First-order phase transitions and baryogenesis in Twin Higgs model

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Based on:
MB, I. Nałęcz **JHEP 02 (2023) 185**
MB, K. Harigaya, I. Nałęcz, to appear

See also: MB, K. Harigaya
JHEP 1706 (2017) 065; JHEP 1710 (2017) 109
PRL 120 (2018) 211803
MB, K. Harigaya, G. Grilli di Cortona
PRL 124 (2020) 12180
JHEP 10 (2022) 057 (+ M. Łukawski)

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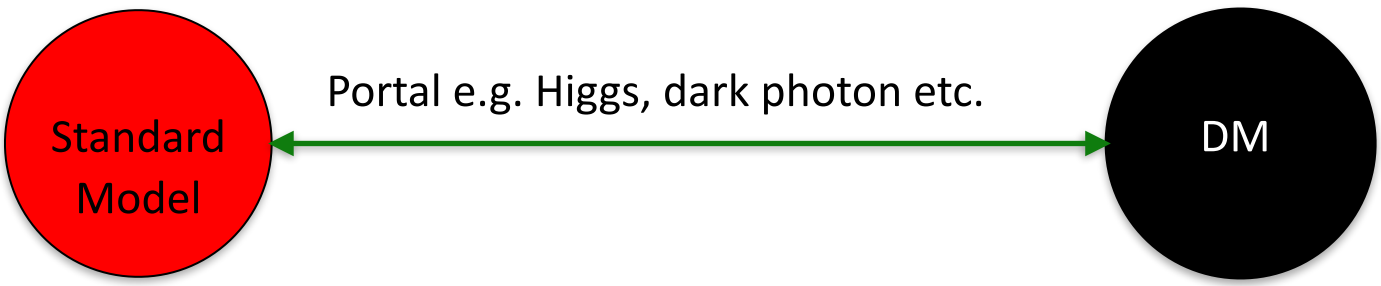
Outline

1. Motivation
2. Twin Higgs mechanism and its SUSY UV completion
3. New dark matter candidates
4. Phase transitions and EW symmetry non-restoration in TH model and GW predictions
5. Implications for baryogenesis (axiogenesis and darkogenesis)
6. Conclusions

Simple Dark Sector

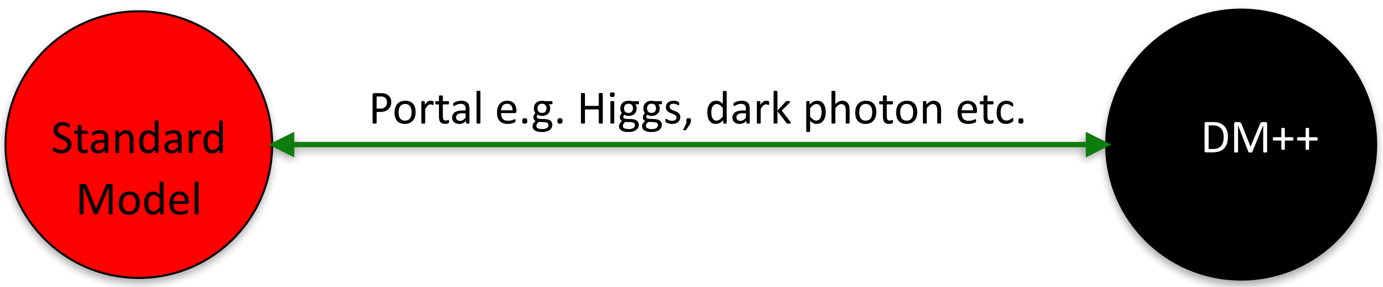
- The simplest dark sector consists of only DM particle



- DM not charged under the SM gauge group and interacts with the SM sector only via portal which relaxes exp. constraints on DM from colliders, direct detection etc.

Dark Sector to rule them all

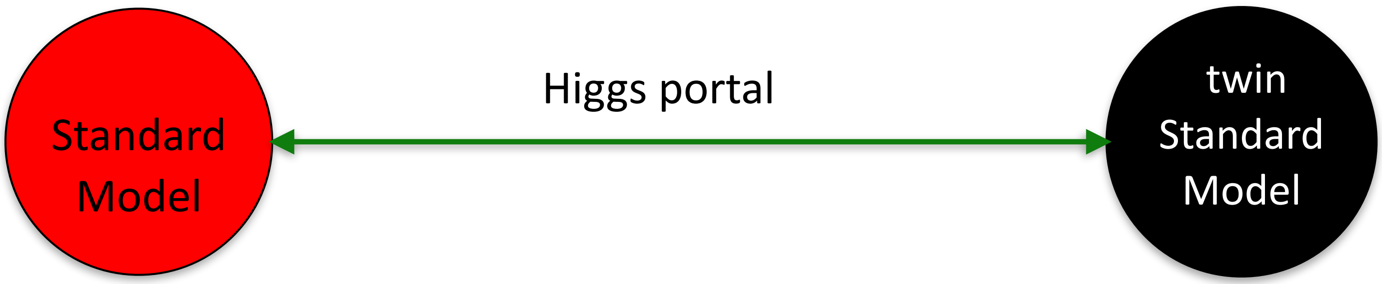
- Dark sector may offer more than just DM particle



- Many problems of the SM may be solved in the Dark Sector at once

Twin Higgs to rule them all

- Dark sector may offer more than just DM particle



- Twin Higgs (complete model of Dark Sector):

✓ solves the hierarchy problem of the SM

✓ naturally provides dark matter candidates

✓ generates baryon asymmetry through first-order phase transition ?

