Schizophrenically talk will be on two topics

"Maximally Natural" SS SUSY / Twin DM

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Oxford University

CERN Neutral Naturalness April 2015

- Savas Dimopoulos, Kiel Howe, JMR; *Maximally Natural Supersymmetry,* arXiv:1404.7554
- Isabel Garcia Garcia, JMR; *Rare Flavor Processes in Maximally Natural Supersymmetry,* arXiv:1409.5669
- (Savas Dimopoulos, Kiel Howe, JMR, James Scoville; *Auto-Concealment of SUSY in Extra Dimensions,* arXiv:1412.0805)
- Isabel Garcia Garcia, Kiel Howe, JMR; *Maximally Natural Scherk-Schwarz Supersymmetry Simplified,* arXiv:1505.XXXXX
- Junwu Huang, JMR; *Unified Maximally Natural Supersymmetry,* arXiv:1505.XXXXX

- Isabel Garcia Garcia, Robert Lasenby, JMR, *Twin DM,* work in progress….
- (Ed Hardy, Robert Lasenby, JMR, Stephen West, *Big Bang Synthesis of Nuclear DM,* arXiv:1411.3739 and
- Ed Hardy, Robert Lasenby, JMR, Stephen West, *Signatures of Large Composite DM States,* arXiv:1504.05419)

Oxford/Stanford PhD students!

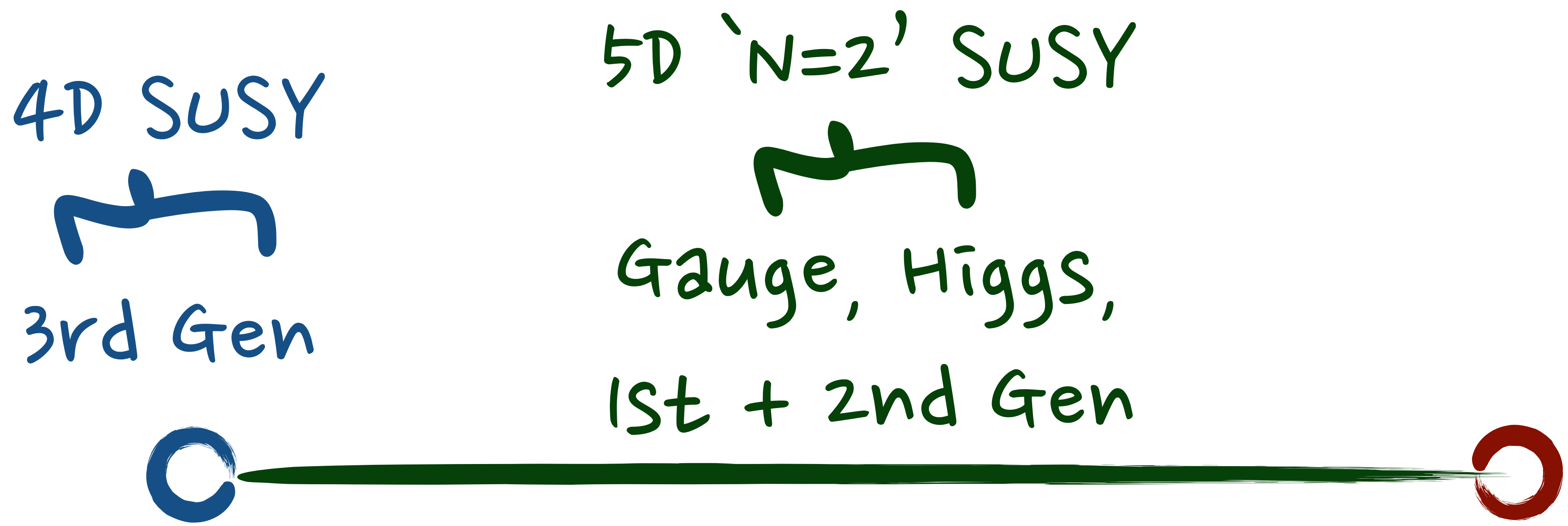
Highlights of Max Nat SS SUSY

Gustavo & David's excellent talks already intro SS SUSY-breaking

Scherk-Schwarz ~~SUSY~~ is *non-local breaking in 5D* using R-symmetry twist - *finite*

Earlier: Antoniadis, Dimopoulos, Pomarol, Quiros '99; Delgado, Pomarol, Quiros '98; Delgado, Quiros, '01
Barbieri, Hall, Nomura '00, '01; Hall, Marandella, Nomura, et. al. '02; Barbieri, Marandella, Papucci, '02,'03;

our geographical set-up



$(\pi M_* R \sim 20)$
(perturbativity)

$R \sim 1/\text{TeV} \sim 1/m_{soft}$

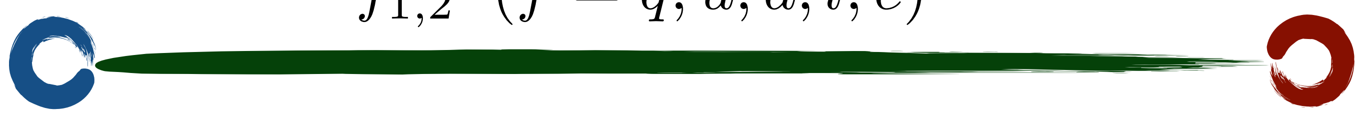
Tree-level Scherk-Schwarz Spectrum

(maximal twist)

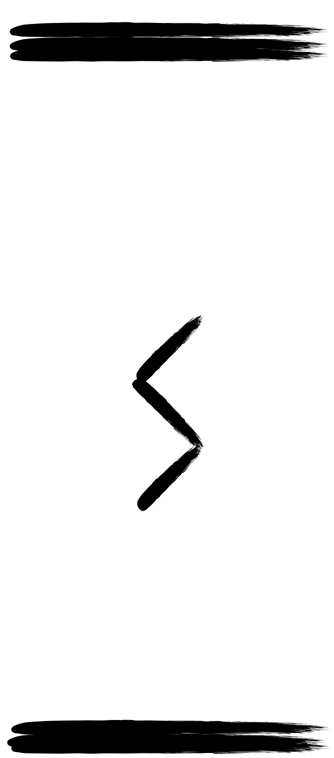
$SU(3) \times SU(2) \times U(1)$ $\quad H_u, H_d$

$f_{1,2} \;\; (f = q, u, d, l, e)$

f_3



$y = 0$ $\qquad y = \pi R$



$$m^2_{\tilde{f}} = m^2_{\tilde{\lambda}} = m^2_{\tilde{H}} = \frac{1}{2R}$$

Direct & universal bulk soft masses

No tree-level tuning!!

Almost exact $U(1)_R$ Dirac Masses

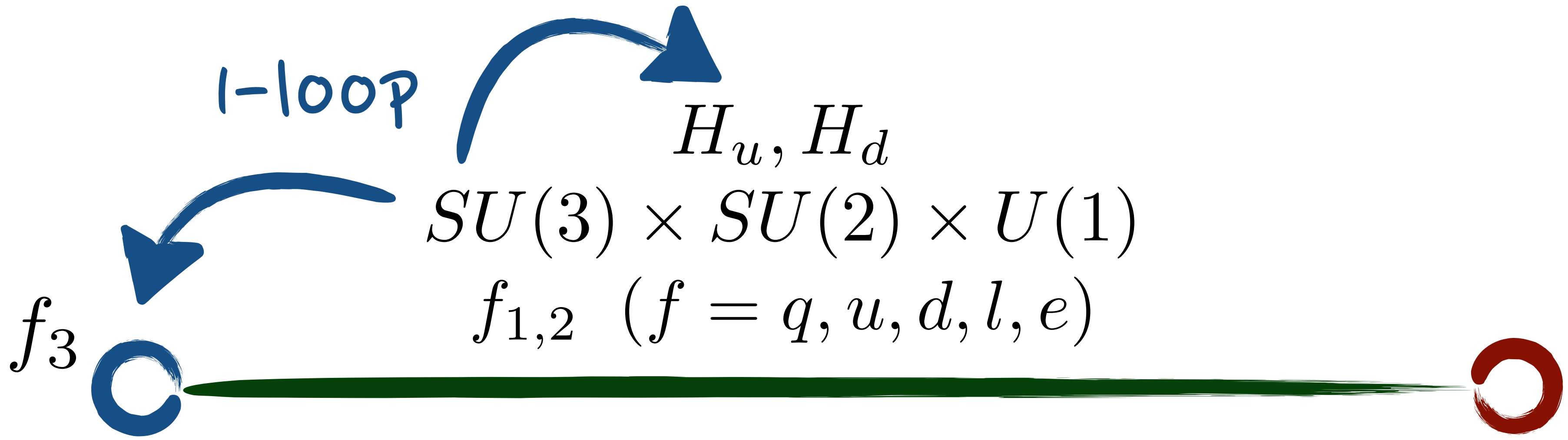
$$m_{\tilde{H}} \tilde{H} \tilde{H}^c \qquad m_{\tilde{\lambda}} \tilde{\lambda} \tilde{\lambda}^c$$

$$m^2_{\tilde{f}_3} = m^2_{h_{u,d}} = 0$$

No mu-term necessary for higgsino masses

locality $\qquad$ zero mode

Loop-level Scherk-Schwarz Spectrum



$$\delta \tilde{m}_i^2 \simeq \frac{7\zeta(3)}{16\pi^4 R^2}\left(\sum_{I=1,2,3} C_I(i) g_I^2 + C_t(i) y_t^2\right)$$

SUSY loops finite (as must go from brane to brane)

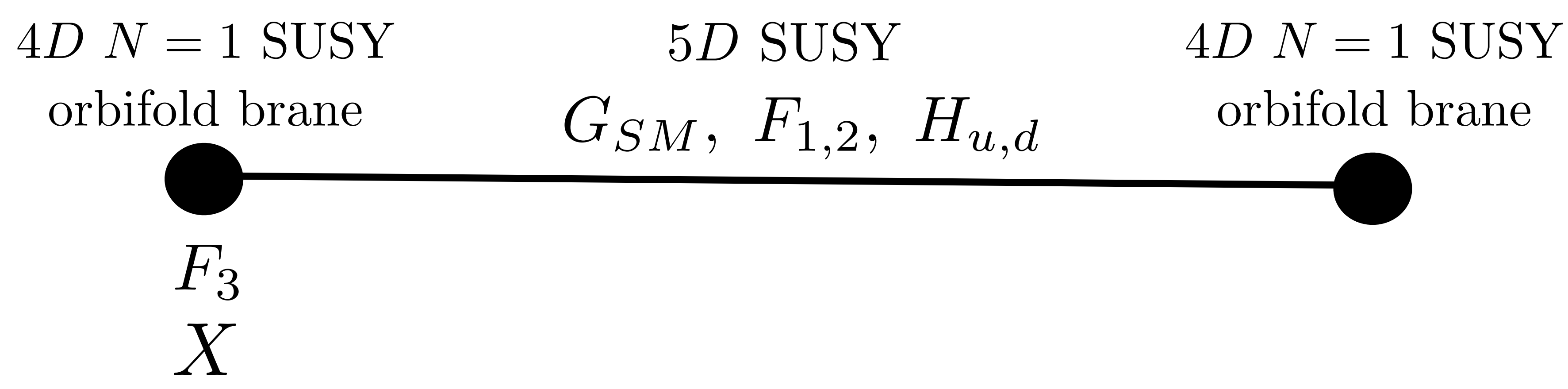
$$m_{H_u}^2 \approx \left(\frac{1}{30} \times \frac{1}{R}\right)^2$$

