_t^2 + \frac{1}{4}(9g^2 - 3g'^2) + 6\lambda\right]$$

Hierarchy Problem and Mirror Twin Higgs

- Usual solutions to the Hierarchy Problem (e.g. Supersymmetry) require existence of colored top partners (Excluded by LHC up to scale ~ 1 TeV)
- Need models that do not require colored partners – **Neutral Naturalness**.
- Mirror Twin Higgs includes the hidden sector (denoted B) is a mirror copy of the SM sector (denoted A):

$$SU(3)_A \times SU(2)_A \times U(1)_A \xleftrightarrow{Z_2} SU(3)_B \times SU(2)_B \times U(1)_B$$

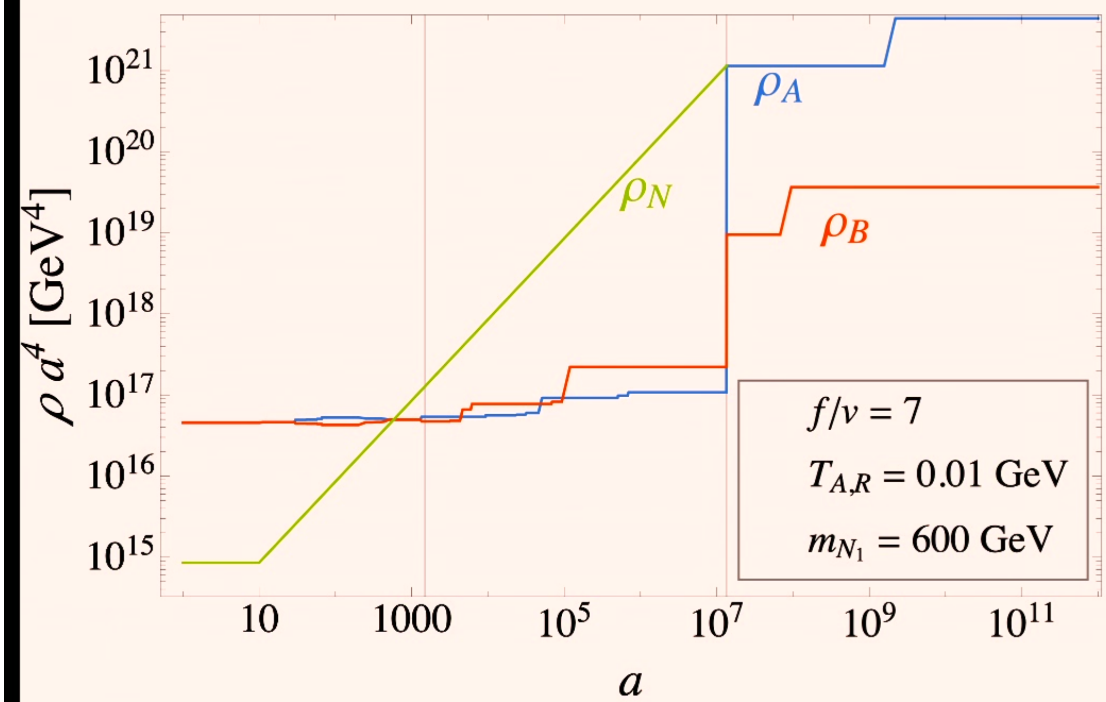
- -Soft $\mathbb{Z}_2$ breaking achieved by making H_B have VEV $f > v$.
- -Diagrammatically, top loop contribution to the Higgs mass cancelled by twin top loop, as shown below:

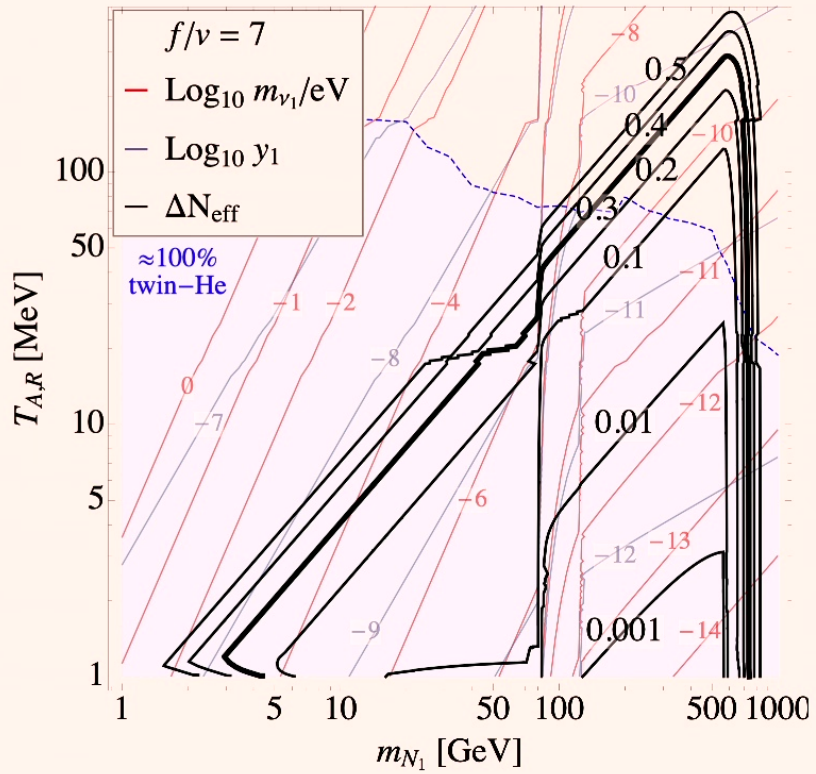


$\Delta N_{\rm eff}$ constraints on MTH and asymmetric reheating

- Original MTH not realized in Nature due to bounds of $\Delta N_{\rm eff}$from CMB and BBN
- Simple calculation shows $\Delta N_{\rm eff} \approx 6$ for MTH, while the experimental value is $\Delta N_{\rm eff} \lesssim 0.23$.
- Potential Solutions: Hard breaking $\mathbb{Z}_2$ (Fraternal MTH) and **Asymmetric Reheating**. (*Chacko et al.* 1611.07975)
- Requires existence of particles *N* outside of SM (decouples from SM bath while relativistic, becomes non-relativistic, decays into two sectors after they decoupled at T ~ 3 GeV).
- *N* decays via weak interactions, dominantly to SM sector, rising its relative temperature compared to the twin sector, suppressing contributions to $\Delta N_{\rm eff}$ from light dofs in twin sector.

ΔN_{eff} constraints on MTH and asymmetric reheating





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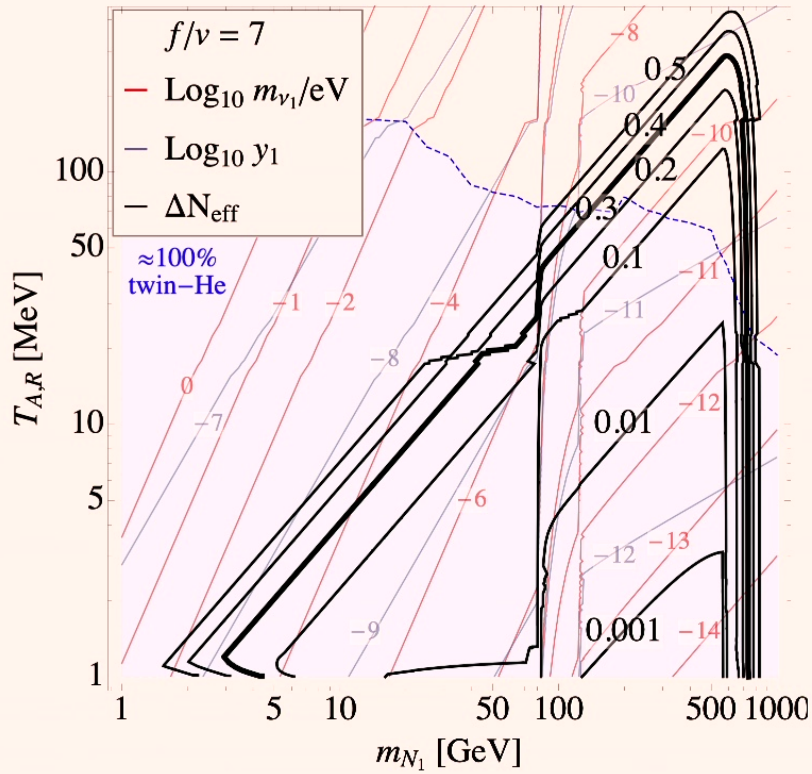
$\Delta N_{\rm eff}$ constraints on MTH and asymmetric reheating