This talk

Twin Higgs model in a nutshell

Chacko, Goh, Harnik '05

- The Higgs is a pNGB of a global SU(4) symmetry
- SU(4) enforced by Z_2 symmetry exchanging two copies of the SM

SM $\rightarrow H \overset{\mathbb{Z}_2}{\longleftrightarrow} H' \leftarrow$ mirror

$$V = \lambda(|H'|^2 + |H|^2)^2 - m^2(|H'|^2 + |H|^2) + \Delta\lambda(|H'|^4 + |H|^4) + \Delta m^2 |H^2|$$

SU(4) symmetric

SU(4) spontaneously broken to SU(3) ⟶ 7 NGB :
6 eaten + massless Higgs

SU(4) breaking

↓

the Higgs is pNGB maximal mixture of H and H'

$SU(4)$ & $\mathbb{Z}_2$ breaking

↓

the Higgs with SM-like couplings

Scale of SU(4) breaking: $f^2 \equiv v^2 + v'^2$ $\quad \langle H \rangle \equiv v \quad \langle H' \rangle \equiv v'$ $\quad \frac{v'}{v} \gtrsim 3$

Fine-tuning in Twin Higgs models

- Maximal gain in fine-tuning depends on the size of λ:

$$\frac{2\lambda}{\lambda_{\rm SM}} \qquad \lambda_{\rm SM} \approx 0.13$$

- TH model solves only the little hierarchy problem so must be UV completed e.g. by SUSY to solve the big hierarchy problem of the SM

- λ depends on particular SUSY UV completion of TH models

Falkowski, Pokorski, Schmaltz ’06 Chang, Hall, Weiner ’06
Craig, Howe ’13 Katz et al. ’16 MB, Harigaya ‘17

The Higgs mass in SUSY Twin Higgs

- In SUSY Twin Higgs SU(4) is broken by the EW gauge interaction

$$V_D = \frac{g^2+g'^2}{8}\left[(|H_u|^2-|H_d|^2)^2+(|H'_u|^2-|H'_d|^2)^2\right] \rightarrow \frac{g^2+g'^2}{8}\cos^2(2\beta) \equiv \Delta\lambda_{\rm SUSY} \approx 0.07\cos^2(2\beta)$$

- The tree-level Higgs mass is given by

$$\left(m_h^2\right)_{\rm tree} \approx 2 M_Z^2 \cos^2(2\beta)\left(1-\frac{v^2}{f^2}\right)+\mathcal{O}(\Delta\lambda/\lambda)$$

- The Higgs mass enhanced by a factor of $\sqrt{2}$ (after Z_2 breaking which is needed anyway) as compared to MSSM.

- $m_h \approx 125\ \mathrm{GeV}$ obtained at tree level in the limit of large $\tan\beta$!

SUSY U(1) D-term Twin Higgs

MB, Harigaya '17

- SU(4) invariant quartic term generated by a D-term potential of a new $U(1)_X$ gauge symmetry

$$V_{U(1)_X} = \frac{g_X^2}{8}\left(|H_u|^2 - |H_d|^2 + |H'_u|^2 - |H'_d|^2\right)^2 \left(1-\epsilon^2\right)$$

$$\epsilon^2 = \frac{m_X^2}{2m_S^2 + m_X^2}$$

$$0 < \epsilon < 1$$

$$\epsilon \ll 1 \text{ preferred}$$

$$\lambda = g_X^2 \frac{\cos^2(2\beta)}{8}\left(1-\epsilon^2\right) \equiv \lambda_D$$