→ 1/R ~ 4 Tev for natural weak scale!

$$m_{\tilde{t}}^2 \approx \left(\frac{1}{10} \times \frac{1}{R}\right)^2 \approx \left(\frac{1}{5} \times M_3\right)^2$$

→ Large stop-gluino hierarchy (gluino doesn't suck)

Radius Stabilization & CC



Crucial extra ingredient - $\langle F_X \rangle \neq 0$ - necessary to give zero CC after radius stabilisation

$$V_{vac} \simeq -\left(\frac{1}{R^2}\right)^4 + |F_X|^2$$

Leads to new sources of soft masses via higher-dim ops (this F-term triggered by SSSB so still no log enhancements)

$$\Delta m^2_{\tilde{f}_3} \sim \frac{F_X^2}{M_*^2} \sim \left(\frac{1}{20} \times \frac{1}{R}\right)^2$$

(comparable to 1-loop)

($\pi M_* R \sim 20$ fixed by perturbativity)

EWSB & Max Natural SUSY

How EWSB works:

$$\delta\tilde{m}_i^2 \simeq \frac{7\zeta(3)}{16\pi^4 R^2}\left(\sum_{I=1,2,3} C_I(i) g_I^2 + C_t(i) y_t^2\right)$$

For light scalar modes & EWSB higher-dimension operators also make important contribution

$$\Delta\mathcal{K}_{m_H^2} = \delta(y)\frac{c_H}{M_5^3} X^\dagger X H_u^\dagger H_u$$

$$\Delta\mathcal{K}_{m_{\tilde{t}}^2} = \delta(y) X^\dagger X \left(\frac{c_Q}{M_5^2} Q_3^\dagger Q_3 + \frac{c_U}{M_5^2} U_3^{c\dagger} U_3^c\right)$$

leading HDOs in our range of parameters

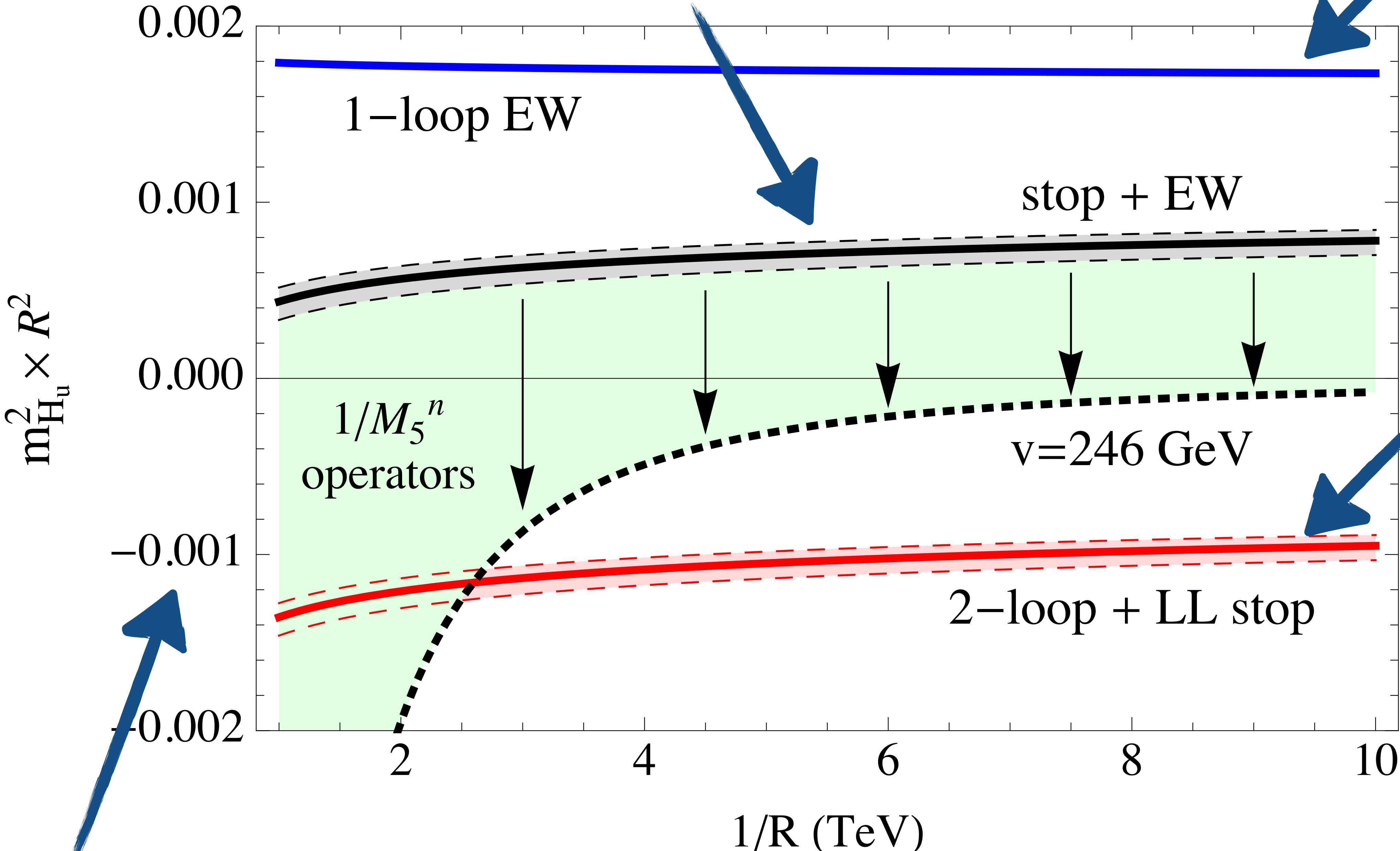
down-like Yukawas: $\delta(y)(H_u(y)^\dagger X^\dagger)\left(\frac{\tilde{y}_b}{M_5^{5/2}} Q_3 D_3^c + ...\right).$

EWSB?

Total Scherk-Schwarz contribution:

1-loop electroweak

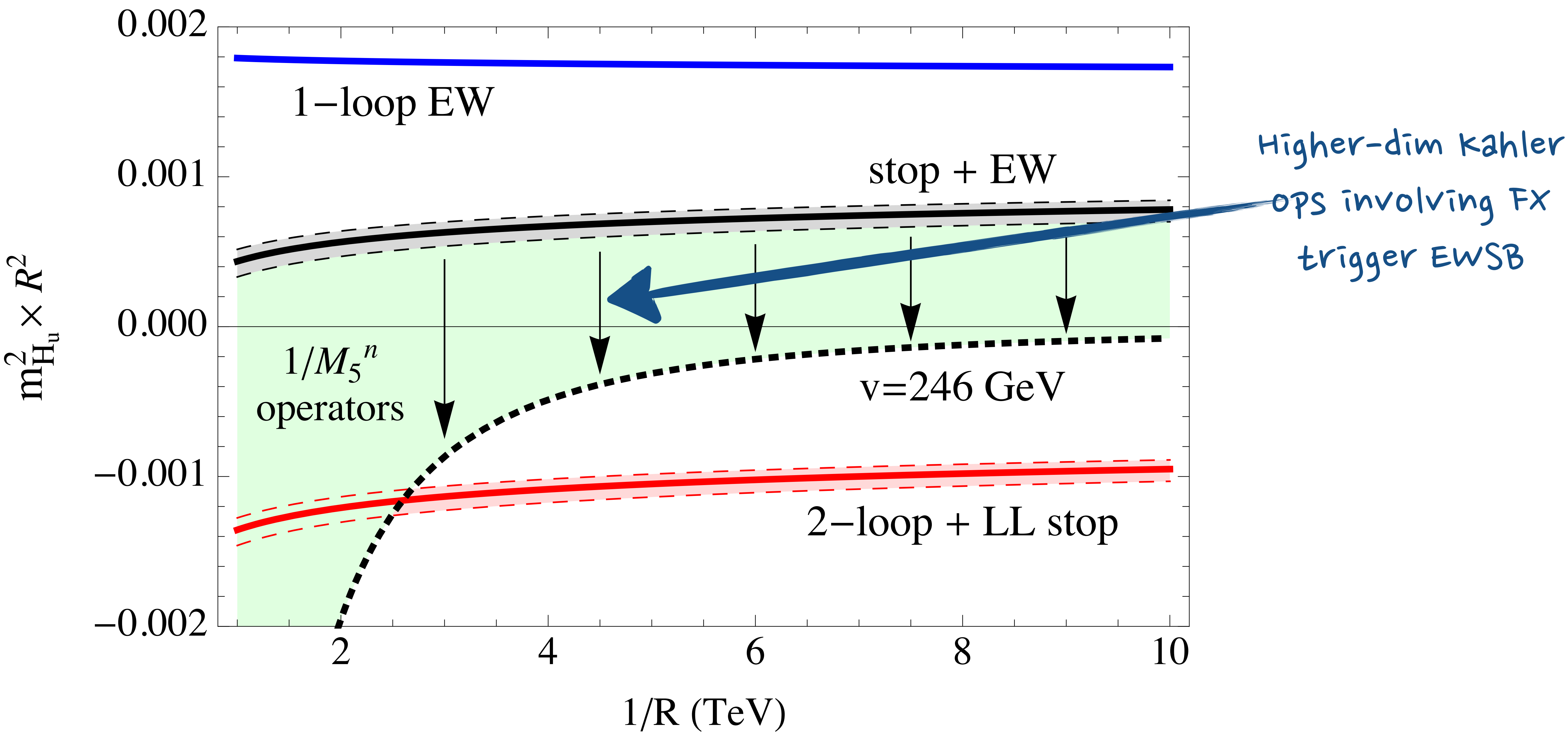
NO EWSB



2-loop stop-gluino

Note scale: very close to EWSB -> small perturbations important

EWSB?


