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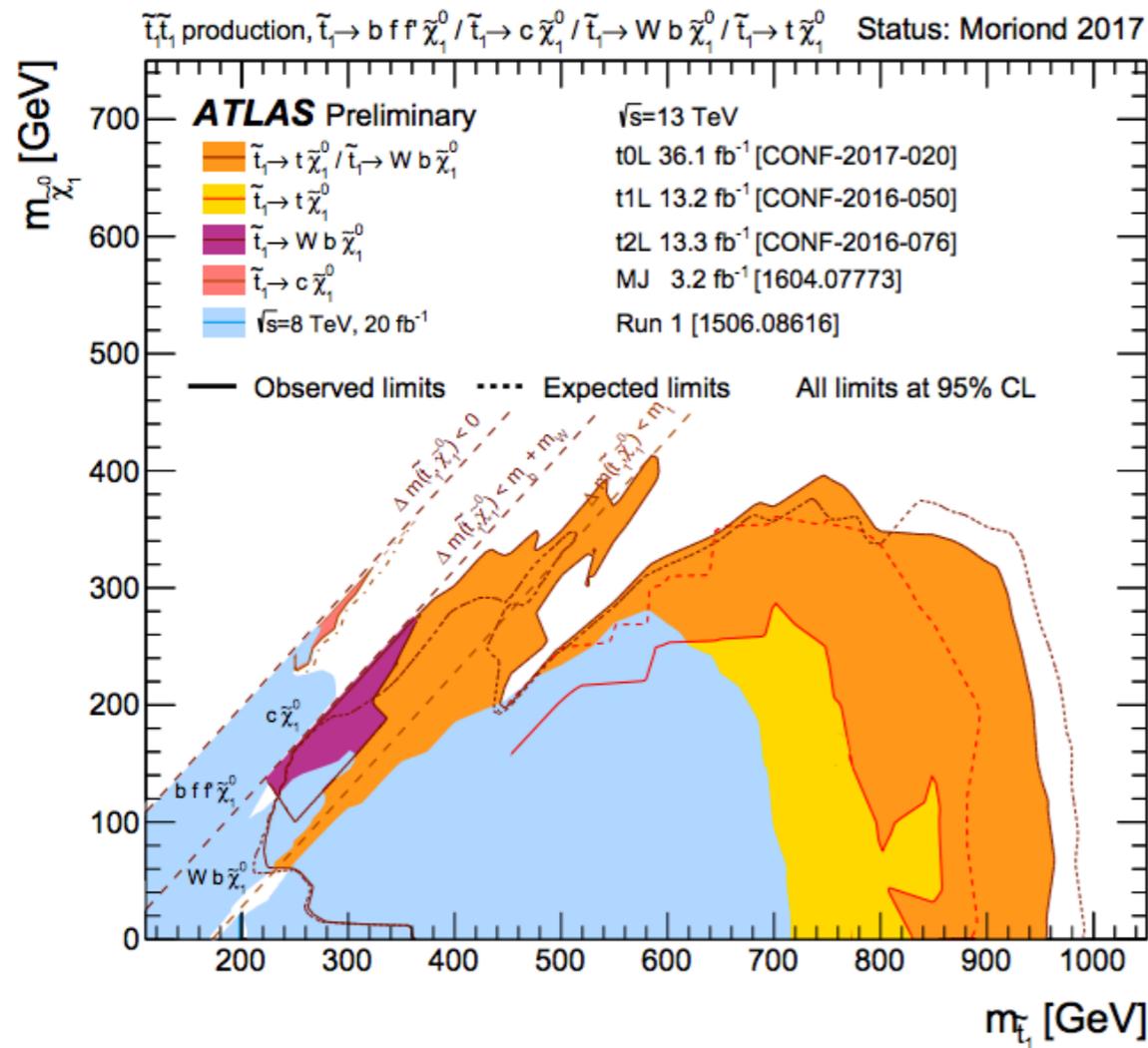
VIABLE TWIN COSMOLOGY VIA NEUTRINO MIXING