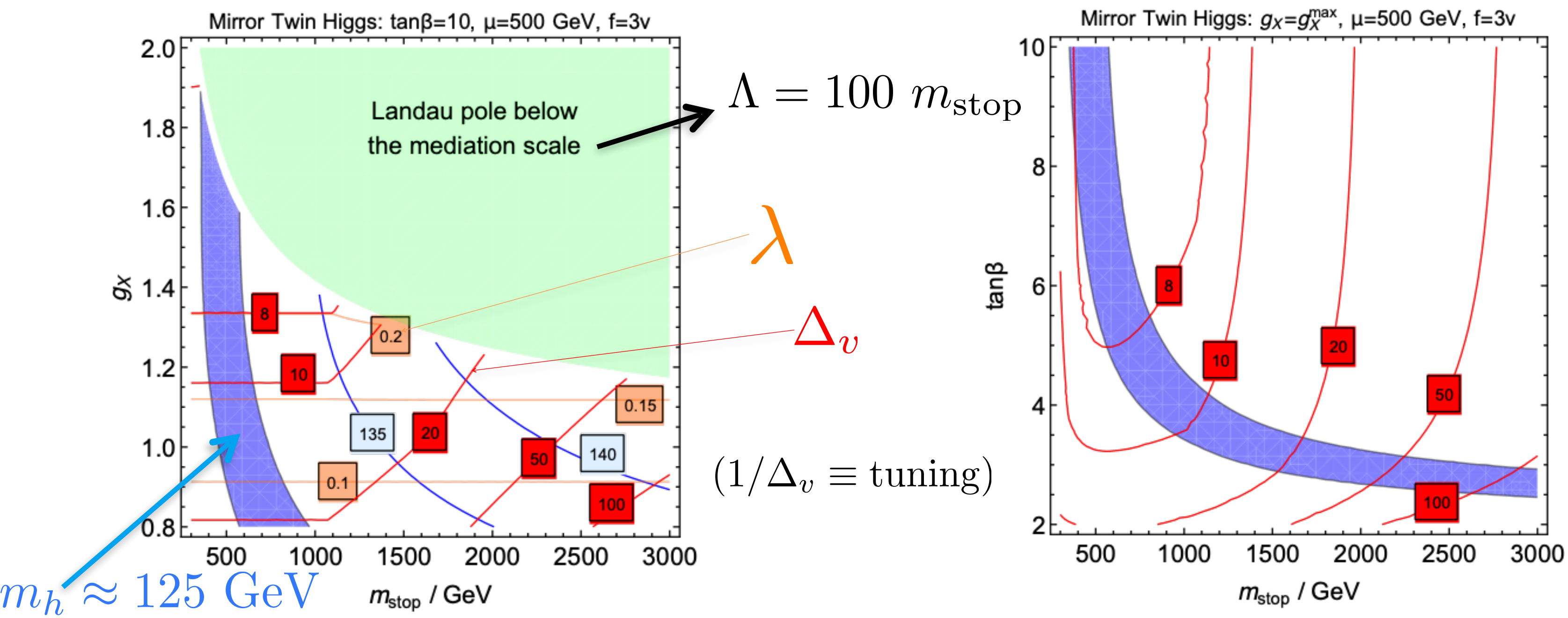
m_X- new gauge boson mass

m_S- soft mass for $U(1)_X$ breaking fields

- Large g_X preferred

SUSY U(1) D-term Mirror Twin Higgs

- All SM fermions have their mirror counterparts



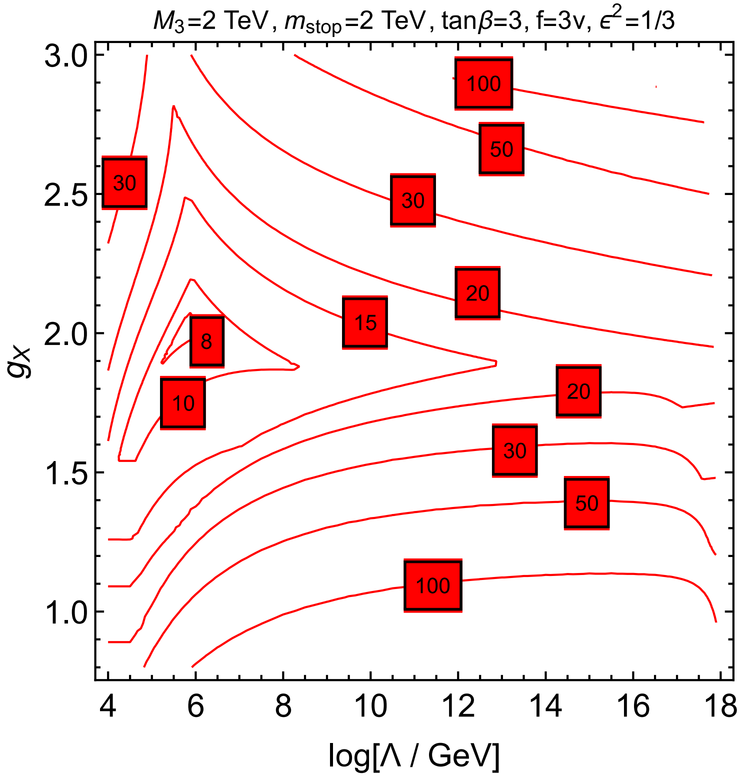
- Correct Higgs mass can be obtained for 1 TeV stops (without stop mixing) with better than 10% tuning

Asymptotically Free SUSY Twin Higgs

Landau pole scale is generically low – can be much higher if the new interaction is non-abelian and only some of the fields are charged under it.