- $m_{e,D} = (f/v)\, m_e$, $m_{p,D} = (1.3 - 1.7)\, m_p$, $\alpha_{EM,D} = \alpha_{EM}$
- For small $\Delta N_{\rm eff} \sim 0.01$, the aDM is completely comprised from twin Helium. (Blue regions) - this is model independent statement, for all models that have asymmetric reheating. Cosmological signatures studied in 2104.02074.
- In white regions, twin BBN proceeds normally. 2110.04317.
- For our baryogenesis purposes, the allowed parameter space happens above blue dashed line.



$\nu\phi$MTH

- $\phi q N$ and $\phi q_i q_j$ (two choices for hypercharge Y= 2/3 or Y=-1/3).
- Require existence of at least **two** generations of RHN with non-aligned phases in their couplings to the colored scalar.
- CPV is then calculated by interference between tree level and 1-loop decay diagrams of N.

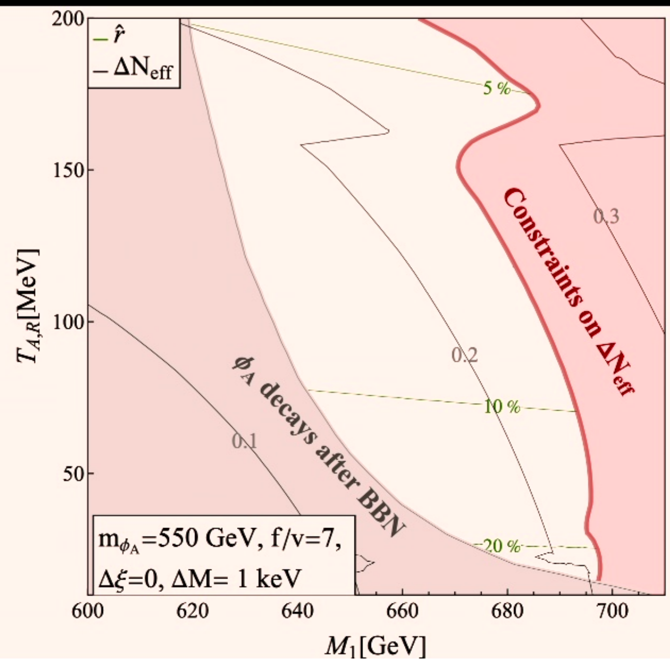
$$\epsilon_{CPV} = \frac{\Gamma(N \to q + X) - \Gamma(N \to \bar{q} + \bar{X})}{\Gamma^N_{tot}}$$

- This can easily be converted to the baryon asymmetry $\eta = \frac{n_N}{s}\epsilon_{CPV}$
- We will assume that strength of the couplings in two sector are the same, use SM baryon asymmetry to set their strength and then predict the abundance of aDM as:

$$\hat{r} = \Omega_{aDM}/\Omega_{DM} = \Omega_b \frac{m_{p,B}}{m_{p,A}} \frac{\eta_B}{\eta_A}$$