0.002
0.001
0.000
−0.001
−0.002
1−loop EW
stop + EW
$1/M_5{}^n$ operators
v=246 GeV
2−loop + LL stop
2
4
6
8
10
1/R (TeV)
$m^2_{H_u} \times R^2$
Higher-dim Kahler ops involving FX trigger EWSB

Who is Higgs?

ONLY $\langle H_u \rangle \neq 0$. Down-like quark and lepton masses from Kahler couplings to $H_u^\dagger$

R. Davies, JMR, M. McCullough, arXiv1103.1647

$$\delta(y)(H_u(y)^\dagger X^\dagger)\left(\frac{\tilde{y_b}}{M_5^{5/2}} Q_3 D_3^c + \ldots\right)$$

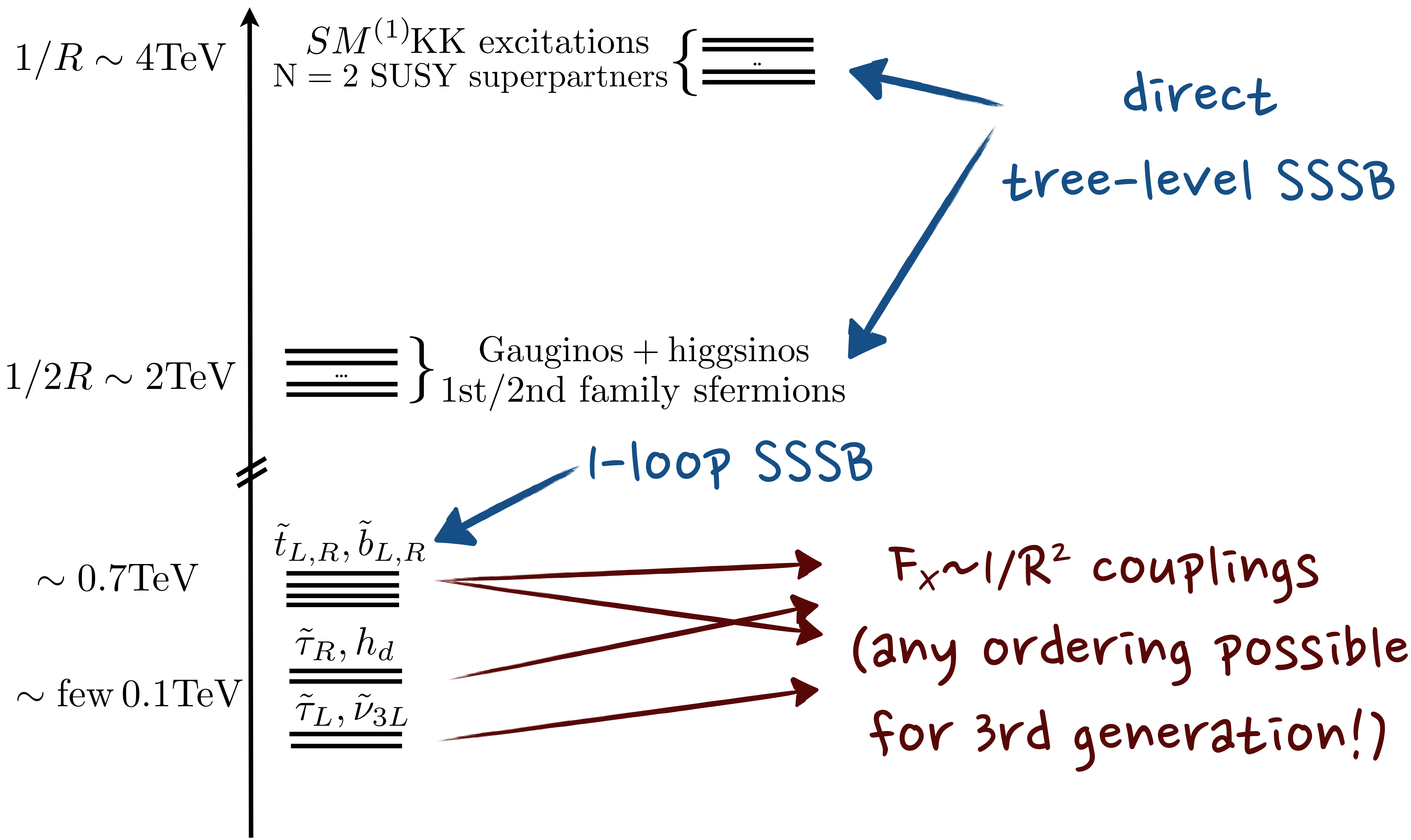
NO $\tan\beta, \; B_\mu, \; \mu$

(Hd is an inert spectator)

Single-Higgs-doublet SUSY is realised in these models

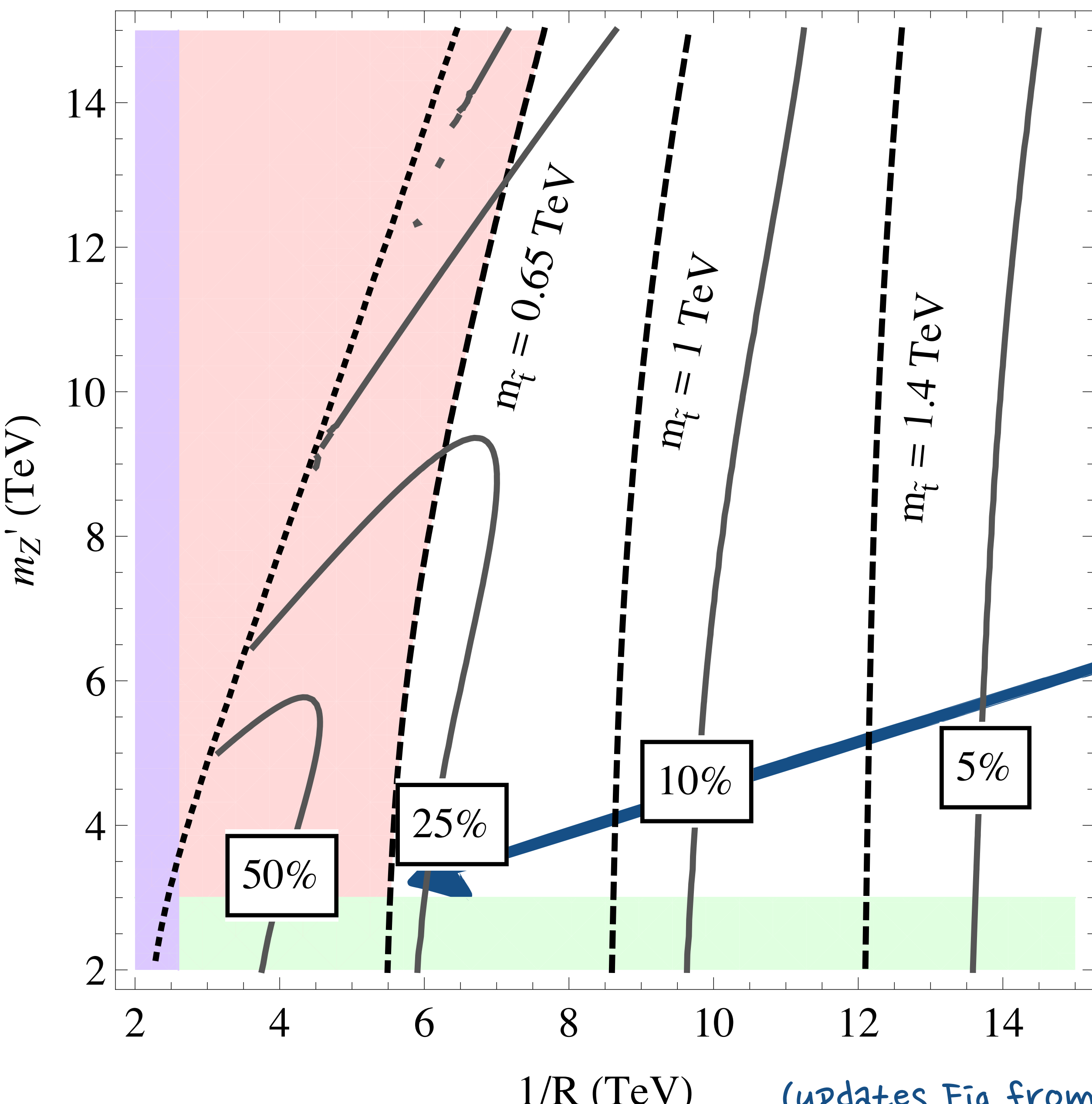
Physical Higgs is automatically SM-like up to loop-level effects!

Overall Spectrum



U(1)' Variation

Need a bit more for Higgs mass



(updates Fig from orig paper)

$$\Delta = \sqrt{\left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{t}}^2}\right)^2 + \left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{Z}'}^2}\right)^2}$$

LOW TUNING(!)