The new interaction can be made asymptotically free: MB, Harigaya '18

- Twin Higgs mechanism works perturbatively even for mediation around the Planck scale
- Tuning better than 5% (for 2 TeV stops and gluino) even for gravity mediation of SUSY breaking



Cosmological implications

SUSY TH predicts new BSM particles which are likely beyond the LHC but…

Cosmological implications

TH predicts new BSM particles which are likely beyond the LHC but…

TH models have several cosmological signatures:

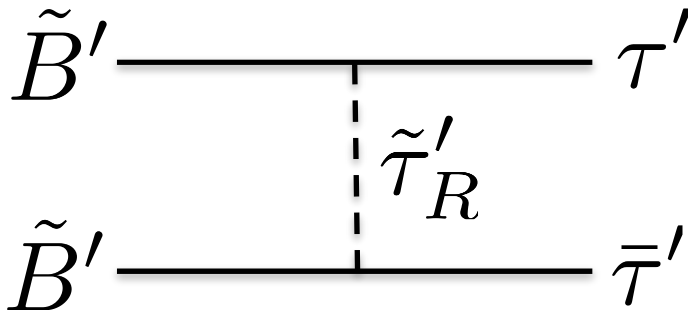
- New dark matter candidates in the twin sector:
  twin fermions, twin baryon, twin neutralino, twin stau…

- Extended Higgs sector may allow for first-order phase transitions
  (Gravitational wave signal? Baryogenesis?)

- Twin photon and twin fermions contribute to ΔN_{eff} (dark radiation) - generically too much to be compatible with Planck satellite data but solutions to this problem exist e.g. Z_2 breaking in light Yukawa couplings reduce ΔN_{eff} below Planck sensitivity but within reach of near-future CMB experiments

  Barbieri, Hall, Harigaya '16, '17

Twin supersymmetric dark matter

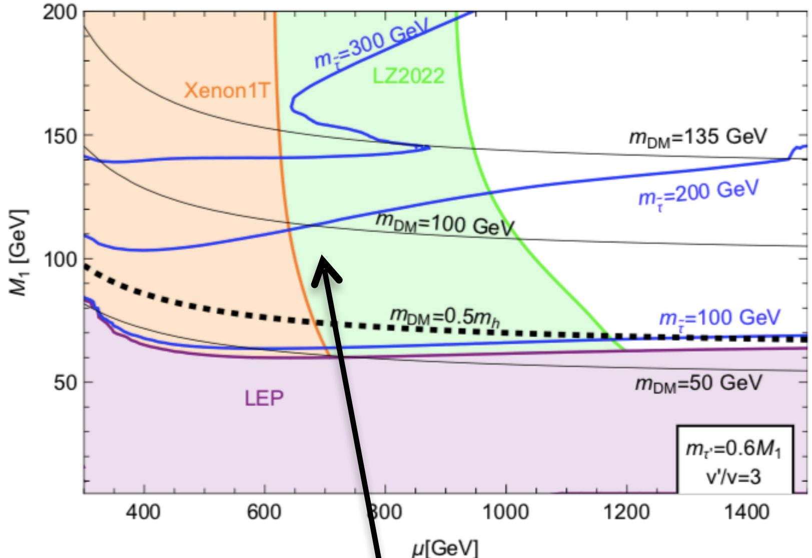


- For many years neutralino has been a great candidate for dark matter in the MSSM but is now essentially excluded by direct detection (DD) experiments (LUX, Xenon1T, LZ)
- Twin neutralino has all the best features of MSSM neutralino but naturally suppressed DD cross-section

Twin Neutralino Dark Matter

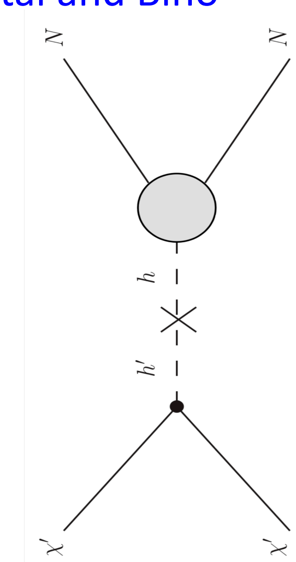
MB, Grilli di Cortona, Harigaya, Łukawski '19 '23

$\Omega_{\rm LSP} h^2 \approx 0.12$



Relic abundance of twin neutralinos is easily in agreement with Planck data for light enough staus

Naturalness of the EW scale implies non-zero DM coupling to nucleons via Higgs portal and Bino-Higgsino mixing



First LZ results probe only part of natural parameter space

LZ will probe all natural values of μ up to 3 TeV

Spin-independent DM scattering on nucleons x-sec

(Spin-dependent DM scattering x-sec strongly suppressed)

Cosmological implications

TH predicts new BSM particles which are likely beyond the LHC but…

TH models have several cosmological signatures:

Rest of the talk

- New dark matter candidates in the twin sector: twin fermions, twin baryon, twin neutralino…
- Extended Higgs sector may allow for first-order phase transitions (Gravitational wave signal? Baryogenesis?)
- Twin photon and twin fermions contribute to ΔN_{eff} (dark radiation) - generically too much to be compatible with Planck satellite data but solutions to this problem exist e.g. Z_2 breaking in light Yukawa couplings reduce ΔN_{eff} below Planck sensitivity but within reach of near-future CMB experiments

Barbieri, Hall, Harigaya '16, '17

Phase transitions in TH models

If the phase transition associated with the breakdown of the ElectroWeak symmetry in the Early Universe was first-order it could lead to:

- Electroweak baryogenesis
- (Observable?) gravitational waves

In the Standard Model the EW phase transition is smooth (would be first-order only if the Higgs mass was below 70 GeV)

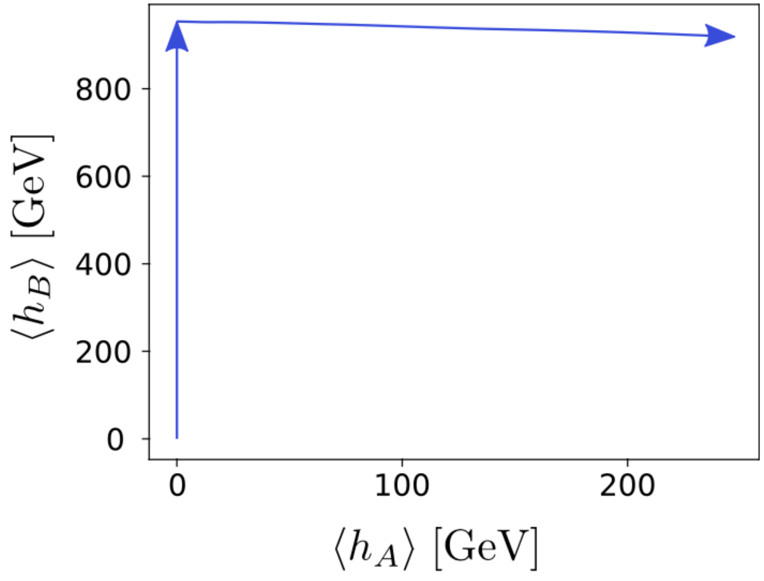
The structure of the Higgs potential in TH models is modified:

Could first-order phase transition be present in TH models?

Phase transitions in TH models

The first study of phase transitions (PT) in TH models found only smooth PT

Fujikura et al. '18



$H \equiv h_A$

$H' \equiv h_B$

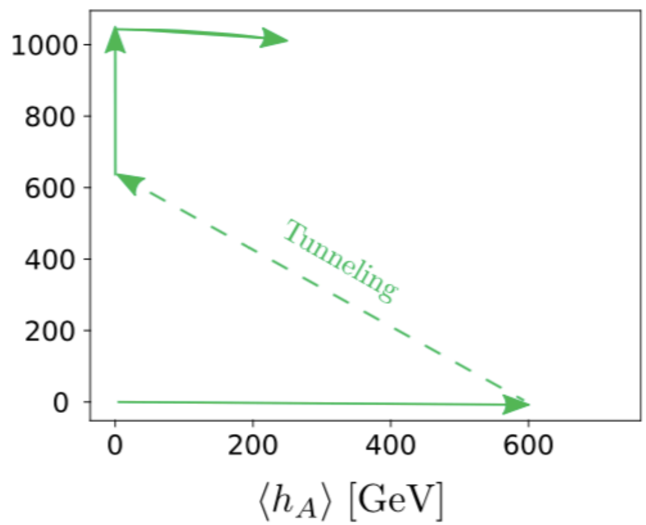
EW symmetry is broken after twin EW symmetry

First-order phase transitions in TH models

MB, Nałęcz ’22

First-order phase transition can be present in TH models if the effects of Z_2 breaking between the SM and twin sector are properly taken into account

PT is 1st order if the SM Higgs gets a vev before the twin Higgs which requires additional source of Z_2 breaking



- It is crucial to take into account two-field dynamics
- EW symmetry is broken before twin EW symmetry at temperature $T \sim f \sim 1$ TeV

