Light Colored Scalars as Messengers of Up-Quark, Down-Quark and Charged Lepton Flavor Dynamics in Grand Unified Theories*

Ilja Doršner

University of Sarajevo, Bosnia and Herzegovina

LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE, La Thuile

March 2nd, 2012

*I.D., Svjetlana Fajfer, Jernej F. Kamenik and Nejc Košnik, *Phys. Lett.* **B** 682 (2009) 67-73**;** *Phys. Rev.* **D** 81 (2010) 055009**,** *Phys. Rev.* **D** 82 (2010) 094015.

*I.D., Jure Drobnak, Svjetlana Fajfer, Jernej F. Kamenik and Nejc Košnik, JHEP (2011) 1111:002.

OUTLINE

- **MOTIVATION**
- **EXPERIMENTAL STATUS**
- $d = 6$ **PROTON DECAY OPERATORS**
  - **SCALAR CONTRIBUTION**
- **LIGHT SCALARS IN** $SU(5)$
- **CONCLUSIONS**

MOTIVATION

Leptoquarks[#] are inherent to any theory that
treats quarks and leptons on the same footing.

- UNIFICATION THEORIES (PATI-SALAM[#], $SU(5)$, $SO(10)$, E_6…)

Leptoquarks can generate proton decay.

LEPTOQUARKS ≡ QUALITATIVELY NEW PHYSICS!

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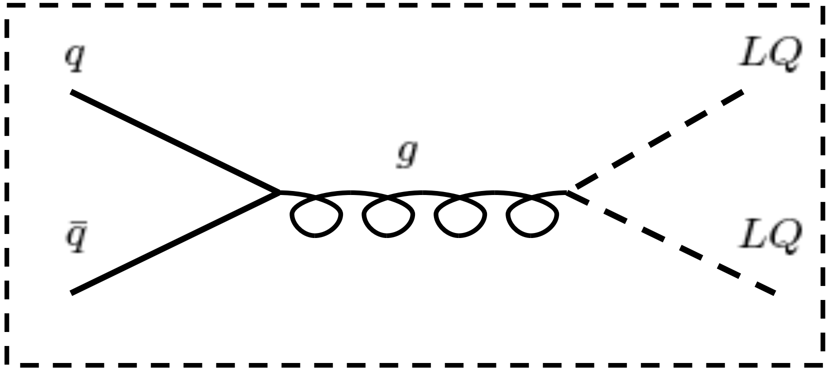
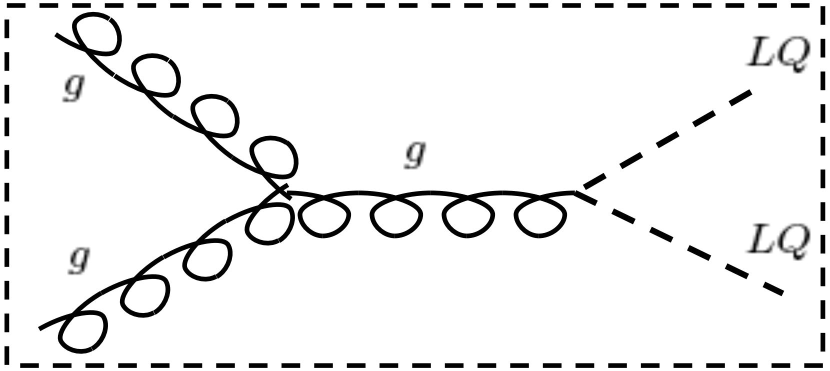
EXPERIMENTAL STATUS

Leptoquarks (*LQ*) can be produced directly in colliders.





EXPERIMENTAL LIMITS:

	CMS	ATLAS
1st	$m_{LQ} > 384\,\mathrm{GeV}$[#]	$m_{LQ} > 660\,\mathrm{GeV}$[*]
2nd		$m_{LQ} > 422\,\mathrm{GeV}$[Ø]
3rd	$m_{LQ} > 350\,\mathrm{GeV}$[&]	

[#] V. Khachatryan et al. (CMS), Phys. Rev. Lett. 106, 201802 (2011), 1012.4031.

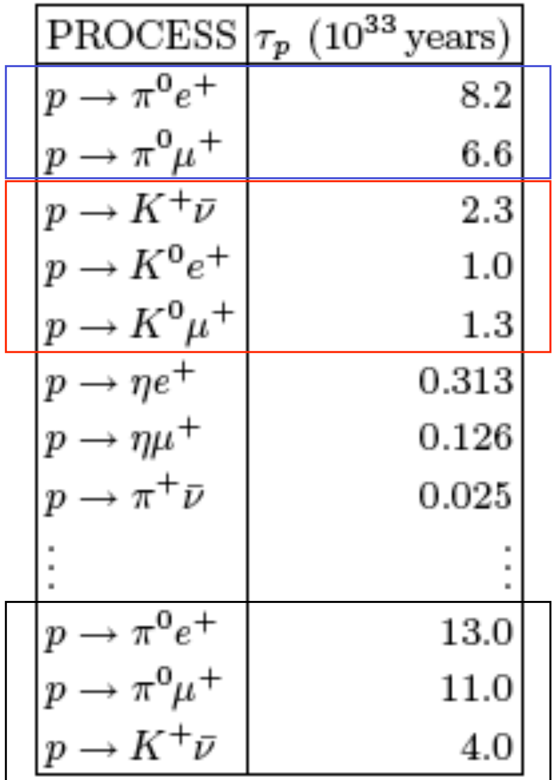
[Ø] G. Aad et al. (ATLAS) (2011), 1104.4481.

[*] ATLAS (2011), arXiv:1112.4828.

[&] CMS PAS EXO-11-030.

EXPERIMENTAL STATUS

(PROTON DECAY)



PROCESS	τ_p (10^{33} years)	
$p \to \pi^0 e^+$	8.2	*
$p \to \pi^0 \mu^+$	6.6	
$p \to K^+ \bar{\nu}$	2.3	@
$p \to K^0 e^+$	1.0	
$p \to K^0 \mu^+$	1.3	
$p \to \eta e^+$	0.313	
$p \to \eta \mu^+$	0.126	
$p \to \pi^+ \bar{\nu}$	0.025	
$\vdots$	$\vdots$	
$p \to \pi^0 e^+$	13.0	¶
$p \to \pi^0 \mu^+$	11.0	
$p \to K^+ \bar{\nu}$	4.0	

[*] [Super-Kamiokande Collaboration], arXiv:0903.0676.

[@] [Super-Kamiokande Collaboration], arXiv:hep-ex/0502026.

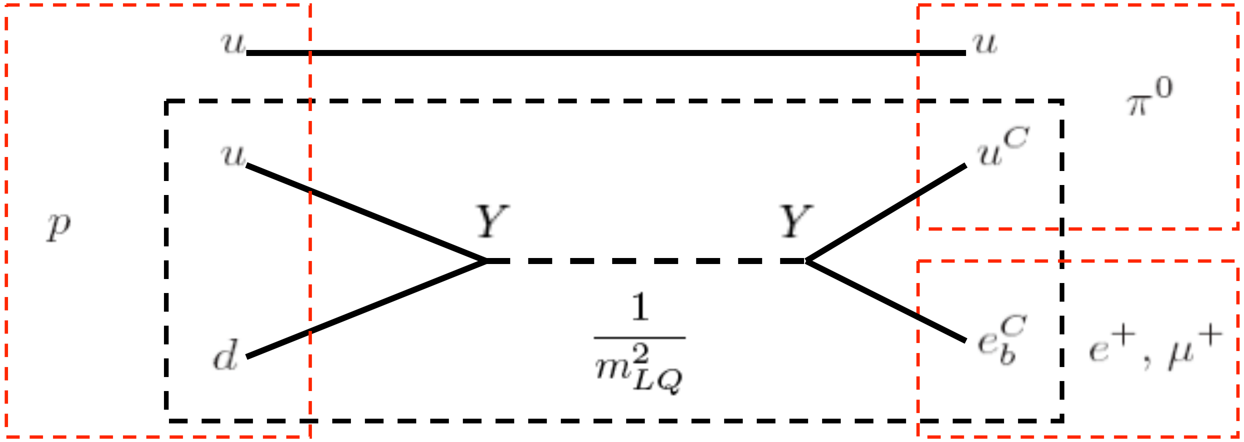
[¶] http://www.phys.utk.edu/blv2011/sessions01-06.html (Makoto Miura)

d=6 PROTON DECAY OPERATORS

(SCALAR CONTRIBUTIONS*)