Csaba Csaki, Eric Kuflik, Sal Lombardo

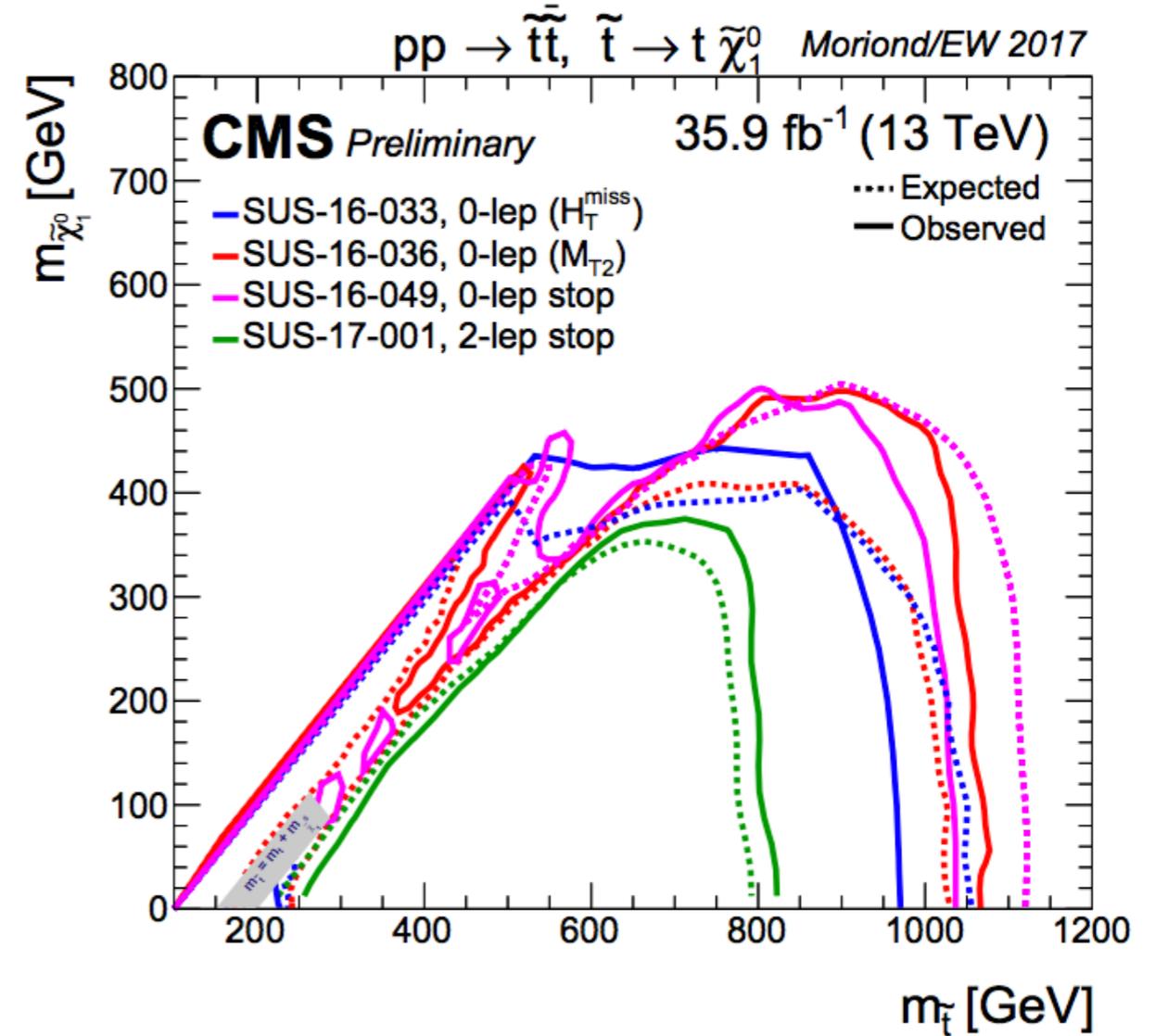
ArXiv: 1703.06884

NO SIGN OF TOP PARTNERS FROM THE LHC

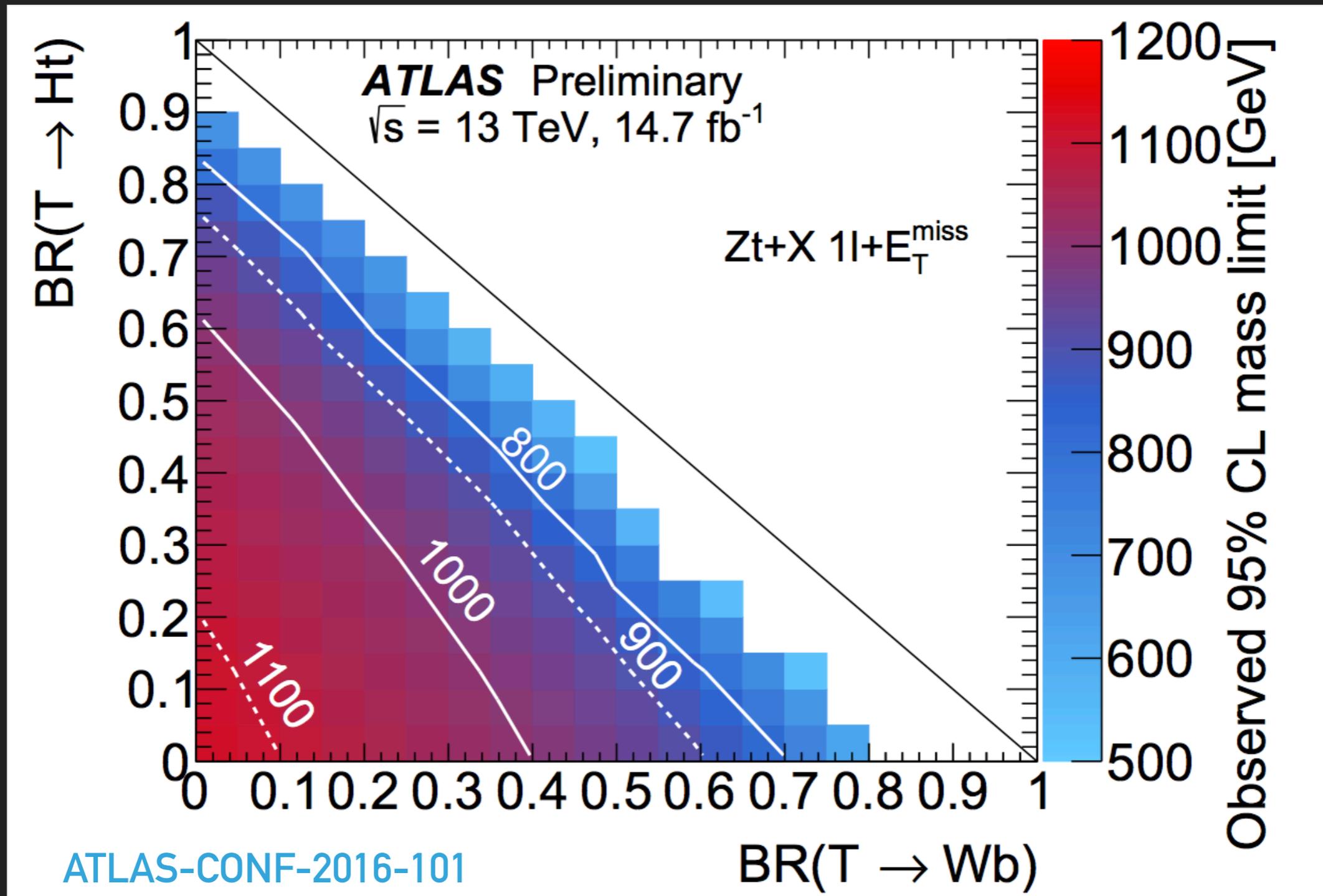
ATLAS



CMS



NO SIGN OF TOP PARTNERS FROM THE LHC



NEUTRAL NATURALNESS

- ▶ A radical approach to the little hierarchy problem is **uncolored** top partners
 - ▶ can arise from a **discrete** symmetry protecting the Higgs mass
- ▶ **Twin Higgs** is the most famous example
 - ▶ SM gauge group is doubled with mirror Z_2 symmetry relating the two sectors
- ▶ Other examples: Folded SUSY, Quirky Little Higgs, Orbifold Higgs...