First-order phase transitions in TH models

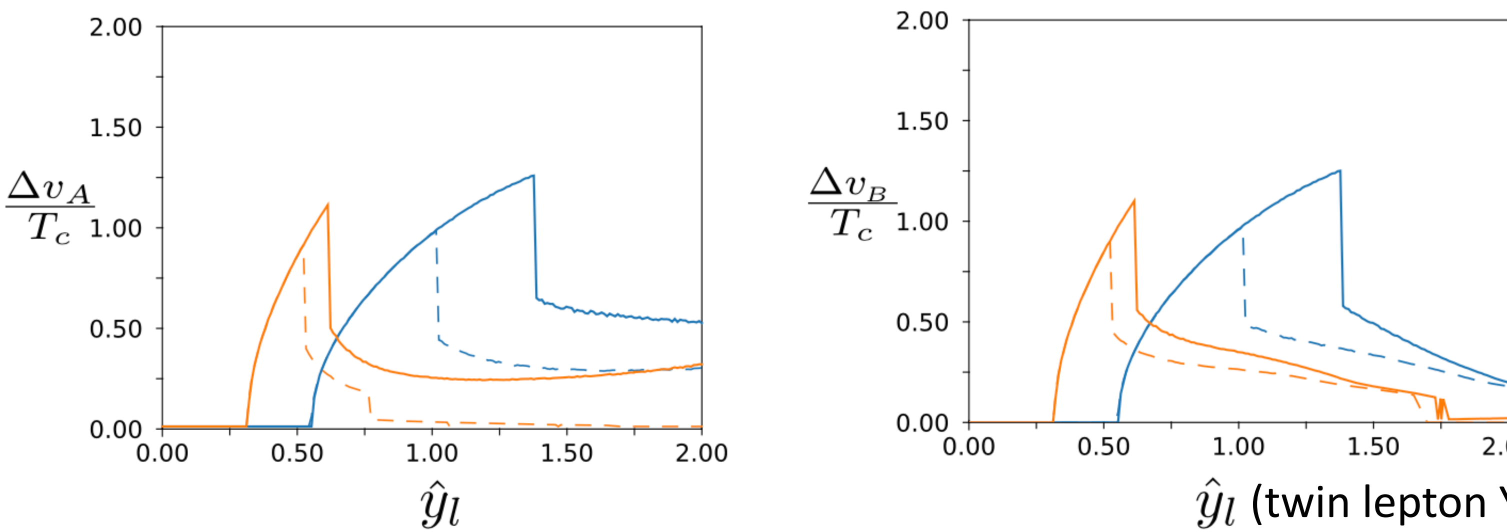
MB, Nałęcz ’22

Thermally corrected masses at the origin of field space for $T \sim f$:

$$m_{h_A}^2(T) \approx \zeta_{SM} T^2 - \lambda f^2 + \Delta m^2 \quad m_{h_B}^2(T) \approx \zeta_{TS} T^2 - \lambda f^2$$

For $\zeta_{TS} \gg \zeta_{SM}$ EW symmetry broken before twin EW symmetry

e.g. Z_2 breaking in Yukawa couplings: $\zeta_{TS} = \frac{\sum_i \hat{n}_i \hat{y}_i^2}{12}$



$\hat{y}_l$ (twin lepton Yukawa)

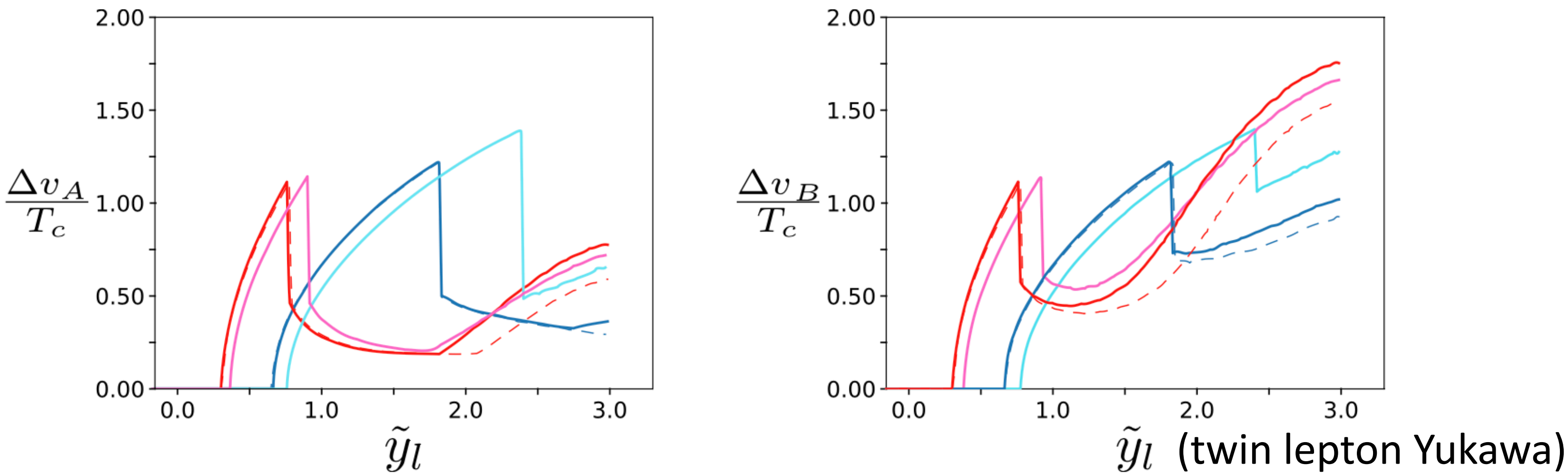
First-order phase transitions in SUSY TH