PROTON DECAY MEDIATING LEPTOQUARKS SHOULD BE VERY HEAVY!

$$\Gamma_6 \sim \frac{Y^4}{m_{LQ}^4} m_p^5 \quad \Rightarrow \quad m_{LQ} > 10^{12}\,\mathrm{GeV}$$



Y ≡ Yukawa coupling(s)

m_{LQ} ≡ Leptoquark mass

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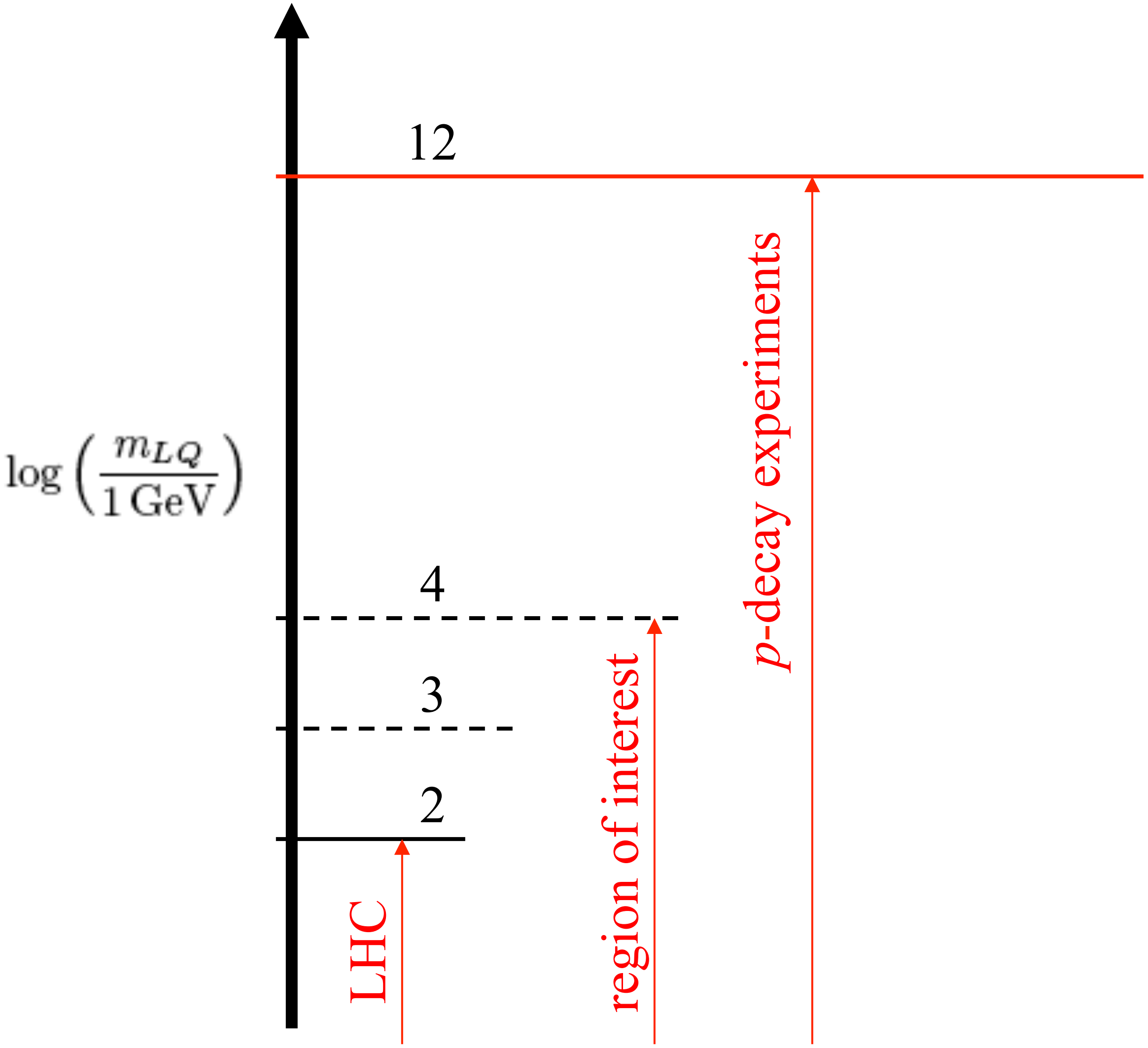
*S. Weinberg, *Phys. Rev.* D 22:1694, 1980.

RELEVANT SCALES



CASE STUDY: AN *SU*(5) SCENARIO[*]

FERMIONS OF THE STANDARD MODEL (SM≡ $SU(3)\times SU(2)\times U(1)$):

$$L_a \equiv (\mathbf{1},\mathbf{2},-1/2)_a = (\nu_a \quad e_a)^T$$

$$e_a^C \equiv (\mathbf{1},\mathbf{1},1)_a$$

LEPTONS

$$Q_a \equiv (\mathbf{3},\mathbf{2},1/6)_a \quad = (u_a \quad d_a)^T$$

$$u_a^C \equiv (\overline{\mathbf{3}},\mathbf{1},-2/3)_a$$

$$d_a^C \equiv (\overline{\mathbf{3}},\mathbf{1},1/3)_a$$

QUARKS

$$a = \mathbf{1},\mathbf{2},\mathbf{3}$$

FAMILY INDEX

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[*] H. Georgi and S.L. Glashow (1974).

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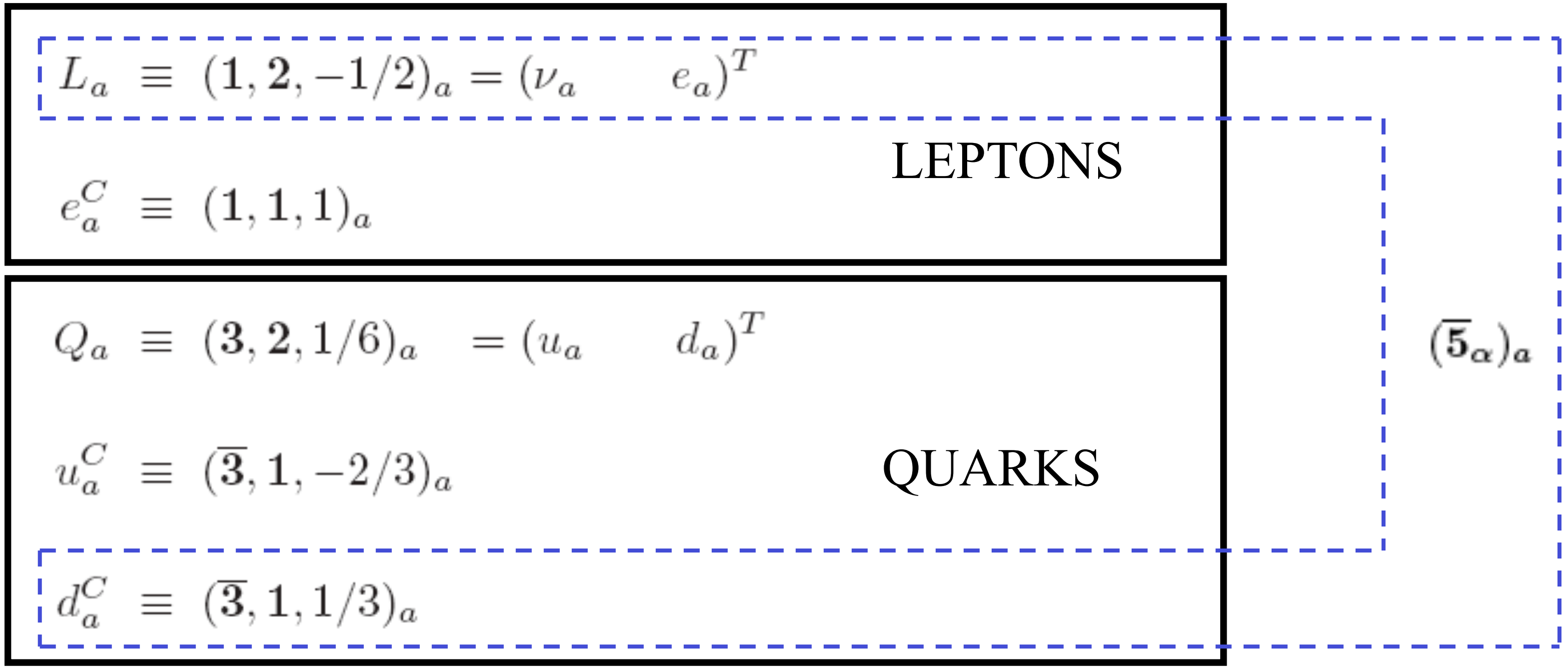