Generation Universal Couplings

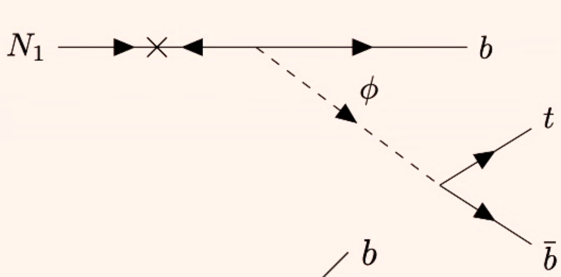
- ϕ couples to all quarks with the same interaction strengths.
- Very constrained by proton decay bounds and requirement that decays to quarks are suppressed in comparison to weak decays of N
- Requires sub-TeV colored scalar (excluded by LHC except band 520-580 GeV)

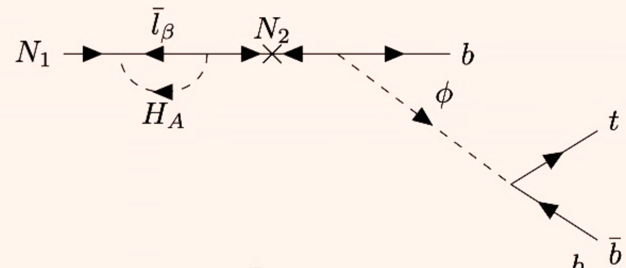


Top-philic Couplings

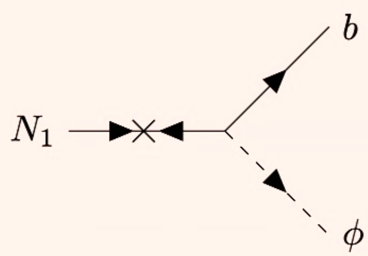
- $\mathscr{L}_{\phi,\text{int}}^{Y_\phi=-1/3} = -\lambda\phi_A b^c N - \lambda'\phi_A^\dagger \bar{t} b^c + \lambda''\phi_A^\dagger QQ + (A \to B)\,.$
- Relaxes proton bounds, allows ϕ to be heavier ~ 1 TeV. Requires modest hierarchy $\lambda'' < \lambda'$, possible with identifying ϕ with **exotic** squark.
- Need to $M_{N_1} - M_{N_2}$ to be similar in size to the radiative correction ~ $\Gamma_{N_2}/2$