MB, Nałęcz ’22

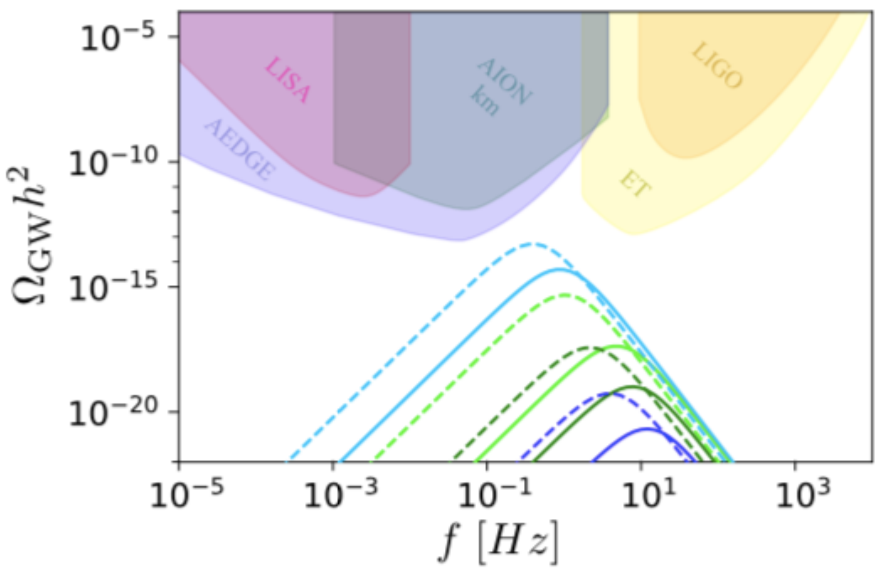
TH models can be UV completed by supersymmetry

Falkowski, Pokorski, Schmaltz ’06 Chang, Hall, Weiner ’06
Craig, Howe ’13 Katz et al. ’16 MB, Harigaya ‘17

Introduction of light twin sleptons mitigates tuning introduced by large twin lepton Yukawa couplings and makes FOPT even stronger



GW spectra from first-order phase transitions in SUSY TH models



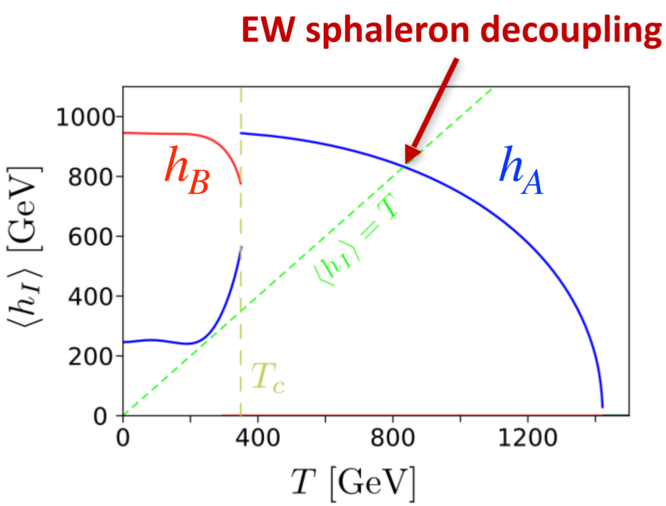
- The strongest GW signal is obtained in SUSY TH with light sleptons but is not large enough to be detected in the near future.

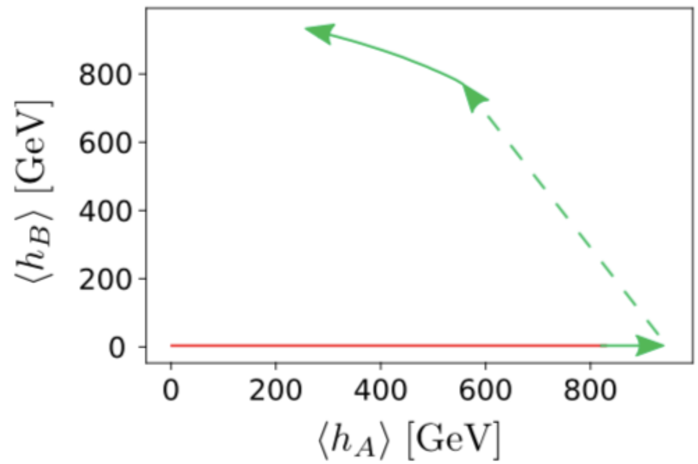
EW Symmetry Non-restoration in (SUSY) TH

MB, Harigaya, Nałęcz, to appear

- twin fermions with large Yukawa couplings lead to EW symmetry non-restoration (SNR) for $\sum_i \hat{n}_i \hat{y}_i^2 \gtrsim 5$ Matzedonsky '21