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LEPTONS

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QUARKS

$(\overline{\mathbf{5}}_{\boldsymbol{\alpha}})_{\boldsymbol{a}}$

$a = 1, 2, 3$
FAMILY INDEX

$\alpha, \beta = 1, 2, 3, 4, 5$
SU(5) GROUP INDICES

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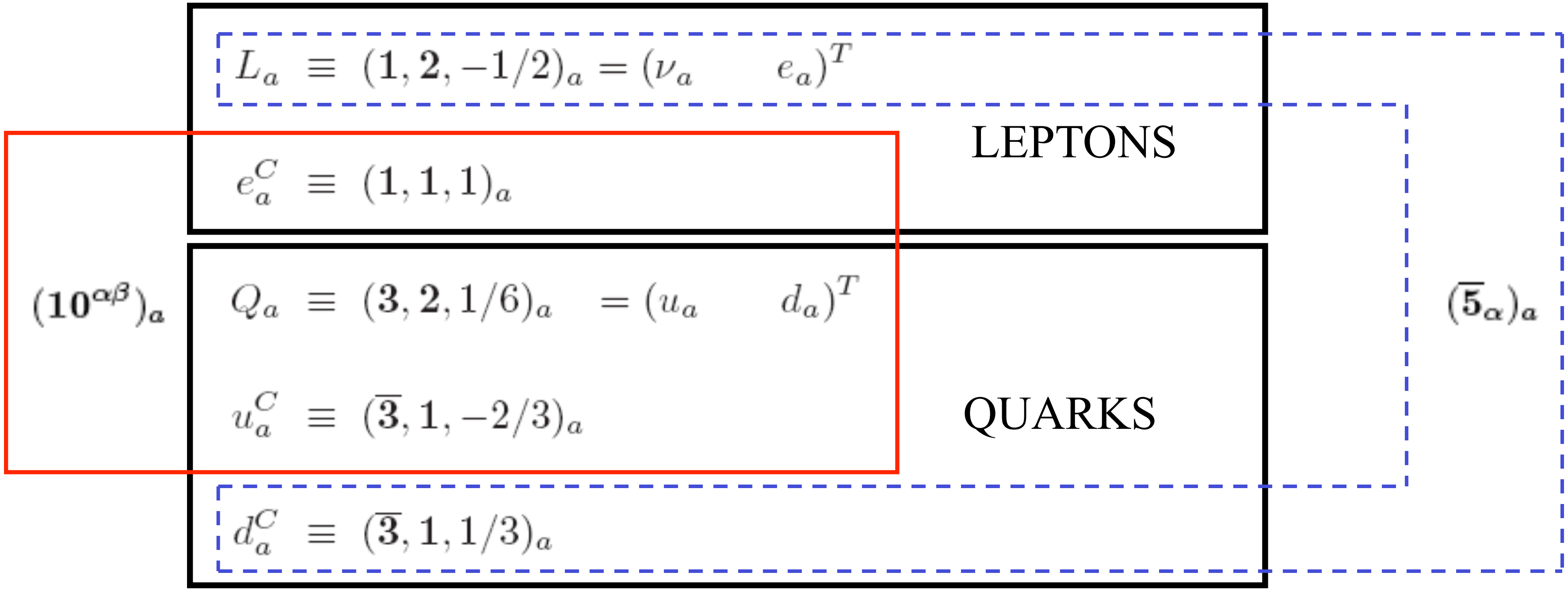
CASE STUDY: AN *SU*(5) SCENARIO[*]

FERMIONS OF THE STANDARD MODEL:



$L_a \equiv (\mathbf{1},\mathbf{2},-1/2)_a = (\nu_a \quad e_a)^T$

$e^C_a \equiv (\mathbf{1},\mathbf{1},1)_a$

LEPTONS

$(\mathbf{10}^{\alpha\beta})_a$

$Q_a \equiv (\mathbf{3},\mathbf{2},1/6)_a = (u_a \quad d_a)^T$

$u^C_a \equiv (\bar{\mathbf{3}},\mathbf{1},-2/3)_a$

QUARKS

$d^C_a \equiv (\bar{\mathbf{3}},\mathbf{1},1/3)_a$

$(\bar{\mathbf{5}}_\alpha)_a$

$a = 1,2,3$
FAMILY INDEX

$\alpha,\beta = 1,2,3,4,5$
SU(5) GROUP INDICES

[*] H. Georgi and S.L. Glashow (1974).

FERMION MASSES

(SCALAR REPRESENTATIONS IN *SU*(5))

$$\boxed{\mathbf{10} \times \overline{\mathbf{5}} = \mathbf{5} \oplus \mathbf{45} \ : \ M_E, M_D}$$

$$\boxed{\overline{\mathbf{5}} \times \overline{\mathbf{5}} = \overline{\mathbf{10}} \oplus \overline{\mathbf{15}} \ : \ M_N}$$

$$\boxed{\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \overline{\mathbf{50}} \ : \ M_U}$$

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$$\boxed{\mathbf{10}\times\mathbf{10}=\overline{\mathbf{5}}\oplus\overline{\mathbf{45}}\oplus\overline{\mathbf{50}}\ :\ M_U}$$

5 **10** **15** **45** **50**

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$$\boxed{\mathbf{10}\times\mathbf{10}=\overline{\mathbf{5}}\oplus\overline{\mathbf{45}}\oplus\cancel{\overline{\mathbf{50}}}\ :\ M_U}$$

$\mathbf{5}$ $\cancel{\mathbf{10}}$ $\mathbf{15}$ $\mathbf{45}$ $\cancel{\mathbf{50}}$

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$\mathbf{5}$ $\quad\cancel{\mathbf{10}}$ $\quad\mathbf{15}$ $\quad\mathbf{45}$ $\quad\cancel{\mathbf{50}}$

$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{5}^*$

$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{45}^*$

$(\overline{\mathbf{5}})_i(\overline{\mathbf{5}})_j\mathbf{15}$

$(\mathbf{10})_i(\mathbf{10})_j\mathbf{5}$

$(\mathbf{10})_i(\mathbf{10})_j\mathbf{45}$

$i, j = 1, 2, 3$

FAMILY INDICES

FERMION MASSES

(SCALAR REPRESENTATIONS IN $SU(5)$)

$\mathbf{10} \times \overline{\mathbf{5}} = \mathbf{5} \oplus \mathbf{45}$: M_E, M_D

$\overline{\mathbf{5}} \times \overline{\mathbf{5}} = \cancel{\overline{\mathbf{10}}} \oplus \overline{\mathbf{15}}$: M_N