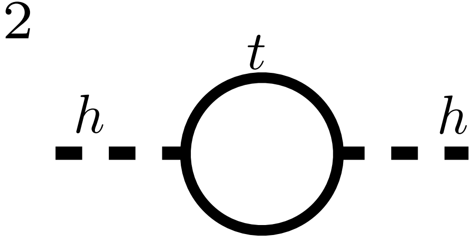
For ~700 Gev Stop &

2 Tev Gluinos/Squarks

<10% tuned

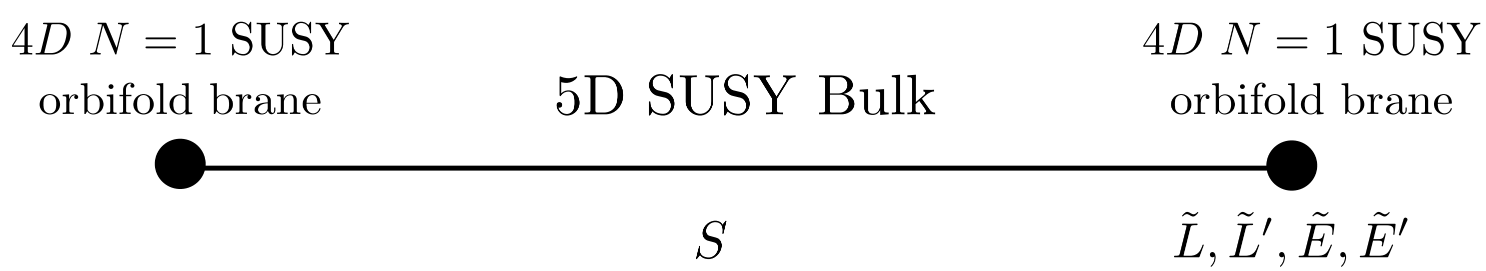
within LHC13 Reach

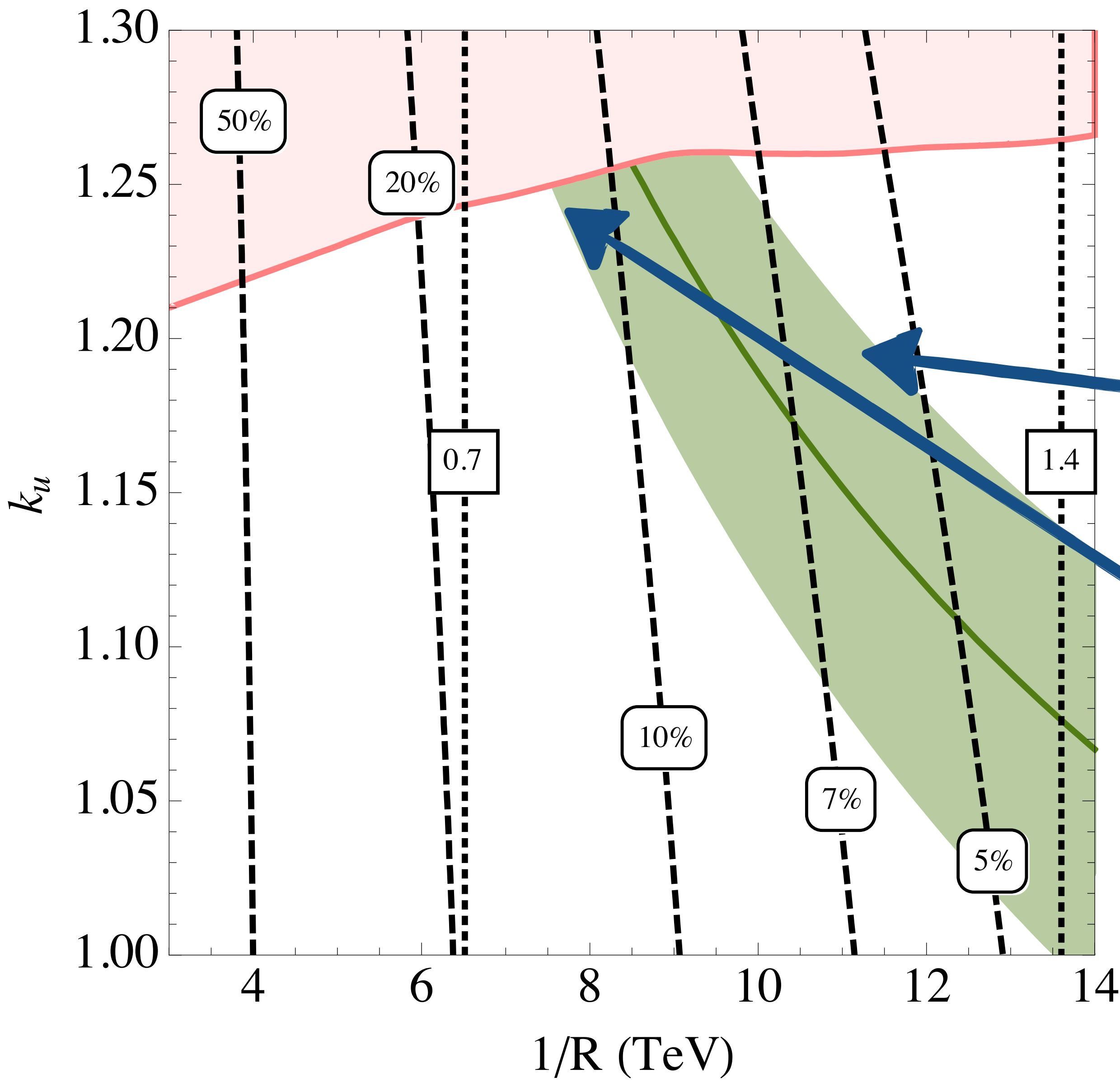
"Maximal" ~ saturates one-loop tuning $\Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2} M^2$



Vector-like Leptons Variation

Need a bit more for Higgs mass





new VL-lepton states with largeish Yukawas

band for correct Higgs mass

~10% tuned

for ~800 GeV stop &

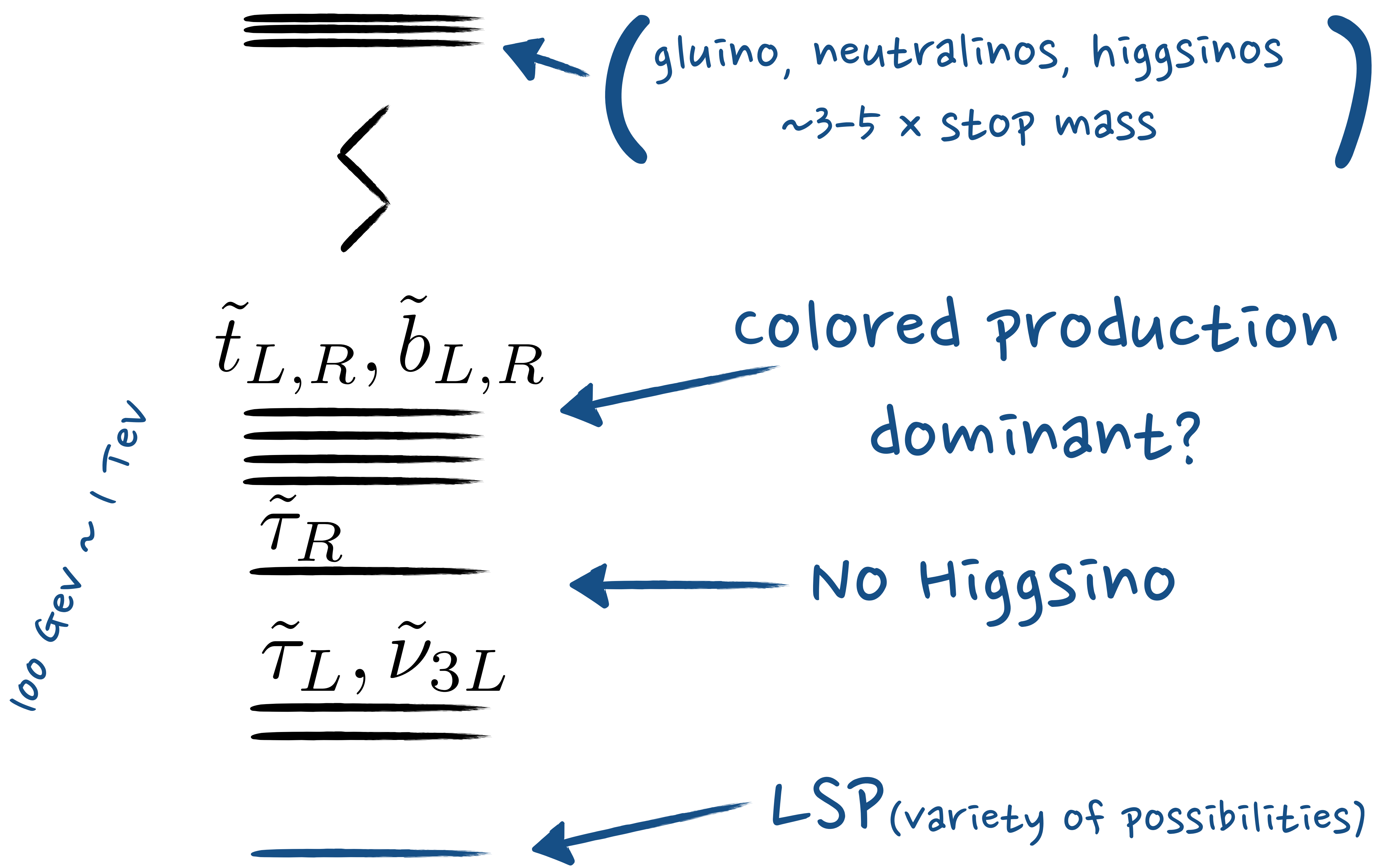
3.5 TeV gluinos/squarks

NMSSM-like variation also possible

Reasons for naturalness

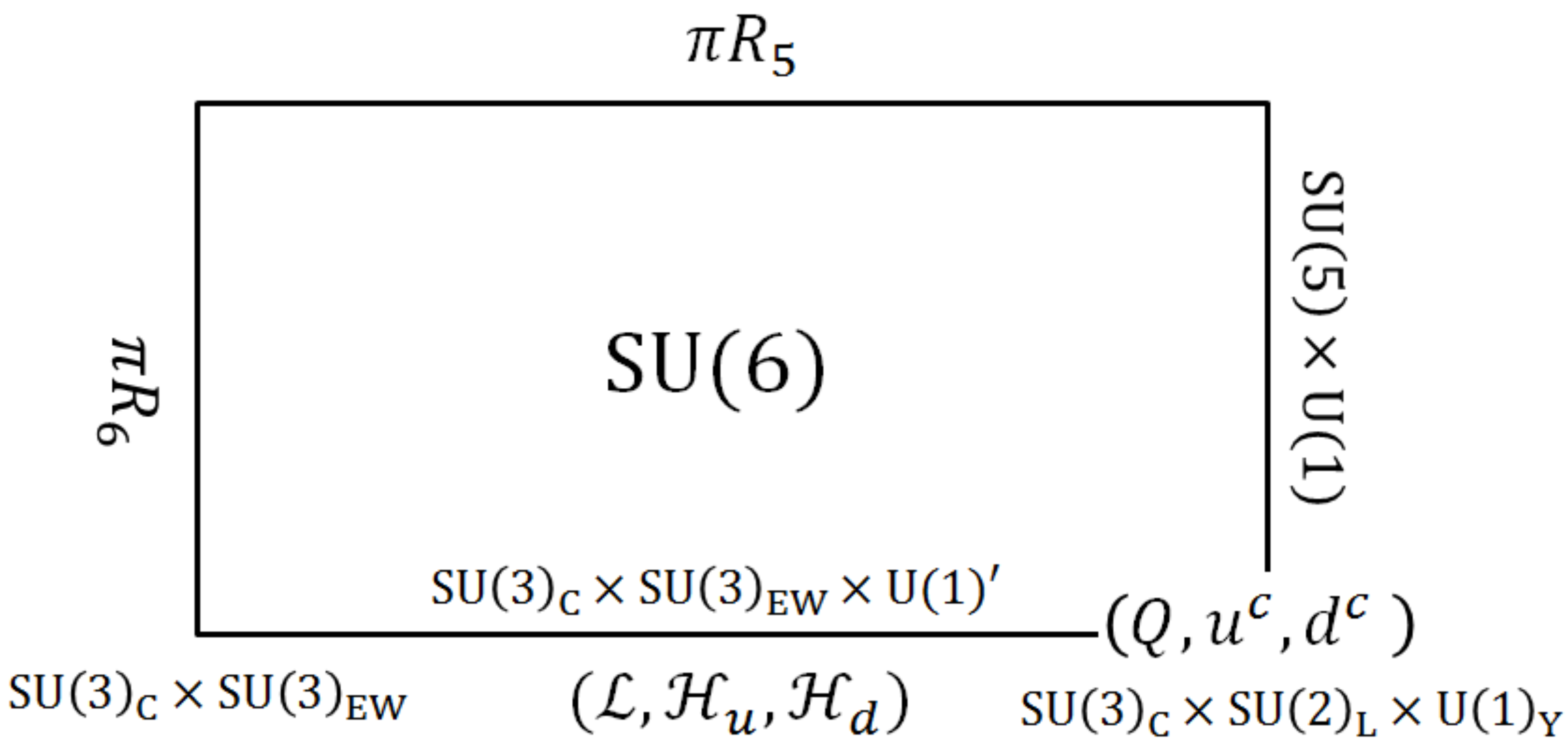
- No tree-level tuning
- SUSY directly communicated to Higgsinos, gauginos, and 1st/2nd family sfermions. 3rd family protected from tree SUSY
- SSSB is super-soft as it is a non-local (in 5d) breaking of SUSY: higgs soft mass not enhanced; gluino sucks problem solved
- A natural SUSY spectrum easy to obtain via localization of the 3rd family on 4D brane (also vital for successful EWSB)