TWIN HIGGS

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

- ▶ $SO(8)$ vector $H \subset SU(2)_L \times SU(2)_R \times SU(2)_{L^m} \times SU(2)_{R^m}$

$$V = -m^2 |H|^2 + \lambda |H|^4$$

- ▶ H acquires a vev, breaking $SO(8) \rightarrow SO(7)$

- ▶ 7 goldstones

- ▶ If $g_A = g_B = g$, leading quadratic corrections are accidentally $SO(8)$ invariant ($\propto |H|^2$)

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

$$\Delta V = \frac{9g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9g_B^2 \Lambda^2}{64\pi^2} H_B^\dagger H_B$$

DARK RADIATION

- ▶ dark radiation parametrized by N_{eff} $\rho_r \equiv \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right)$
- ▶ Planck: $N_{\text{eff}} = 3.15 \pm 0.23$
- ▶ mirror twin ($T' = T, \nu = f/\sqrt{2}$): $\Delta N_{\text{eff}} = 3 + 4.4 = 7.4$
- ▶ lift/remove light twin DOF
 - [Craig, Katz, Strassler, Sundrum \[1501.05310\]](#)
 - [Farina \[1506.03520\]](#)
 - [Barbieri, Hall, Harigaya \[1609.05589\]](#)
- ▶ reduce T' relative to T
 - ▶ SM re-heated by GeV right-handed neutrino

[Chacko, Craig, Fox, Harnik \[1611.07975\]](#)

GOAL

- ▶ lift twin neutrinos to be heavier than a few GeV to **reduce rel. DOF** at decoupling & BBN
- ▶ Break Z_2 by a large difference in seesaw scales for twin/SM neutrinos
 - ▶ $M \gg \Lambda \Rightarrow$ need **UV completion** to address Higgs mass corrections
- ▶ use resulting neutrino-twin neutrino scattering to **reduce T'**
- ▶ naturally realized in composite Twin Higgs with a composite twin RH neutrino
 - ▶ use neutrino **Z_2 breaking** to generate $v \ll f$

N_{EFF} REVISITED

- ▶ Allowing for $T' \neq T$

$$N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \frac{4}{7} (11/4)^{4/3} g'_{\star}$$

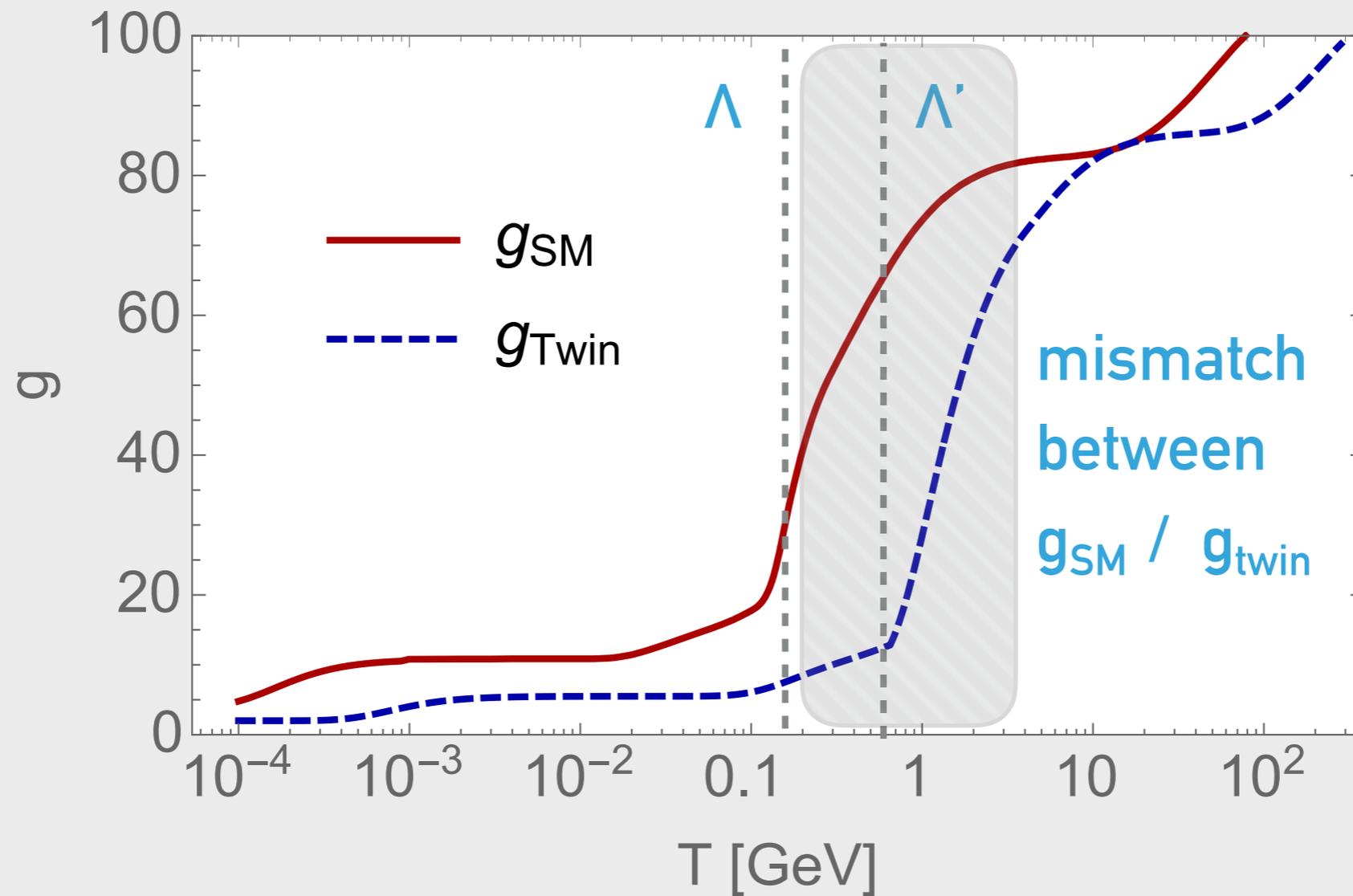
$$g'_{\star} = \sum_i s_i g_i \left(\frac{T'_i}{T} \right)^4$$