$\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \cancel{\overline{\mathbf{50}}}$: M_U

$\mathbf{5}$ $\cancel{\mathbf{10}}$ $\mathbf{15}$ $\mathbf{45}$ $\cancel{\mathbf{50}}$

$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{5}^*$		$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{45}^*$	M_E, M_D
	$(\overline{\mathbf{5}})_i(\overline{\mathbf{5}})_j\mathbf{15}$		M_N
$(\mathbf{10})_i(\mathbf{10})_j\mathbf{5}$		$(\mathbf{10})_i(\mathbf{10})_j\mathbf{45}$	M_U

$i, j = 1, 2, 3$

FAMILY INDICES

FERMION MASSES

(SCALAR REPRESENTATIONS IN *SU*(5))

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$\overline{\mathbf{5}} \times \overline{\mathbf{5}} = \cancel{\overline{\mathbf{10}}} \oplus \overline{\mathbf{15}} \ : \ M_N$

$\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \cancel{\overline{\mathbf{50}}} \ : \ M_U$

$\mathbf{5}$ $\cancel{\mathbf{10}}$ $\mathbf{15}$ * $\mathbf{45}$ $\cancel{\mathbf{50}}$

$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{5}^*$		$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{45}^*$	M_E, M_D
	$(\overline{\mathbf{5}})_i(\overline{\mathbf{5}})_j\mathbf{15}$		M_N
$(\mathbf{10})_i(\mathbf{10})_j\mathbf{5}$		$(\mathbf{10})_i(\mathbf{10})_j\mathbf{45}$	M_U

$i, j = 1, 2, 3$
FAMILY INDICES

*I.D., Pavel Fileviez Pérez, *Nucl. Phys.* **B** 723 (2005) 53-76.

FERMION MASSES

(SCALAR REPRESENTATIONS IN $SU(5)$)

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$\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \cancel{\overline{\mathbf{50}}} \; : \; M_U$

$\mathbf{5}$

$\mathbf{45}$

$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{5}^*$		$(\mathbf{10})_i(\overline{\mathbf{5}})_j\mathbf{45}^*$	M_E, M_D
$(\mathbf{10})_i(\mathbf{10})_j\mathbf{5}$		$(\mathbf{10})_i(\mathbf{10})_j\mathbf{45}$	M_U

LEPTOQUARKS IN *SU*(5)

$$\mathbf{5} = (D, T)$$

$$\begin{aligned} D &= (\mathbf{1}, \mathbf{2}, 1/2) \\ T &= (\mathbf{3}, \mathbf{1}, -1/3) \end{aligned}$$

$$\mathbf{45} = (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$

$$\begin{aligned} \Delta_1 &= (\mathbf{8}, \mathbf{2}, 1/2) \\ \Delta_2 &= (\overline{\mathbf{6}}, \mathbf{1}, -1/3) \\ \Delta_3 &= (\mathbf{3}, \mathbf{3}, -1/3) \\ \Delta_4 &= (\overline{\mathbf{3}}, \mathbf{2}, -7/6) \\ \Delta_5 &= (\mathbf{3}, \mathbf{1}, -1/3) \\ \Delta_6 &= (\overline{\mathbf{3}}, \mathbf{1}, 4/3) \\ \Delta_7 &= (\mathbf{1}, \mathbf{2}, 1/2) \end{aligned}$$

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$$\underline{\Delta_7 \;=\; (\mathbf{1}, \mathbf{2}, 1/2)}$$

– – – ≡ Higgs doublet

LEPTOQUARKS IN *SU*(5)

$$\mathbf{5} = (D, T)$$

$$D = (\mathbf{1}, \mathbf{2}, 1/2)$$

- - - - - - - - -

$$T = (\mathbf{3}, \mathbf{1}, -1/3)$$

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$$\underline{\Delta_4 = (\overline{\mathbf{3}}, \mathbf{2}, -7/6)^{*}}$$

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- - - - - - - - -

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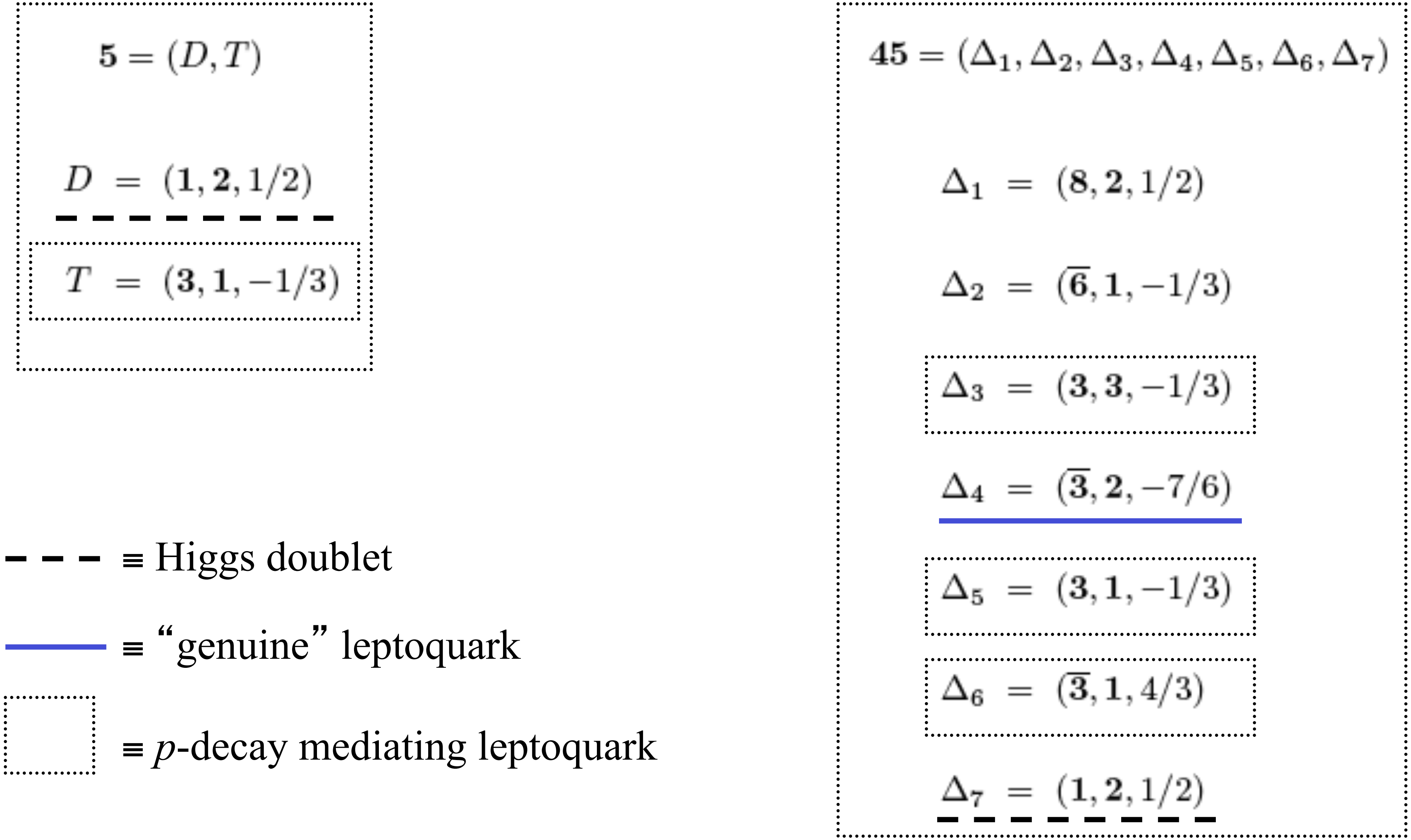
—— ≡ “genuine” leptoquark

*I.D., Svjetlana Fajfer, Jernej F. Kamenik and Nejc Košnik, *Phys. Lett.* **B** 682 (2009) 67-73.