- In SUSY TH adding light twin sleptons help to achieve SNR (for smaller twin fermion Yukawas) and allow for SNR and FOPT simultaneously

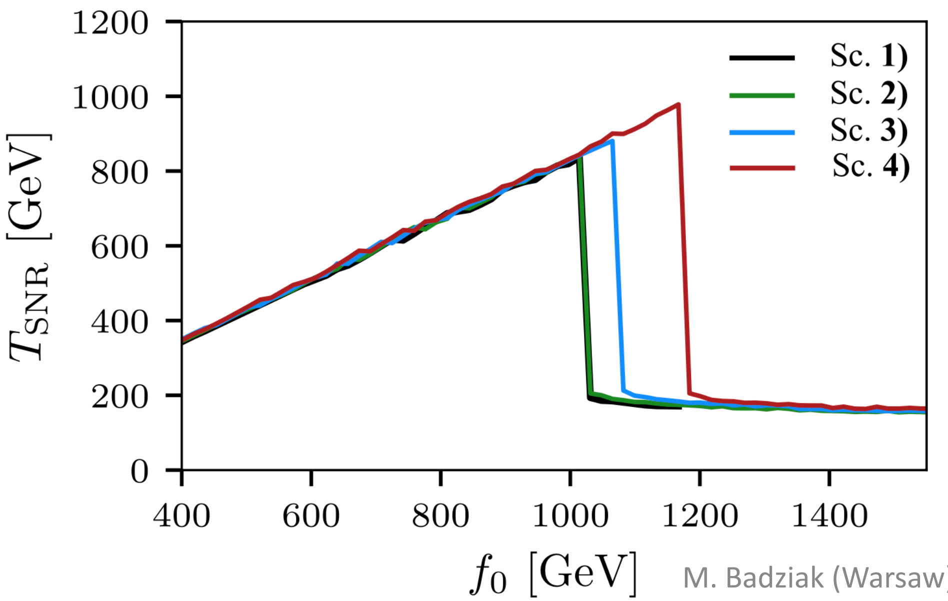




EW Symmetry Breaking Temperature

MB, Harigaya, Nałęcz, to appear

- EWSB temperature T_{SNR} is correlated with the scale of SU(4) breaking but cannot be arbitrary large
- lighter twin scalars and larger twin Yukawas lead to larger T_{SNR} (but the latter are bounded from above by naturalness)



T_{SNR} up to 1 TeV possible

Implications for axiogenesis

MB, Harigaya, Nałęcz, to appear

- Higher T_{SNR} allows to realise minimal axiogenesis scenario in which baryon asymmetry and dark matter abundance is explained by the QCD axion with non-zero initial velocity. Co, Harigaya '19
- Very predictive scenario:

$$\frac{\Omega_{\rm DM,a}h^2}{\Omega_{\rm b}h^2} \simeq 360 \left(\frac{f_a}{10^8\ {\rm GeV}}\right)\left(\frac{130\ {\rm GeV}}{T_{\rm sph}}\right)^2\left(\frac{0.1}{c_B}\right)c_a.$$

- $T_{sph} = T_{SNR}$ is temperature of EW sphaleron decoupling
- In the SM $T_{sph} \approx 130\ {\rm GeV}$ and DM is overproduced unless axion is astrophobic (avoids astro constraints which typically exclude $f_a \lesssim 10^8\ {\rm GeV}$) see MB, Harigaya '23
- For $T_{SNR} \sim 1\ {\rm TeV}$ standard axion models allow for successful axiogenesis

Darkogenesis in TH models

MB, Harigaya, Nałęcz, in progress

- Twin EW sphalerons decouple after FOPT:

$$\frac{v_B}{T} > 1$$

- This fulfills a necessary condition for generation of twin baryon asymmetry paving the way towards darkogenesis

Shelton, Zurek '10

- To generate the SM baryon asymmetry two more ingredients needed:

1. CP violation in the twin sector e.g. from CP phases of twin soft SUSY breaking terms; EDM suppressed due to higher temperature of FOPT
2. Transfer of B' asymmetry to the SM sector e.g. neutron portal

$$\frac{1}{M^5}\bar{u}_R\bar{d}_R\bar{d}_R\hat{u}_L\hat{d}_L\hat{d}_L$$

Conclusions

- Twin Higgs is a complete model of Dark Sector which naturally explains the EW scale in spite of absence of top partners at the LHC
- Twin Higgs provides DM candidates which naturally escape detection
- Z_2 breaking in Higgs thermal masses leads to first-order phase transition at $T \sim f \sim 1 \text{ TeV}$ which may lead to darkogenesis
- twin fermions with large Yukawas and light twin sfermions in SUSY TH allow for EW symmetry non-restoration up to $T \sim f \sim 1 \text{ TeV}$ simultaneously with first-order phase transition
- TH model is a well motivated framework for BSM and it is a great adventure to explore its signatures (collider, cosmo, astro…)