LHC Pheno: 3rd Generation Sfermion Signatures



Unification?

can get an extended version of 5d $SU(3)_{EW}$ unification (with tree-level s^2=1/4) which further unifies with $SU(3)_c$ into N=2 SU(6) theory in 6d



After log differential running get s^2 = 0.2315 to 2%

(but prediction for g_3 only good to ~15% as afflicted by non-SU(6) 5d-brane kinetic terms)

Twin Dark Matter

General comments

- When you twin the SM there are (unsurprisingly) a **HUGE** range of possibilities for stable states with very rich dynamics (variety of WIMP's but also nucleon DM, atomic DM, nuclear DM, meson DM, spin 1 DM, molecular DM(?), ···) (cf Andrei and Marco's talks)

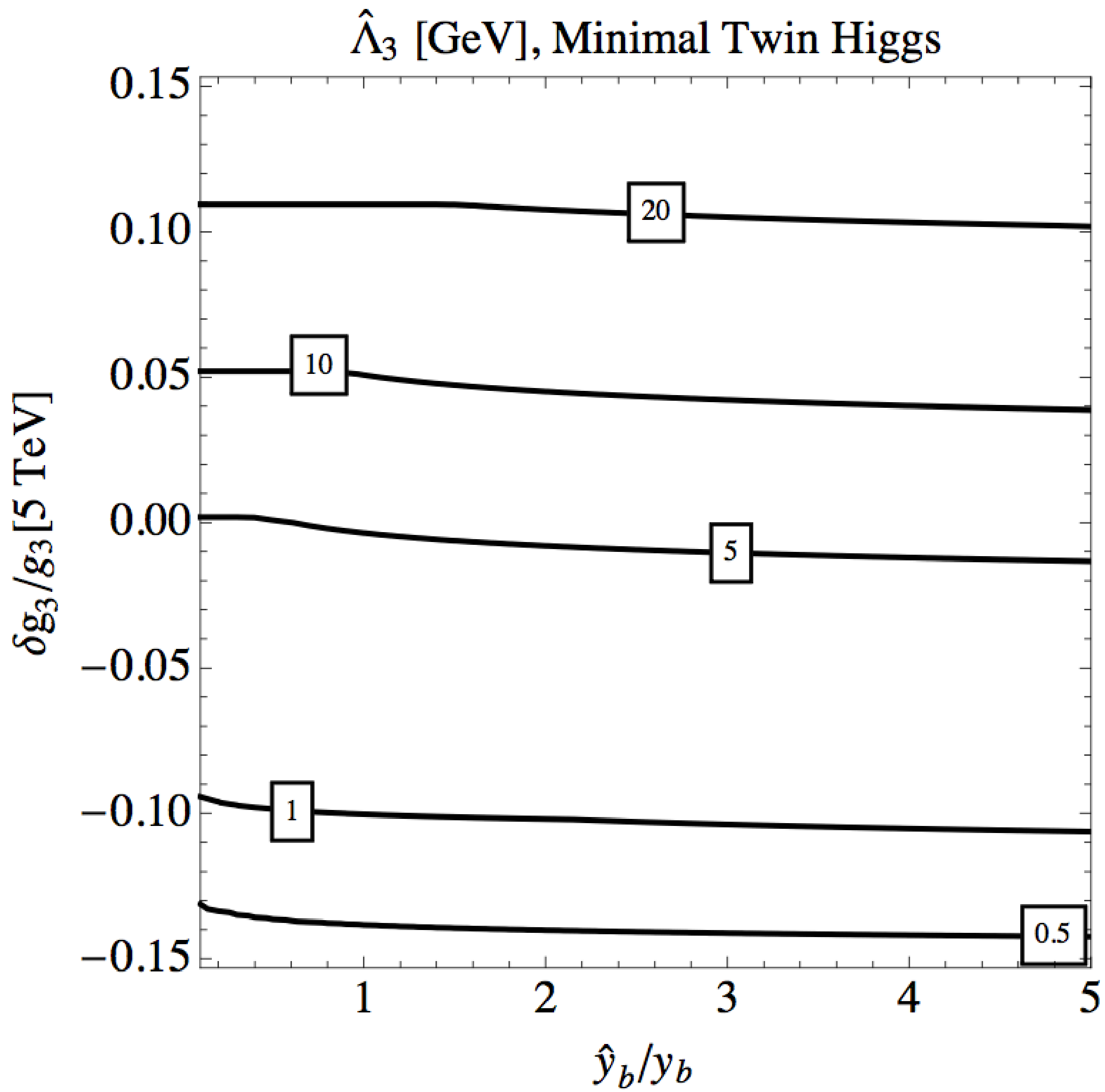
- In many (most?) parts of parameter space the DM is a multi-component cocktail. Sub-dominant parts can be interesting (halo dynamics, late decays & BBN, spectrum of states in direct or indirect detection, inelasticity, ···)

- Higgs portal gives definite and very interesting predictions for DD and ID signals even in most minimal vanilla cases.

Twin Dark Matter

General comments

- Asymmetric DM is a very natural possibility. Twin models have the potential to solve the `coincidence of scales' problem that exists in ADM (cf Marco's talk), eg



from NC etal , arXiv:1501.05310

(Fraternal)Twin DM

Given richness of possibilities useful to start with minimal case first

Just 3rd generation of B-sector with twin-hypercharge just global (could be explicitly broken if you wanted — also will later turn off leptons in 2 generation model with just ADM nucleons)

$$[\ SU(3) \times SU(2)\ ] \times [U(1)_Q \times U(1)_B \times U(1)_L\ ]$$

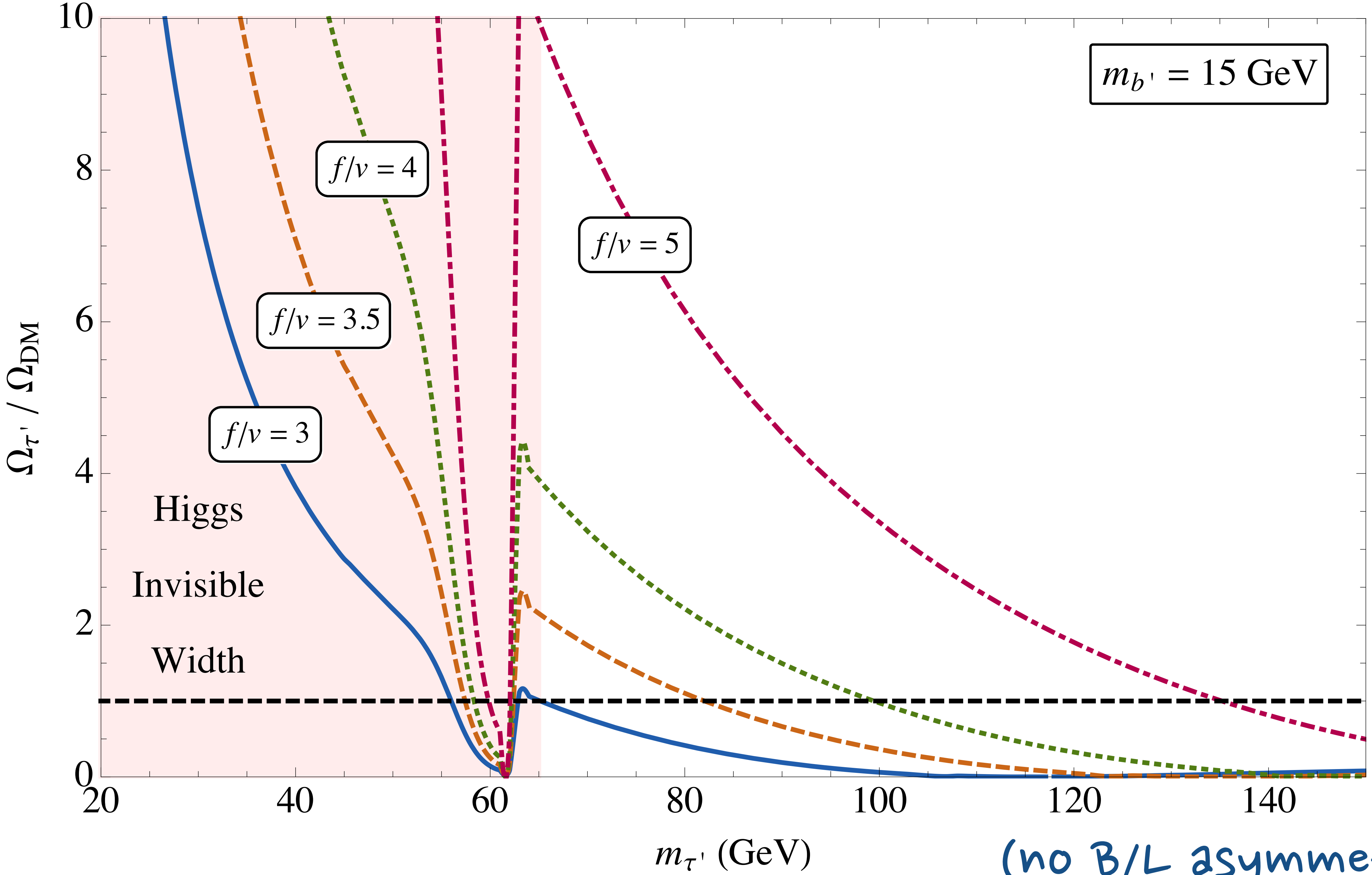
Lightest twin-lepton, twin-baryon (spin 3/2) B=bbb, and twin-$U(1)_Q$ states stable.