- ▶ T' determined from entropy conservation after decoupling

$$\frac{T'}{T} = \left(\frac{g_{\star s}(T) g'_{\star s}(T_d)}{g'_{\star s}(T) g_{\star s}(T_d)} \right)^{1/3} \quad \text{for } T < T_d$$

RELATIVISTIC DOF

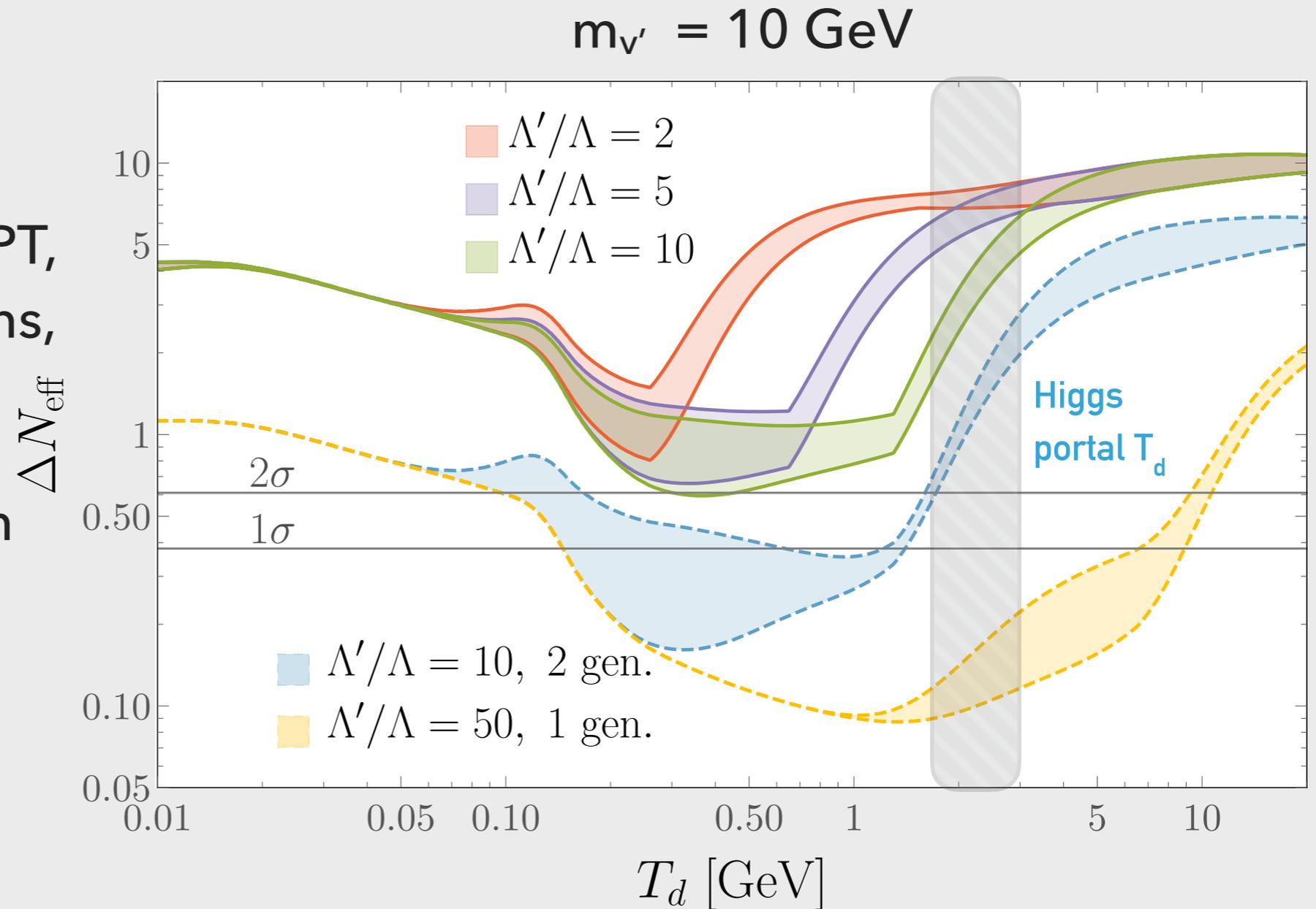
$$f/v = 5, \Lambda'/\Lambda = 5$$



$$N_{\text{eff}} \propto \left(\frac{g'_{\star}(T_d)}{g_{\star}(T_d)} \right)^{4/3}$$