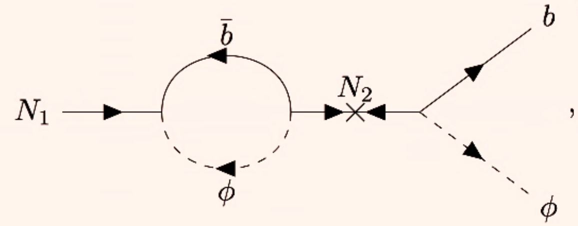
A sector



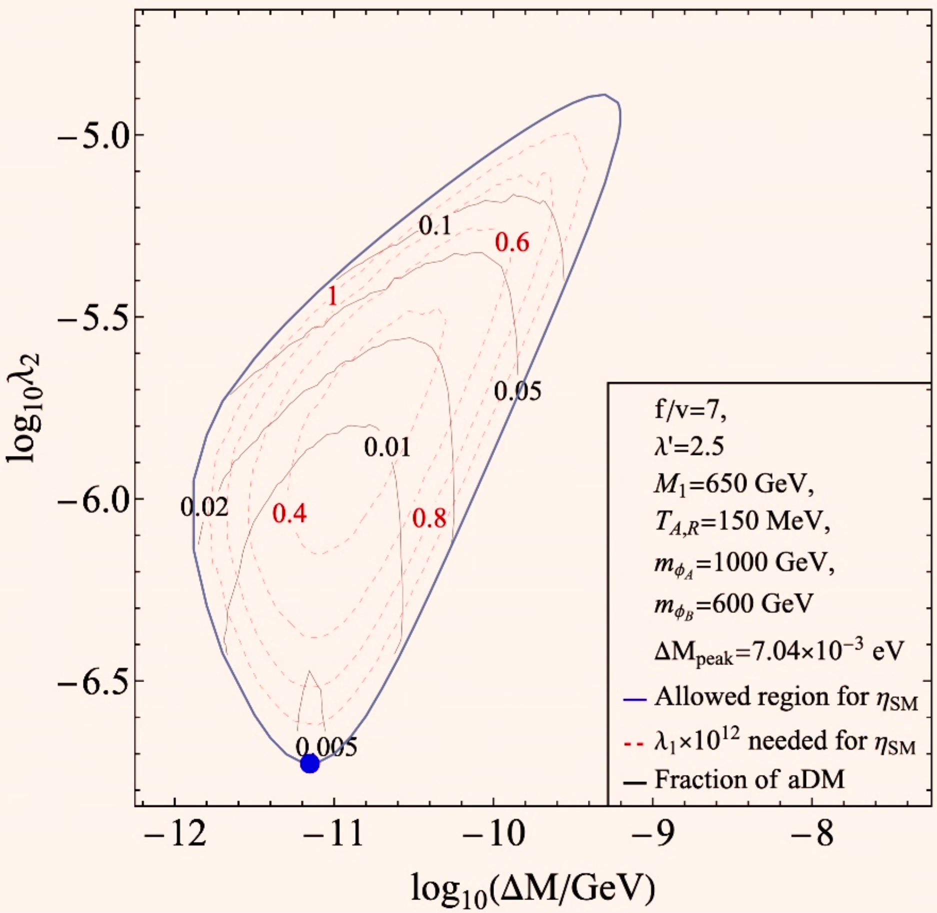


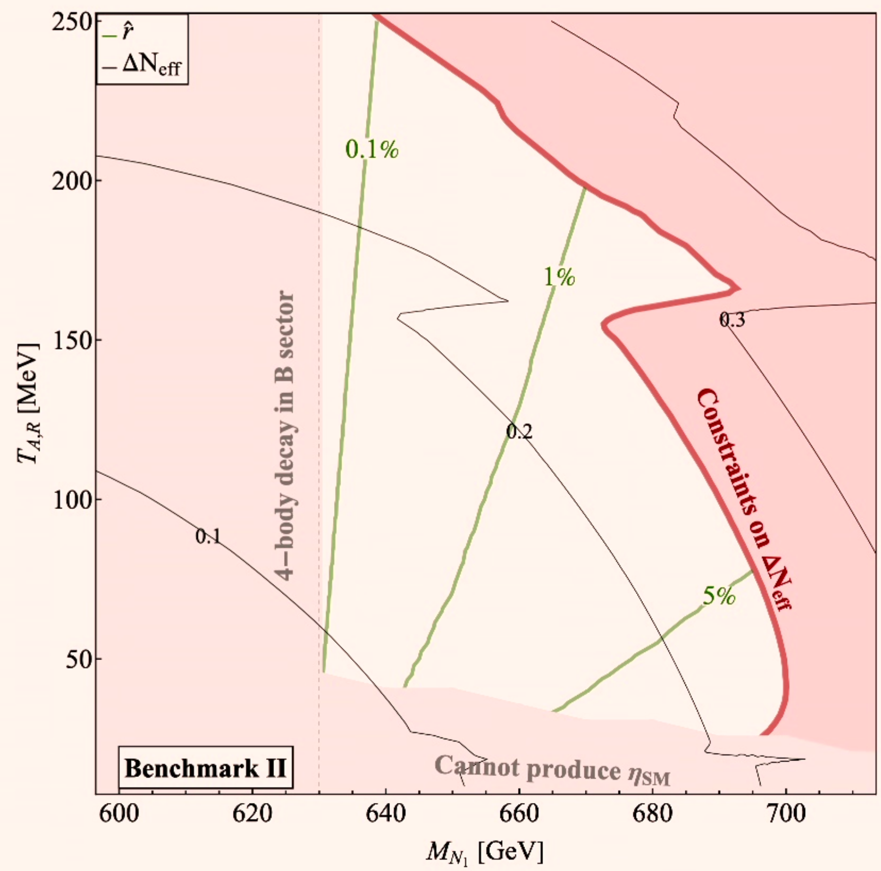
B sector





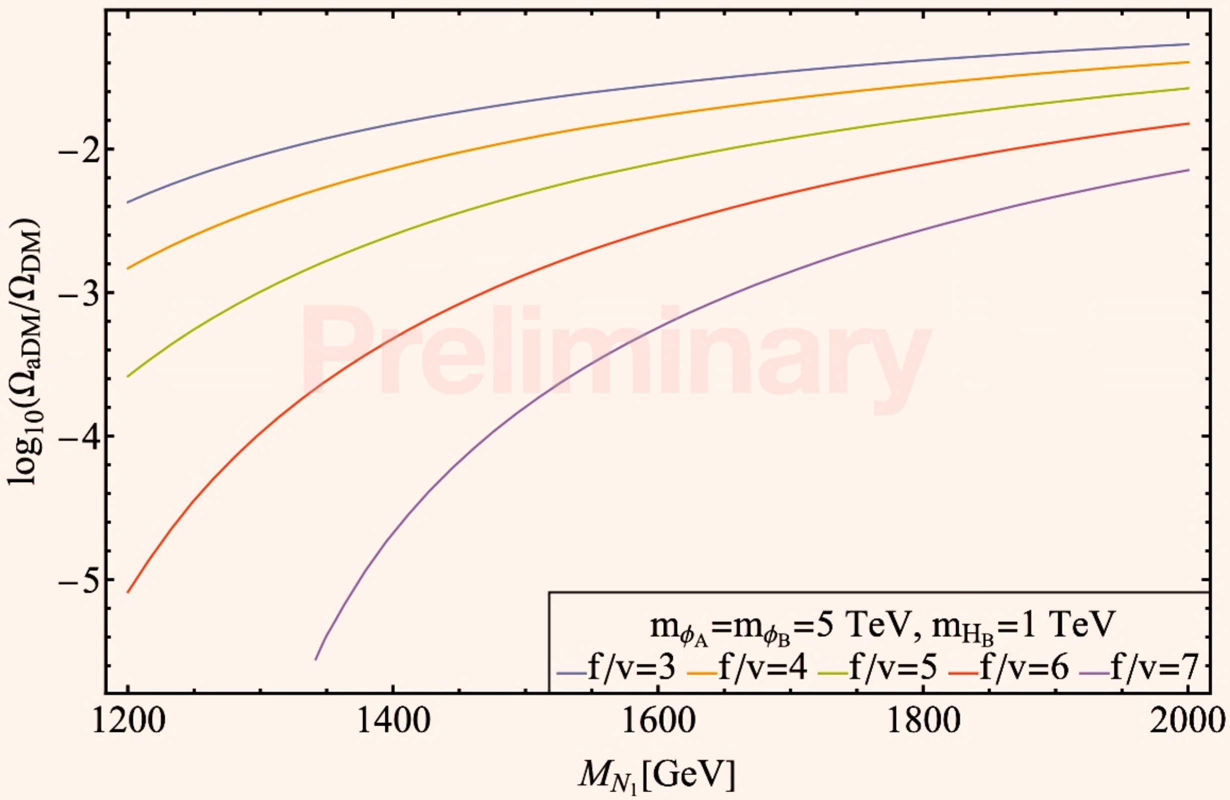
Top-Philic Couplings





Outlook

- Working on the scenario in which both reheating and baryogenesis is done by N_1 decays to quarks. This allows to even further increase mass of ϕ.



Conclusion

- We presented extension of MTH with asymmetric reheating to include baryogenesis.
- We have found a desirable scenario where we produce wide range of atomic Dark Matter fractions, especially ones in range $\hat{r} \sim 0.1 - 20\,\%$. **Motivates aDM searches in cosmology and astrophysics!**
- It might need to re-introduce colored scalars at collider range (possible resolved by a follow-up project). Is this picture general?
- Found a model independent conclusion that for models with asymmetric reheating, for low reheating temperatures, all of the aDM is twin helium

Thank you for listening! Questions? :)