Also often other (meta)stable states by J^{PC} or kinematics

Let's first assume for simplicity/definiteness no asymmetry, b is heavy so that glueballs are light hadrons, and twin-neutrinos are massless. Heavy twin-tau is then simple WIMP candidate

(Fraternal) Twin DM

Result of FO calculation for tau (B density vanishingly small)

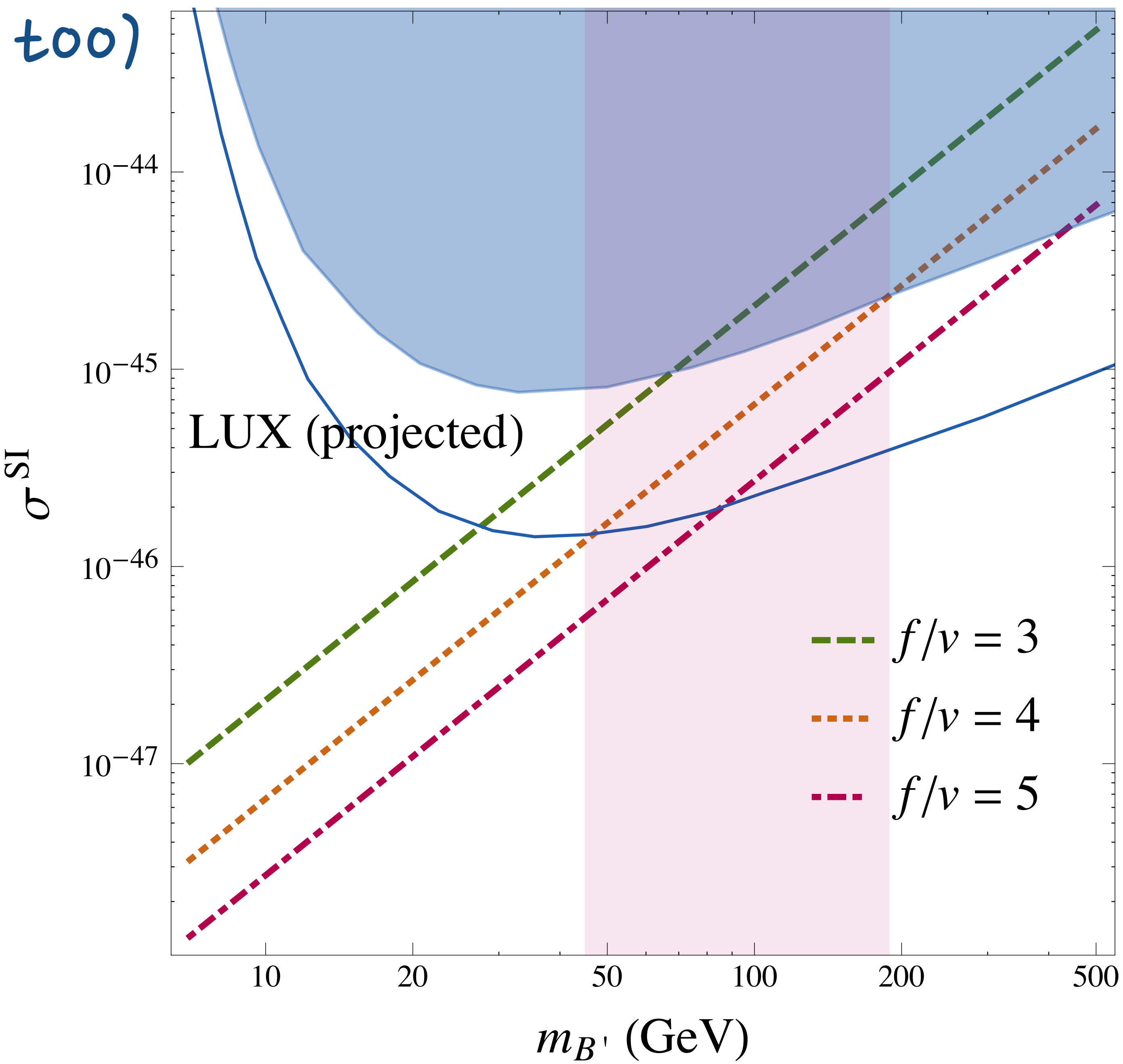


(no B/L asymmetry)

has SI DD cross section in interesting region

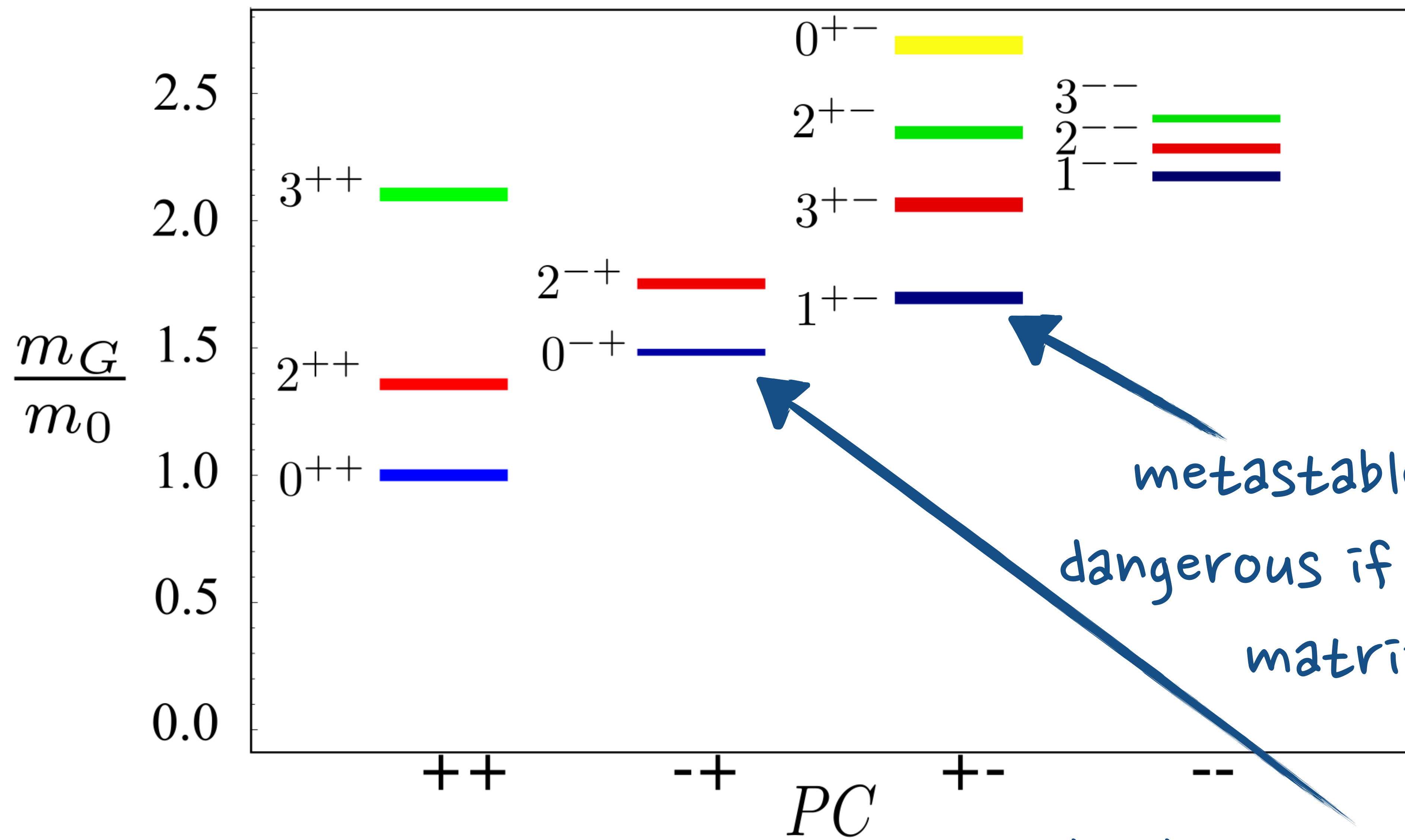
Asymm (Fraternal) Twin DM

SI DD cross section for B baryon with asymmetry via higgs portal (plot assumes m_b > twin QCD scale so b's weakly bound - other case interesting too)