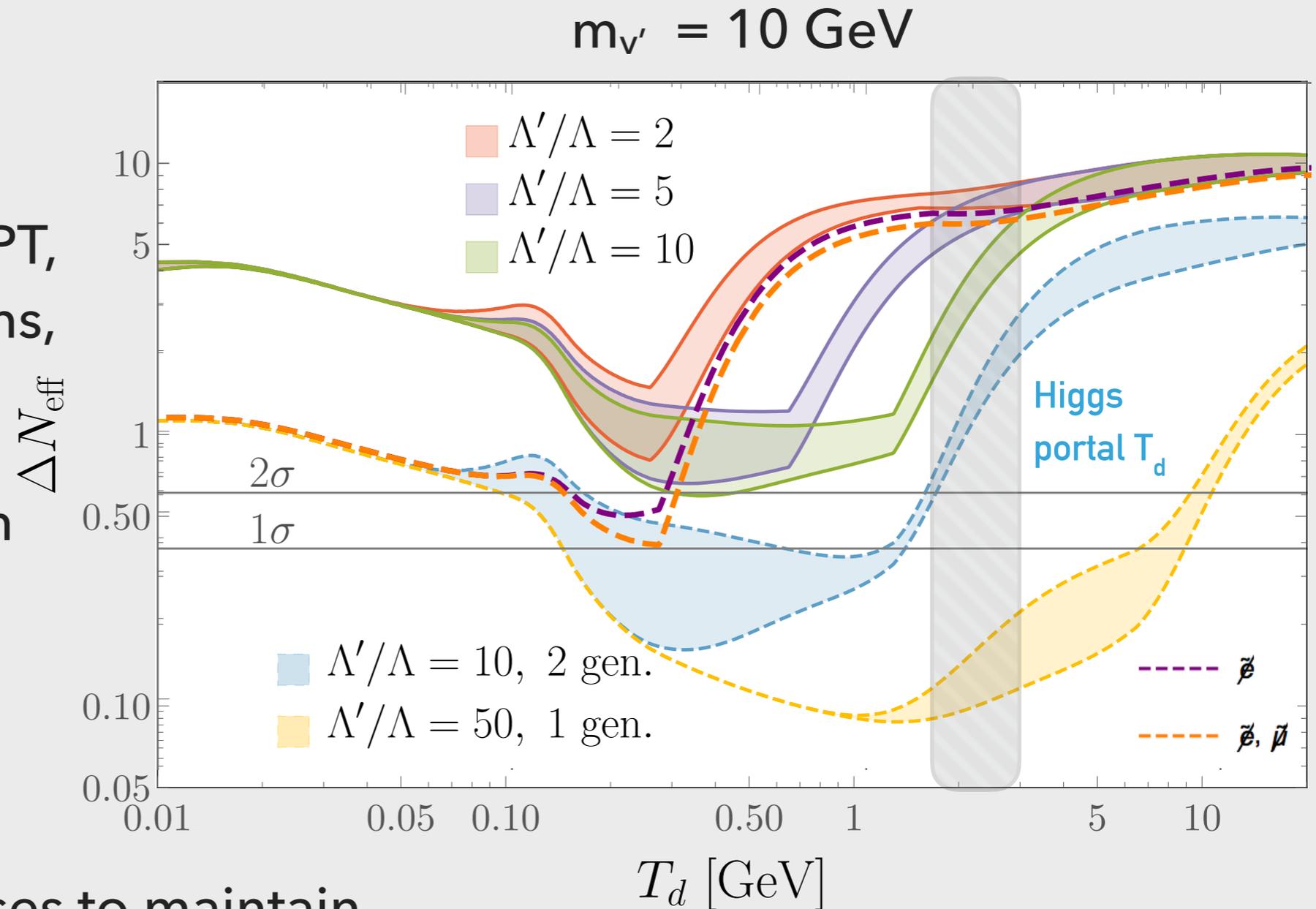
N_{EFF} REVISITED

- ▶ Assume heavy $m_{\nu'}$
- ▶ Includes twin QCD PT, pions, quarks/leptons, $U(1)^m$ gauged
- ▶ 3 gen. still in tension with bound



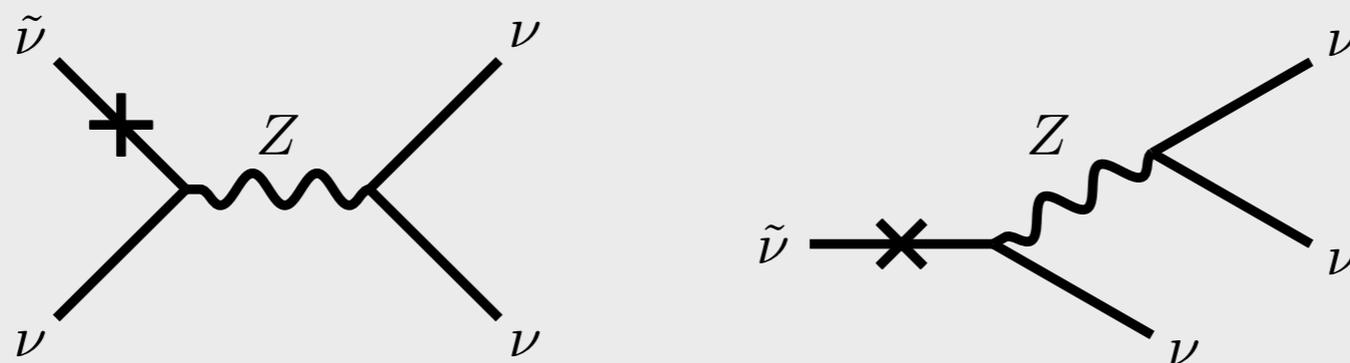
N_{EFF} REVISITED

- ▶ Assume heavy $m_{\nu'}$
- ▶ Includes twin QCD PT, pions, quarks/leptons, $U(1)^m$ gauged
- ▶ 3 gen. still in tension with bound
- ▶ optimal decoupling $0.2 < T_d < 1$ GeV
- ▶ require new processes to maintain thermal eq. below Λ'