LEPTOQUARKS IN *SU*(5)

(*p*-DECAY MEDIATING LEPTOQUARK)



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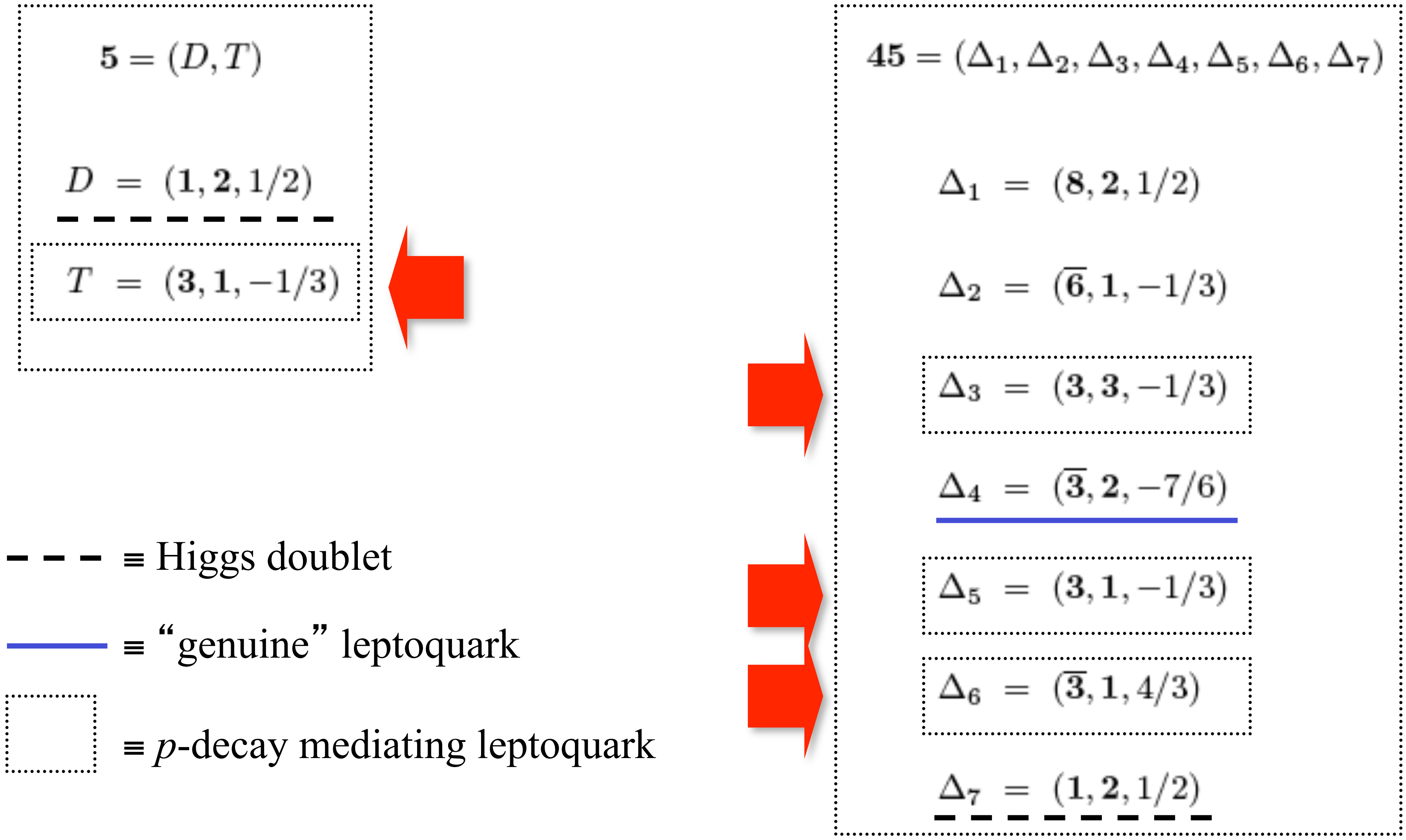
– – – ≡ Higgs doublet

— ≡ “genuine” leptoquark

☐ ≡ *p*-decay mediating leptoquark

LEPTOQUARKS IN *SU*(5)

(*p*-DECAY MEDIATING LEPTOQUARK)



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- - - ≡ Higgs doublet

— ≡ “genuine” leptoquark

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LEPTOQUARKS IN *SU*(5)

(*p*-DECAY MEDIATING SCALAR LEPTOQUARKS)

$$\mathbf{5} = (D, T)$$

$$D \;=\; (\mathbf{1}, \mathbf{2}, 1/2)$$

$$\boxed{T \;=\; (\mathbf{3}, \mathbf{1}, -1/3)}$$

$$\mathbf{10} = (\Psi_a, \Psi_b, \Psi_c)$$

$$\Psi_a \;=\; (\mathbf{1}, \mathbf{1}, 1)$$

$$\boxed{\Psi_b \;=\; (\overline{\mathbf{3}}, \mathbf{1}, -2/3)}$$

$$\Psi_c \;=\; (\mathbf{3}, \mathbf{2}, 1/6)$$

$$\mathbf{45} = (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$

$$\Delta_1 \;=\; (\mathbf{8}, \mathbf{2}, 1/2)$$

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□ ≡ *p*-decay mediating leptoquark

LEPTOQUARKS IN *SU*(5)

(*p*-DECAY MEDIATING SCALAR LEPTOQUARKS)

ALL IN ALL, THERE ARE EIGHTEEN (FIFTEEN) PROTON DECAY MEDIATING SCALARS IF NEUTRINOS ARE DIRAC (MAJORANA)!*

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*I.D., Svjetlana Fajfer and Nejc Košnik, work in progress.

LEPTOQUARKS IN THE 5 OF *SU*(5) *

(*p*-DECAY MEDIATING SCALAR LEPTOQUARKS)

*I.D., Svjetlana Fajfer and Nejc Košnik, work in progress.

T

$(\mathbf{3}, \mathbf{1}, -1/3)$

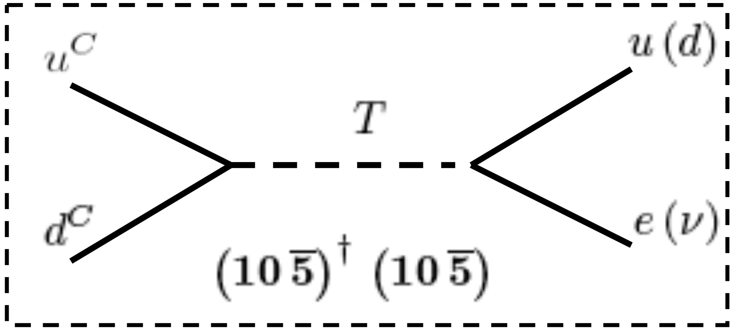
$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\alpha)_j\mathbf{5}^*_\beta$