(Fraternal) Twin DM

But don't forget glueball spectrum in heavy m_b limit



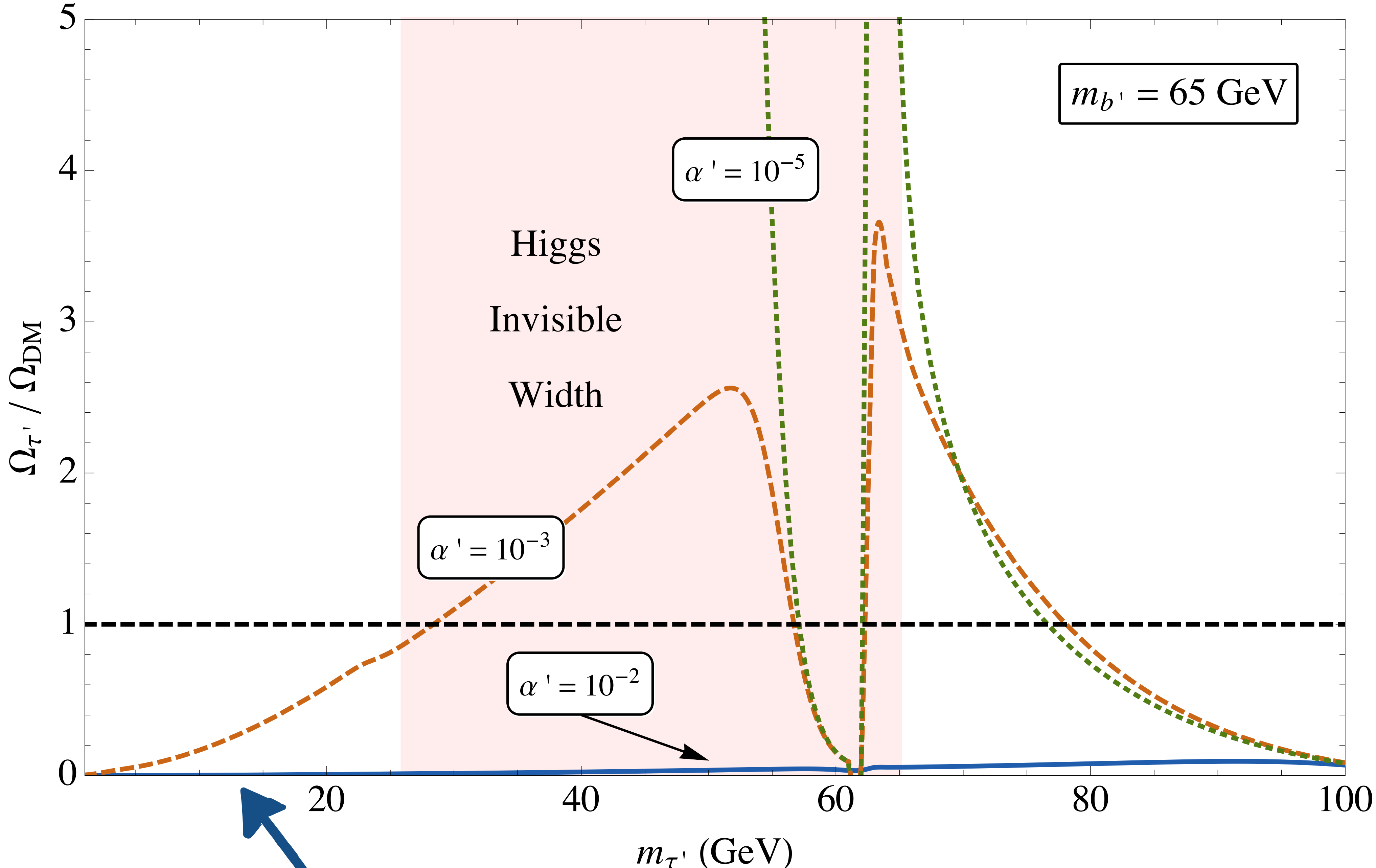
metastable - potentially dangerous if $t > t_{CMB}$ (unknown matrix element)

stable by twin-CP conservation & only higgs portal to SM

we find relative energy density of 0^{-+} state to be $\sim 10^{-7}$ of DM

(Fraternal)Twin DM

Now turn on twin photon (will come back to #rel dof)



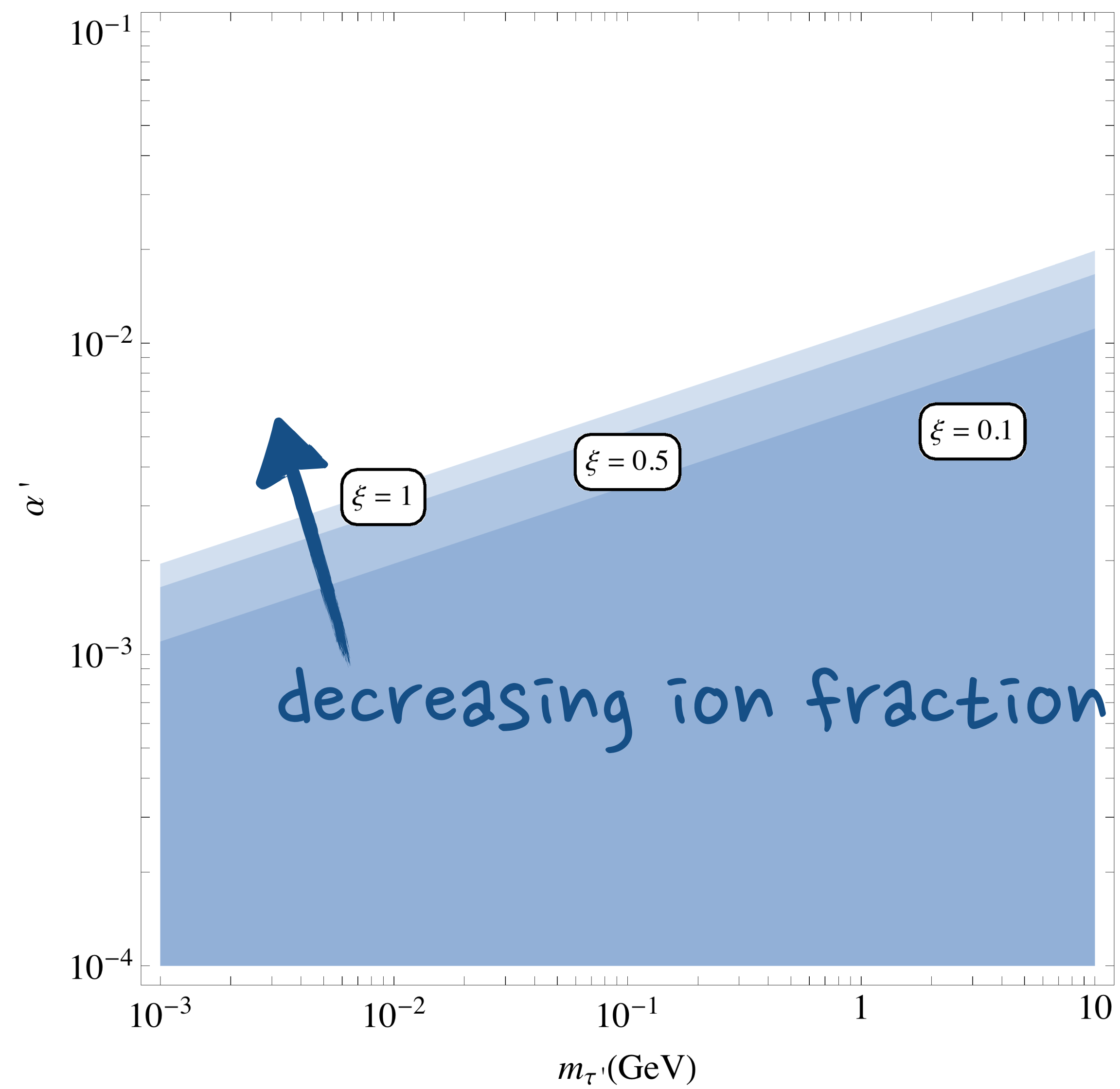
good region for ADM (both tau and B if b light)

(no B/L asymmetry)

(Fraternal)Twin DM

In presence of twin photon and asymmetries have twin B-tau atoms from twin-recombination (here twin photon assumed massless otherwise new hierarchy to explain)

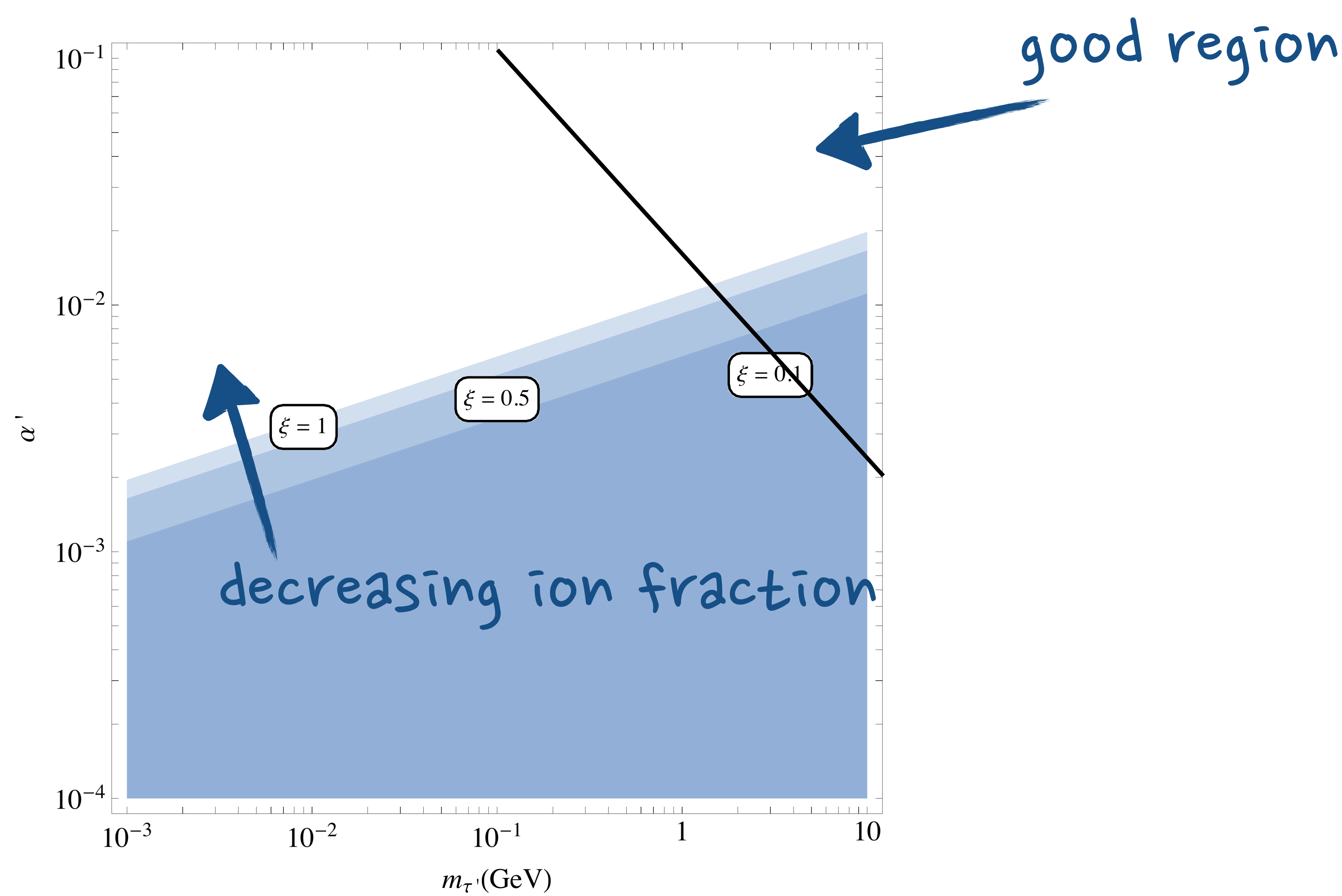
This recombination must be efficient (small ion density) if not to be ruled out by galactic halo constraints