NEUTRINO-TWIN NEUTRINO MIXING

- ▶ Need new processes to sustain equilibration down to $T < 1$ GeV
- ▶ Explanation of heavy neutrinos in the composite TH picture leads to "large" mixing



- ▶ Twin neutrino semi annihilation & decays freeze out later than the Higgs portal for sufficient mixing

DECOUPLING TEMPERATURE

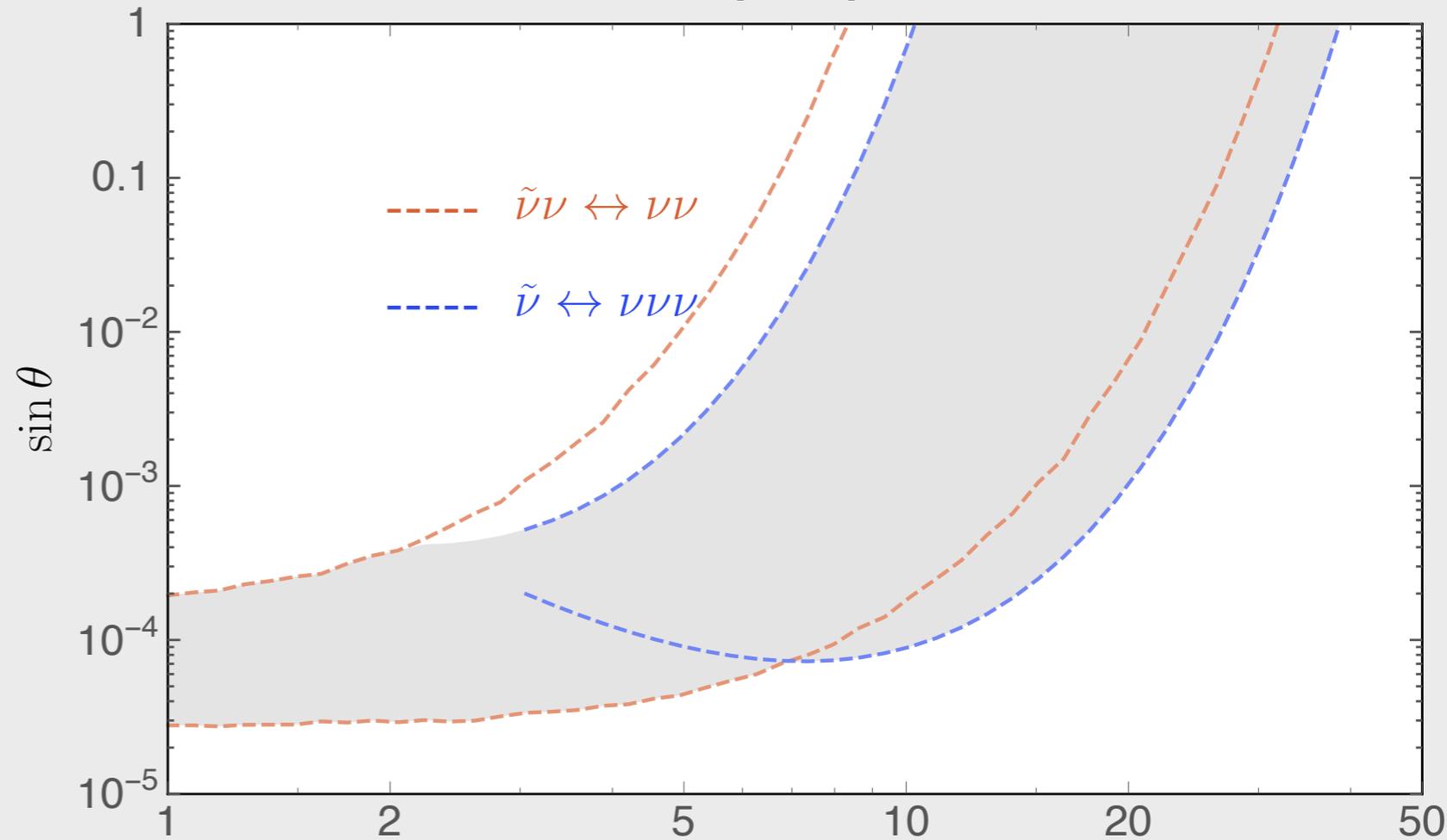
- ▶ decoupling occurs when energy transfer rate reaches Hubble rate

$$\Gamma^E(T_d) \simeq H(T_d)$$

$$T_d \in [0.5, 1] \text{ GeV}$$

- ▶ $m_{\tilde{\nu}} \sim 1\text{-}20 \text{ GeV}$

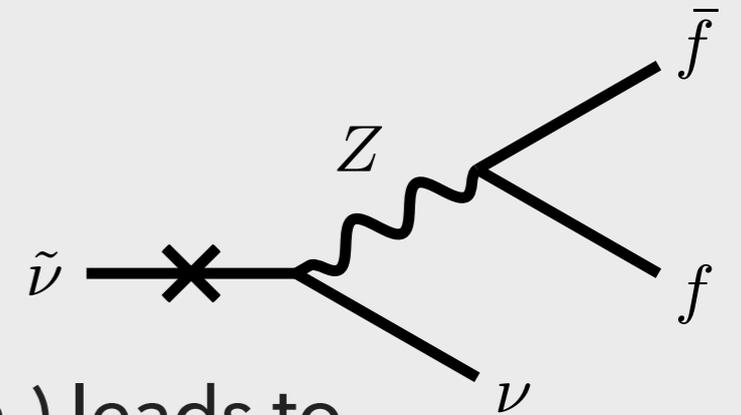
- ▶ $\theta \sim 10^{-3}\text{-}10^{-4}$



$$\frac{m_{\tilde{\nu}}}{T_d} \simeq 17.6 + \log \left(\frac{s_\theta}{10^{-3}} \right)^2 \left(\frac{m_{\tilde{\nu}}}{10 \text{ GeV}} \right)^3 \left(\frac{g_{\star s}}{69} \right)^{\frac{1}{2}} \left(\frac{m_{\tilde{\nu}}}{17.6} \right)^{\frac{9}{2}} \quad \text{inverse decays}$$