$M_E = M_D^T$

$u^{C\,T}_{a\,i} C d^C_{b\,j} T^*_c$

$u^T_{a\,i} C e_j T^*_a$

$d^T_{a\,i} C \nu_j T^*_a$

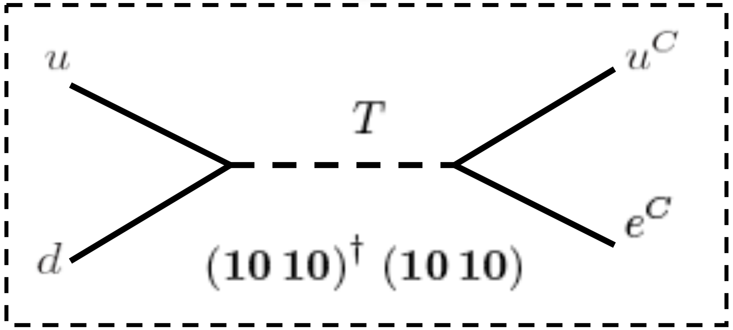


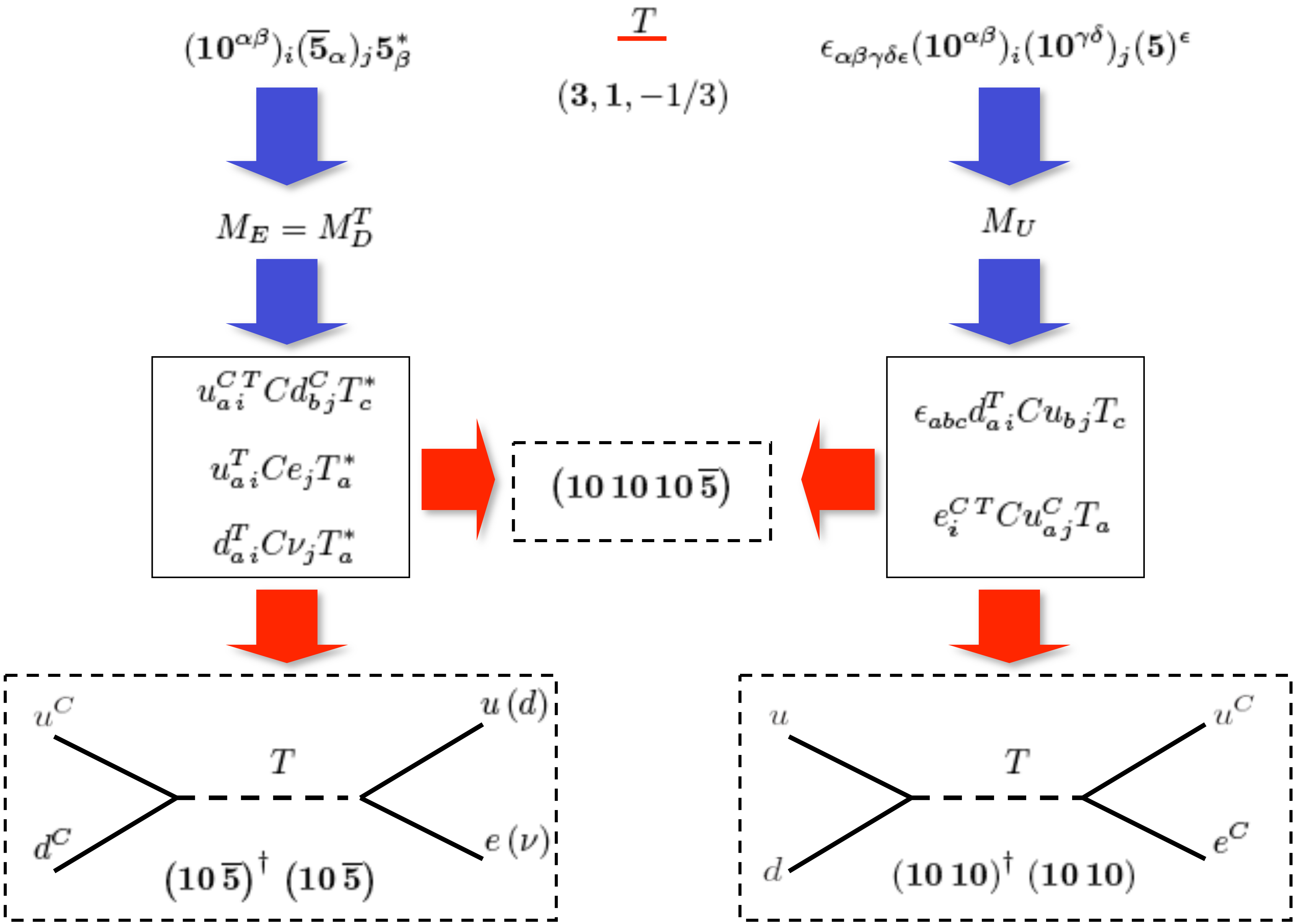
$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$

M_U

$\epsilon_{abc} d^T_{a\,i} C u_{b\,j} T_c$

$e^{C\,T}_i C u^C_{a\,j} T_a$





$\underline{T}$

$(\mathbf{3}, \mathbf{1}, -1/3)$

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\alpha)_j \mathbf{5}^*_\beta$

$M_E = M_D^T$

$u^{C\,T}_{a\,i} C d^C_{b\,j} T^*_c$

$u^T_{a\,i} C e_j T^*_a$

$d^T_{a\,i} C \nu_j T^*_a$

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$

M_U

$\epsilon_{abc} d^T_{a\,i} C u_{b\,j} T_c$

$e^{C\,T}_i C u^C_{a\,j} T_a$

$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$

$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\ (\mathbf{10}\,\overline{\mathbf{5}})$

$(\mathbf{10}\,\mathbf{10})^\dagger\ (\mathbf{10}\,\mathbf{10})$

LEPTOQUARKS IN THE 5 OF *SU*(5)

(*p*-DECAY MEDIATING SCALAR LEPTOQUARKS)

$$\Gamma(p \to e^+\pi^0) \sim \frac{\alpha^2}{v_5^4 m_\Delta^4}\left|\frac{3}{8}(V_{UD})_{11}(V_{UD})_{13} m_\tau m_b\right|^2$$

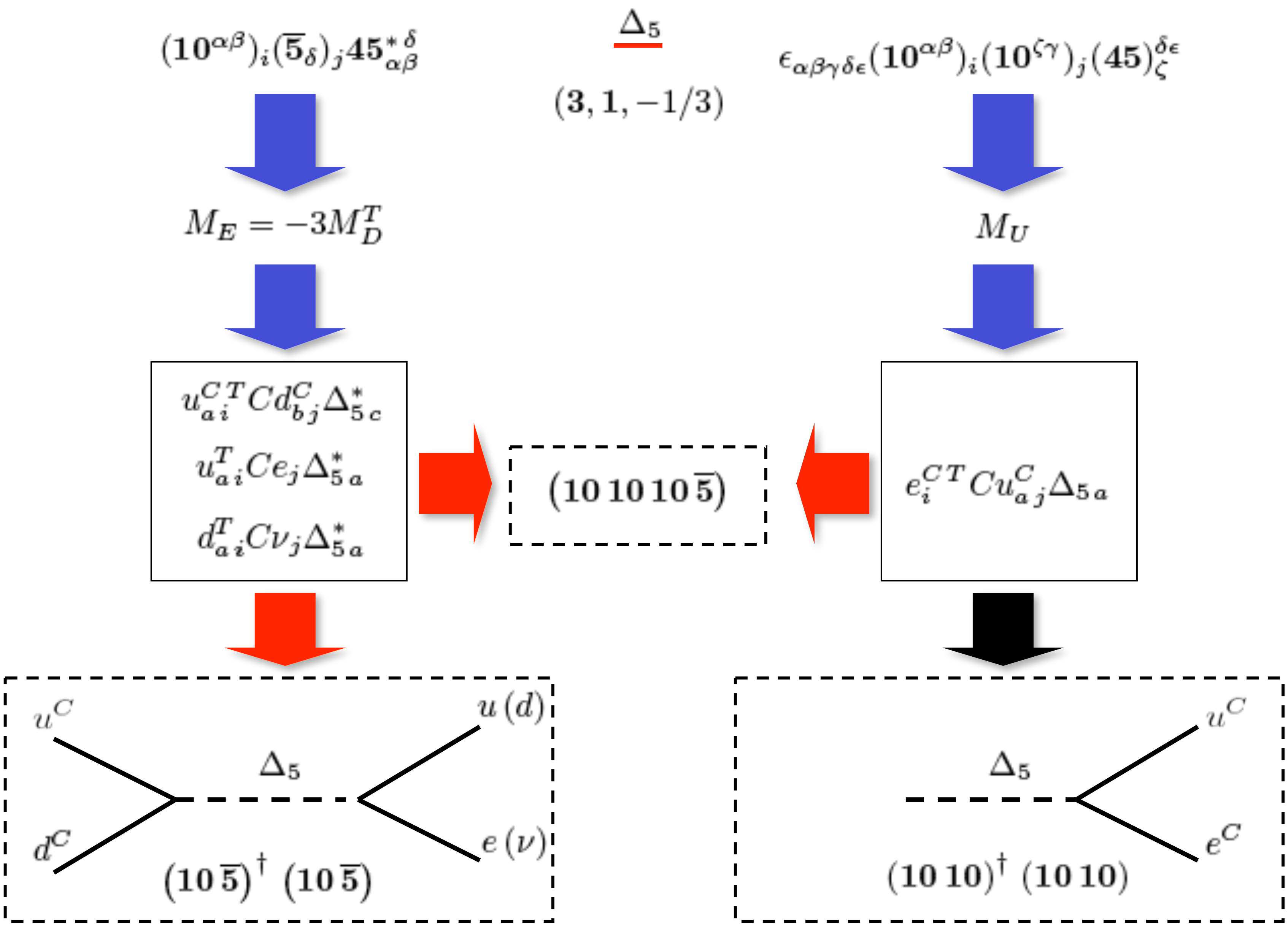
$$\Gamma(p \to \mu^+\pi^0) \sim \frac{\alpha^2}{v_5^4 m_\Delta^4}\left|\frac{3}{8}(V_{UD})_{11}(V_{UD})_{12} m_\tau m_s\right|^2$$