(Fraternal)Twin DM

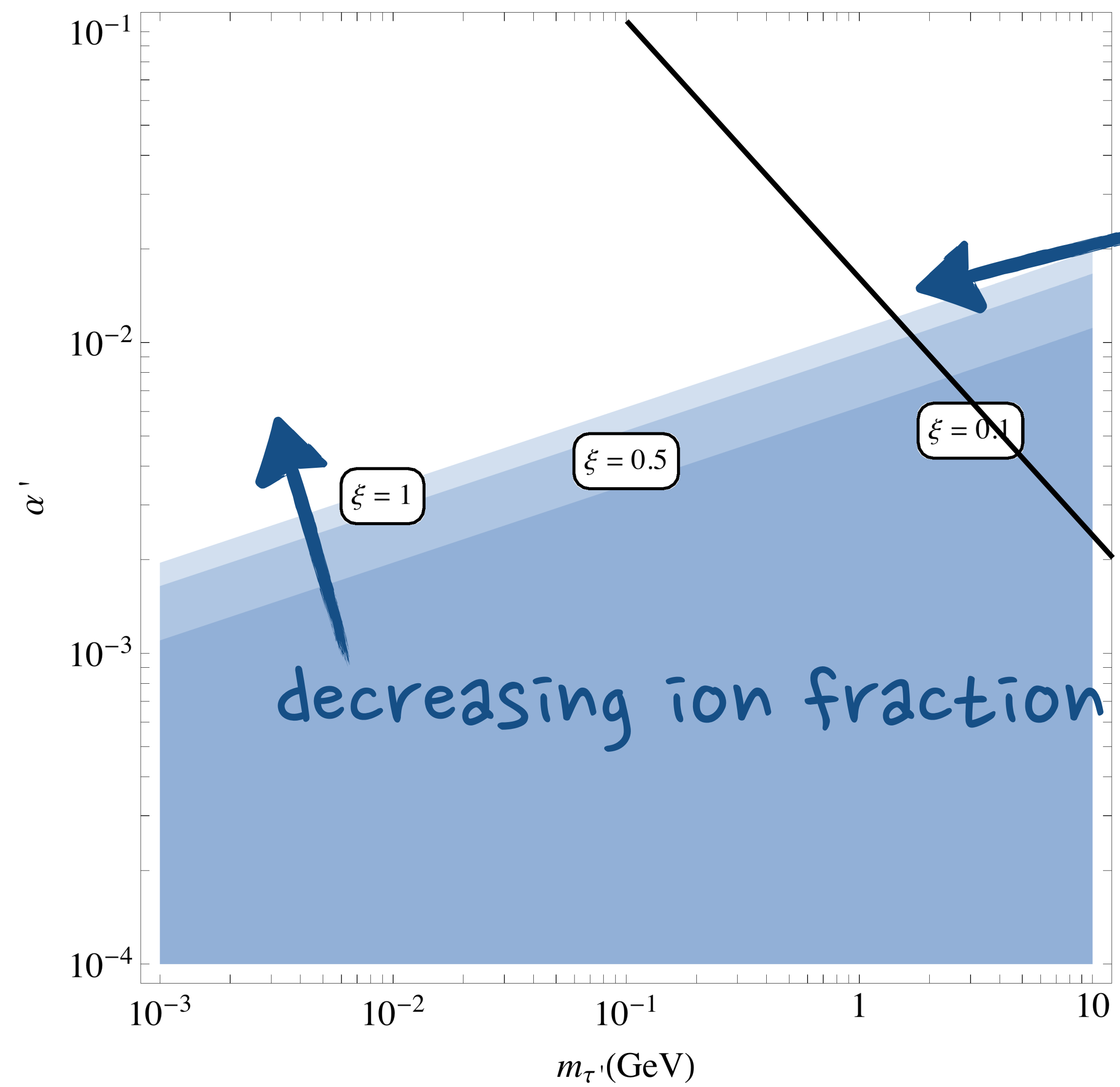
In presence of twin photon and asymmetries have twin B-tau atoms from twin-recombination (here twin photon assumed massless otherwise new hierarchy to explain)

But also atom-DM self interactions must not be too large limiting Bohr radius from above



(Fraternal) Twin DM

But also atom-DM self interactions must not be too large limiting Bohr radius from above



Twin "H_2" molecules **might** late-time form in this region where ionisation fraction not << 1 (would have striking DD pheno as spatially extended)

Twin Nuclear DM

In just 3rd generation case don't form significant di-B and beyond as even with photon present the radiative capture rate too slow (both M1 and E1 processes zero by fact that B is only (semi-)stable nucleon)

can get twin nuclear DM — possibly with large nucleon number A if turn back on 2nd generation with now both "p" and "n" like states (if $m_p > m_n$ so that p eventually decays to n + twin leptons no coulomb barrier at large A, and no dark atoms either)

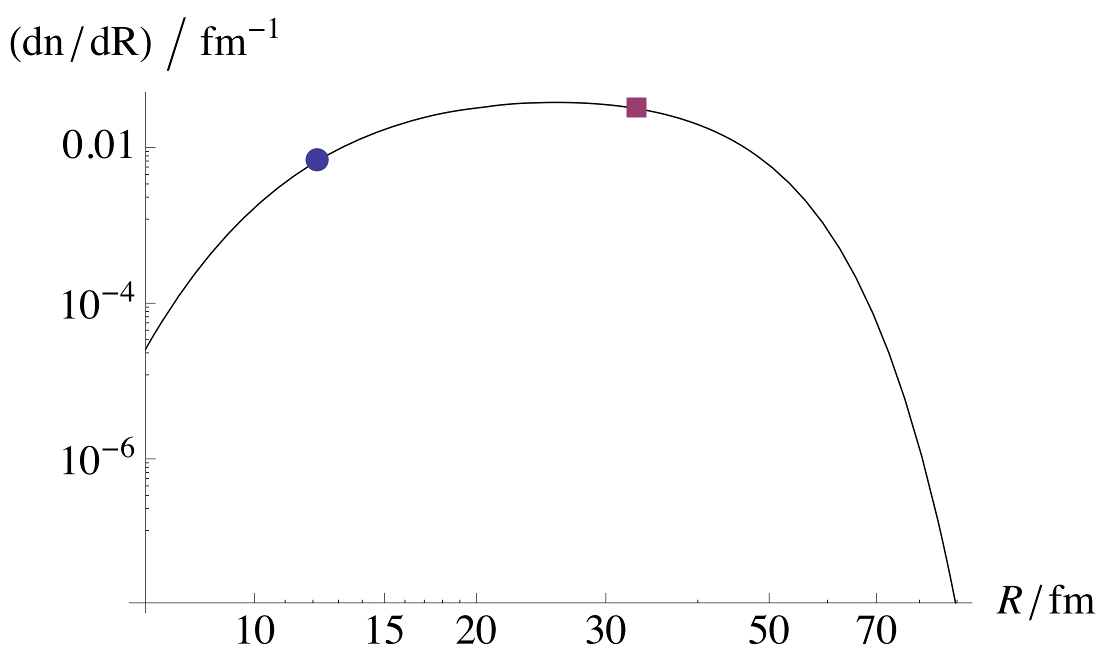
Twin Nuclear DM

comment: Get all the attractiveness of ADM with m_B = 5Gev without having halo DM states actually at mass 5Gev. They can have much bigger mass Ax5Gev with baryon number A! (potentially changes DD region/pheno a lot)

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

This would still be true with $\eta_X = \eta_B$

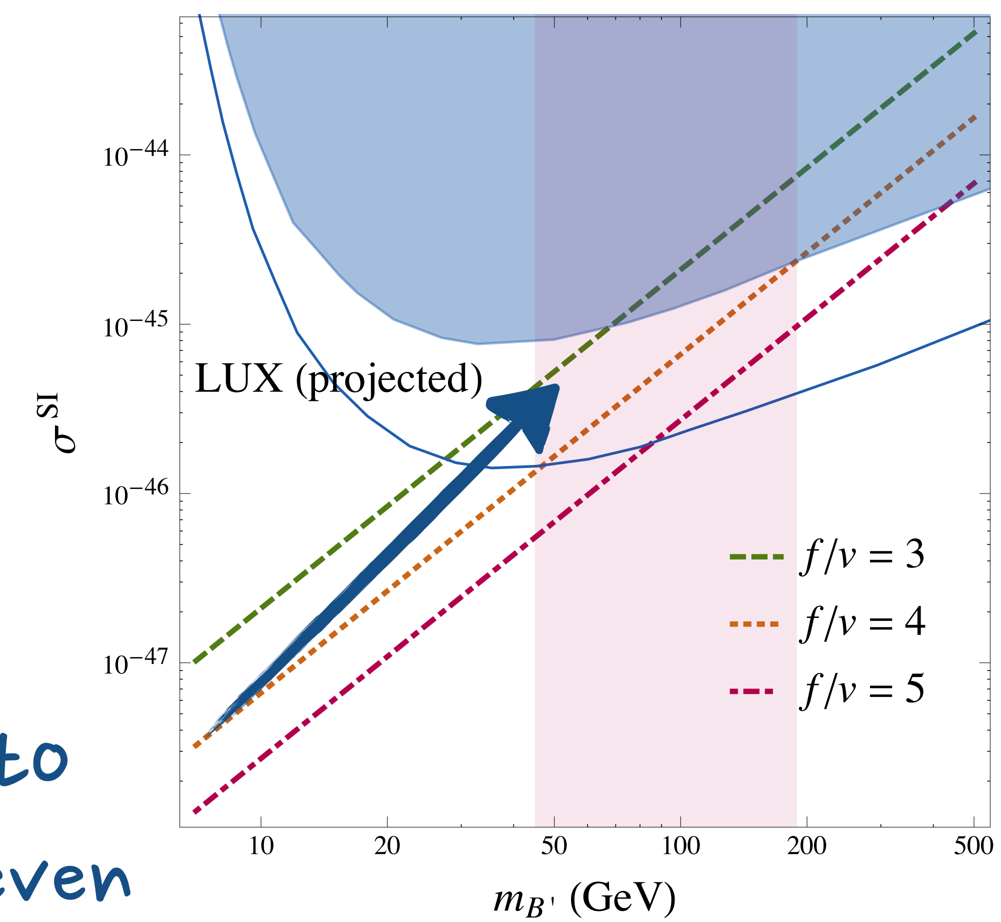
Note: example of dark-sector BBN result for number dist'n



Twin Nuclear DM

If get through bottleneck region at small A number then can potentially build up large nuclei. Interesting case for us is A~10

Such large-A (and thus spatially extended) dark nuclei have effective coherent enhancement of DD cross section by A^2 (but more massive by A)



can effectively move DD signal to higher mass and cross section even if m_B=5Gev