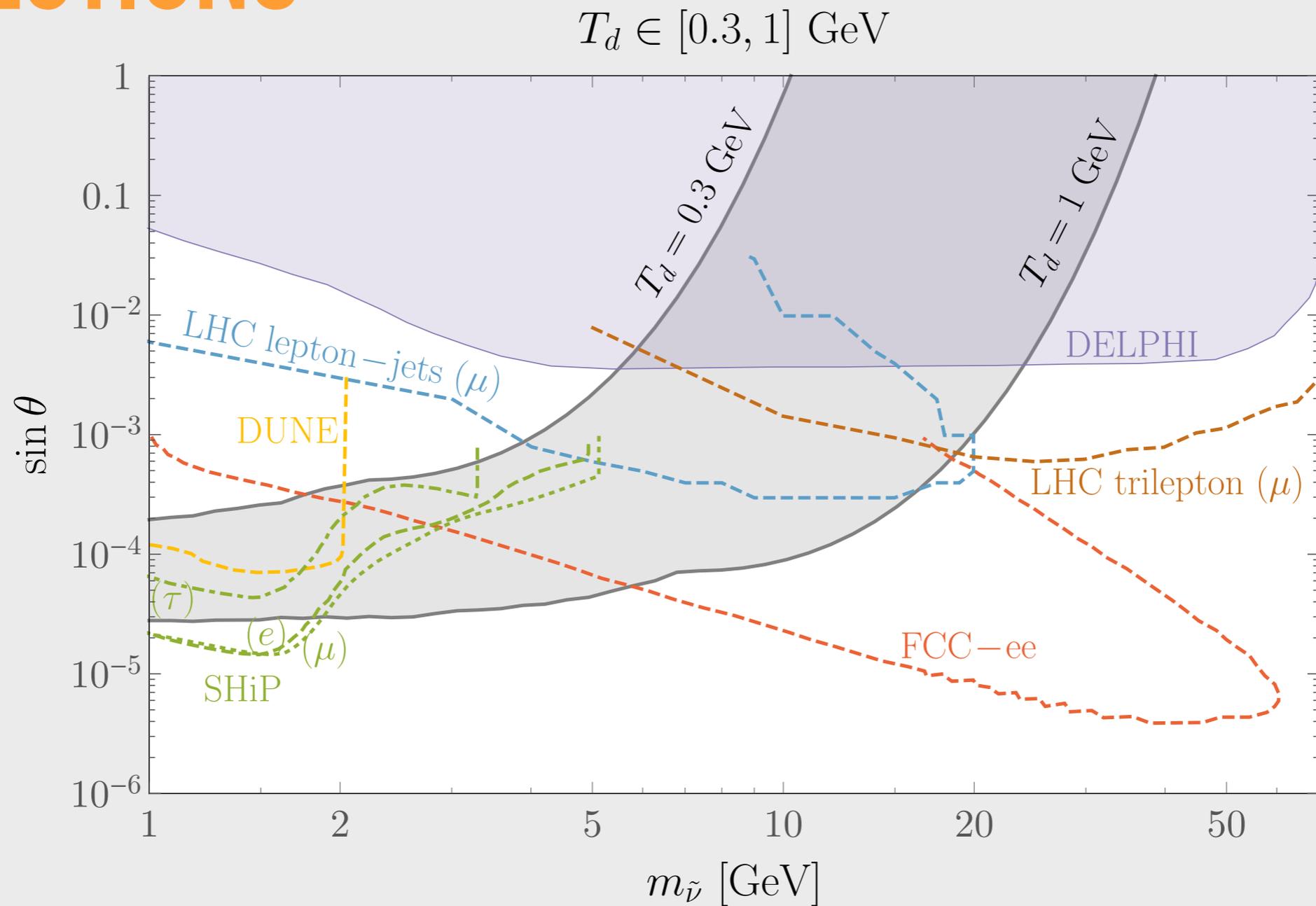
SIGNATURES

- ▶ first sign of TH may come from ΔN_{eff}
 - ▶ 2 & 3 generational models are being probed **now**
 - ▶ FTH with massless stable twin neutrino: $\Delta N_{\text{eff}} > 0.065$ stage 4 target:
 $\sigma(N_{\text{eff}}) \sim 0.027$
 - ▶ w/ massless twin photon $\Delta N_{\text{eff}} > 0.088$
- ▶ single generation models:
 - ▶ Mixing & mass which minimize ΔN_{eff} (single gen.) leads to macroscopic lifetimes



$$\tau_{\tilde{\nu}} = 0.38 \text{ mm} \left(\frac{10^{-3}}{s_{\theta}} \right)^2 \left(\frac{10 \text{ GeV}}{m_{\tilde{\nu}}} \right)^5$$