*I.D., Svjetlana Fajfer and Nejc Košnik, work in progress.

LEPTOQUARKS IN THE 45 OF *SU*(5) *

(*p*-DECAY MEDIATING SCALAR LEPTOQUARKS)

*I.D., Svjetlana Fajfer and Nejc Košnik, work in progress.



$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$\underline{\Delta_5}$

$(\mathbf{3},\mathbf{1},-1/3)$

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_{\zeta}$

$M_E = -3M_D^T$

M_U

$u^{C\,T}_{a\,i}Cd^C_{b\,j}\Delta^*_{5\,c}$

$u^T_{a\,i}Ce_j\Delta^*_{5\,a}$

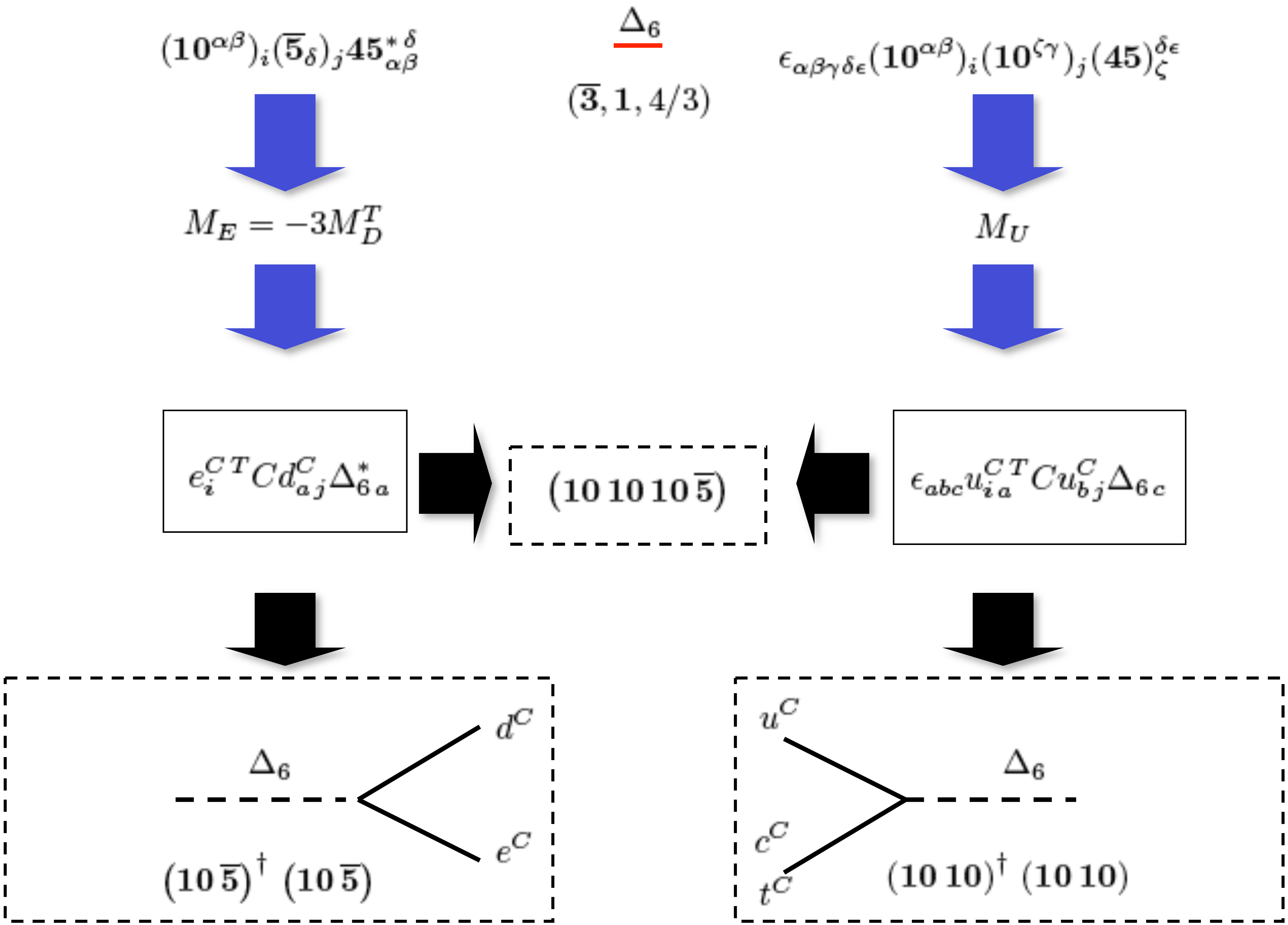
$d^T_{a\,i}C\nu_j\Delta^*_{5\,a}$

$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$

$e^{C\,T}_i Cu^C_{a\,j}\Delta_{5\,a}$

$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\,(\mathbf{10}\,\overline{\mathbf{5}})$