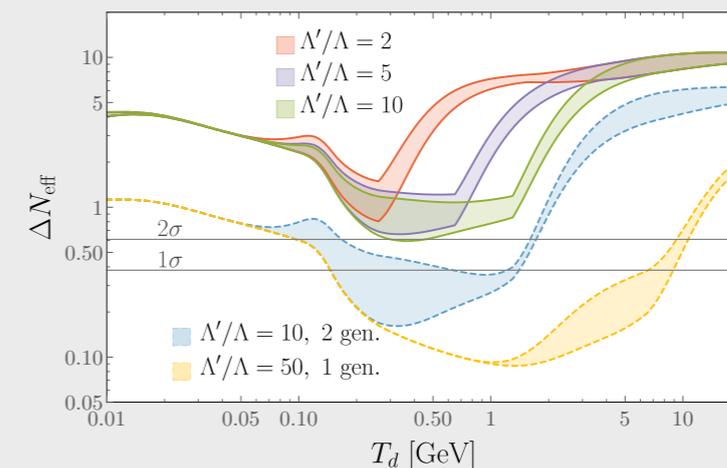
PROJECTIONS



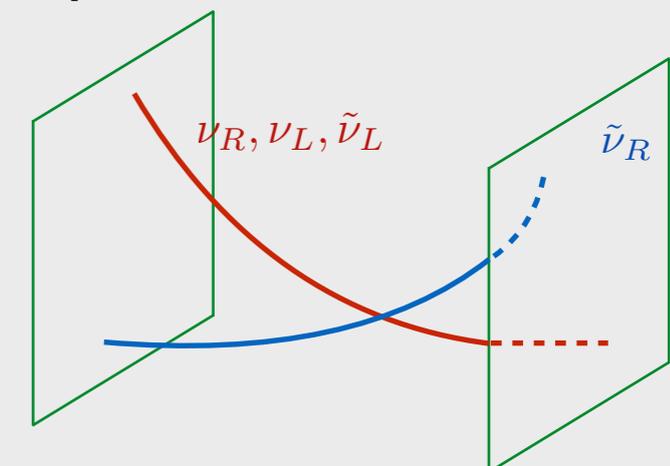
- **conclusion:** expect measurable ΔN_{eff} **or** long-lived particles in these scenarios

SUMMARY

- ▶ Considered modified cosmological histories of TH models
 - ▶ expect to see dark radiation **or** long-lived particles in most scenarios
 - ▶ twin neutrino-neutrino mixing can affect T_d and reduce N_{eff}



- ▶ large mixing and heavy twin neutrinos are natural with a composite twin neutrino

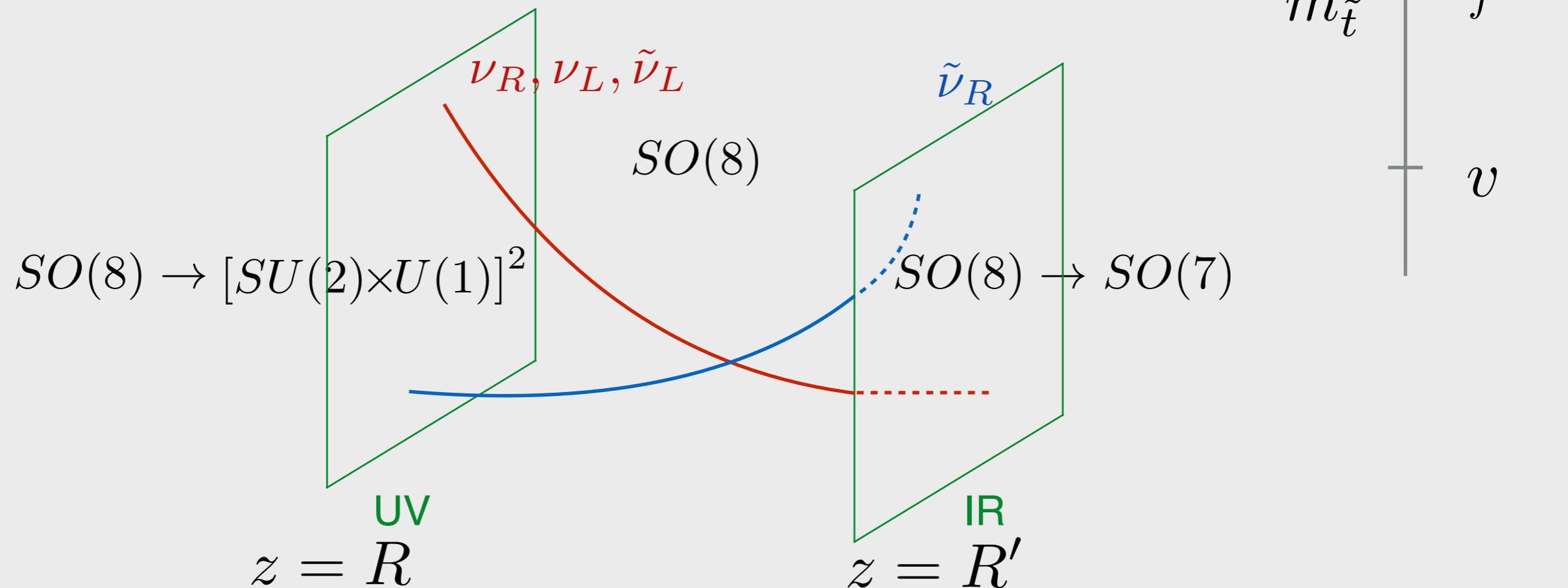


- ▶ Higgs mass corrections do not destroy the TH mechanism

UV COMPLETION

Geller, Telem [1411.2974]

- ▶ holographic composite Twin Higgs
 - ▶ 5D RS setup
 - ▶ $SO(8)$ bulk gauge symmetry



SIZE OF CORRECTIONS

- ▶ NDA:
$$\delta m_h^2 \sim \frac{y^2 g_*^2}{4\pi^2} M_{KK}^2$$
- ▶ contribution from all KK modes is suppressed from NDA

$$\delta m_h^2 \simeq O(1) \times \frac{g_*^2}{4\pi^2} M_{KK}^2 \frac{(2c_8^m - 1)}{4} \left(\frac{R}{R'} \right)^{2c_8^m - 1} \quad c_8^m \gg 1/2$$

- ▶ does not destroy TH mechanism
- ▶ can be used as dominant Z_2 breaking source in Higgs potential