$(\mathbf{10}\,\mathbf{10})^\dagger\,(\mathbf{10}\,\mathbf{10})$



$\underline{\Delta_6}$

$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$M_E = -3M_D^T$

$e_i^{C\,T} C d^C_{a\,j} \Delta^*_{6\,a}$

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_{\zeta}$

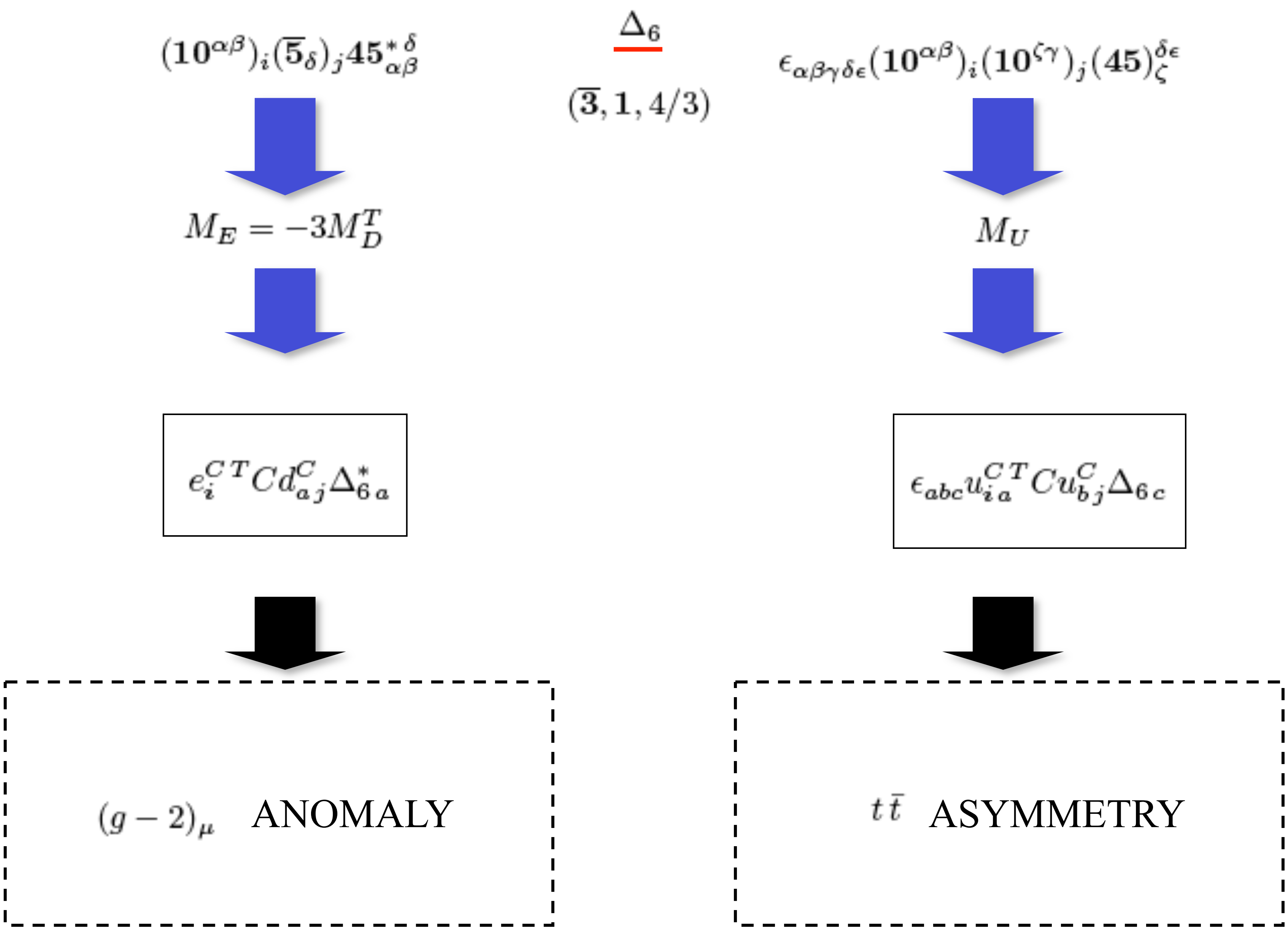
M_U

$\epsilon_{abc} u^{C\,T}_{i\,a} C u^C_{b\,j} \Delta_{6\,c}$

$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$

$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\;(\mathbf{10}\,\overline{\mathbf{5}})$

$(\mathbf{10}\,\mathbf{10})^\dagger\;(\mathbf{10}\,\mathbf{10})$



$\underline{\Delta_6}$

$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$M_E = -3M_D^T$

$e_i^{C\,T} C d^C_{a\,j} \Delta^*_{6\,a}$

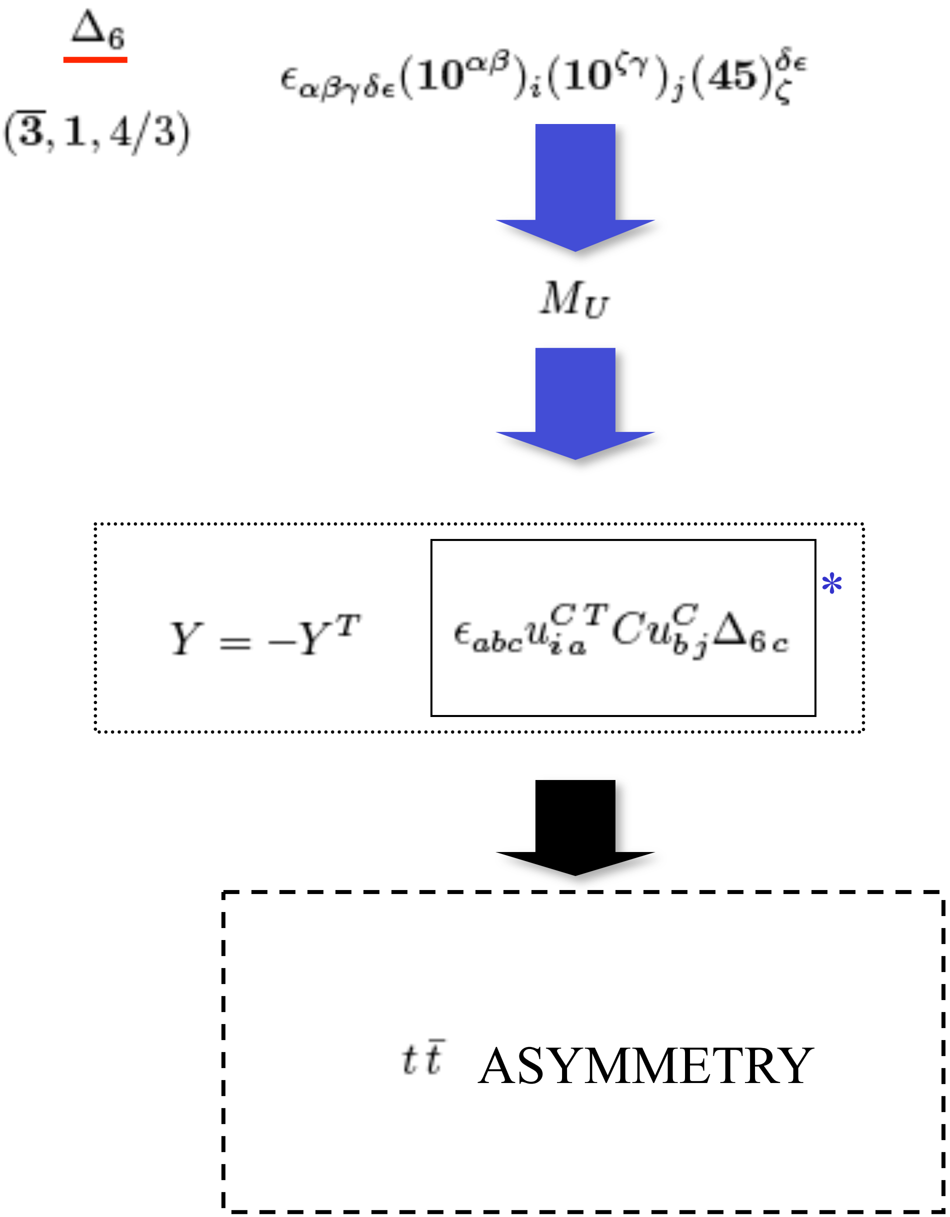
$(g-2)_\mu$ ANOMALY

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_{\zeta}$

M_U

$\epsilon_{abc} u^{C\,T}_{i\,a} C u^C_{b\,j} \Delta_{6\,c}$

$t\,\bar{t}$ ASYMMETRY



$\underline{\Delta_6}$

$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_{\zeta}$

M_U

$Y = -Y^T$

$\boxed{\epsilon_{abc} u^{C\,T}_{i\,a} C u^{C}_{b\,j} \Delta_{6\,c}}$ *

$t\bar{t}$ ASYMMETRY

*I.D., Svjetlana Fajfer, Jernej F. Kamenik and Nejc Košnik, *Phys. Rev.* **D** 81 (2010) 055009, *Phys. Rev.* **D** 82 (2010) 094015.

Δ_6 LEPTOQUARK: UP-QUARK SECTOR

CONSTRAINTS ON Y ORIGINATE FROM
THE UP-QUARK PHENOMENOLOGY!

$m_{\Delta_6} = 400\,\mathrm{GeV}$

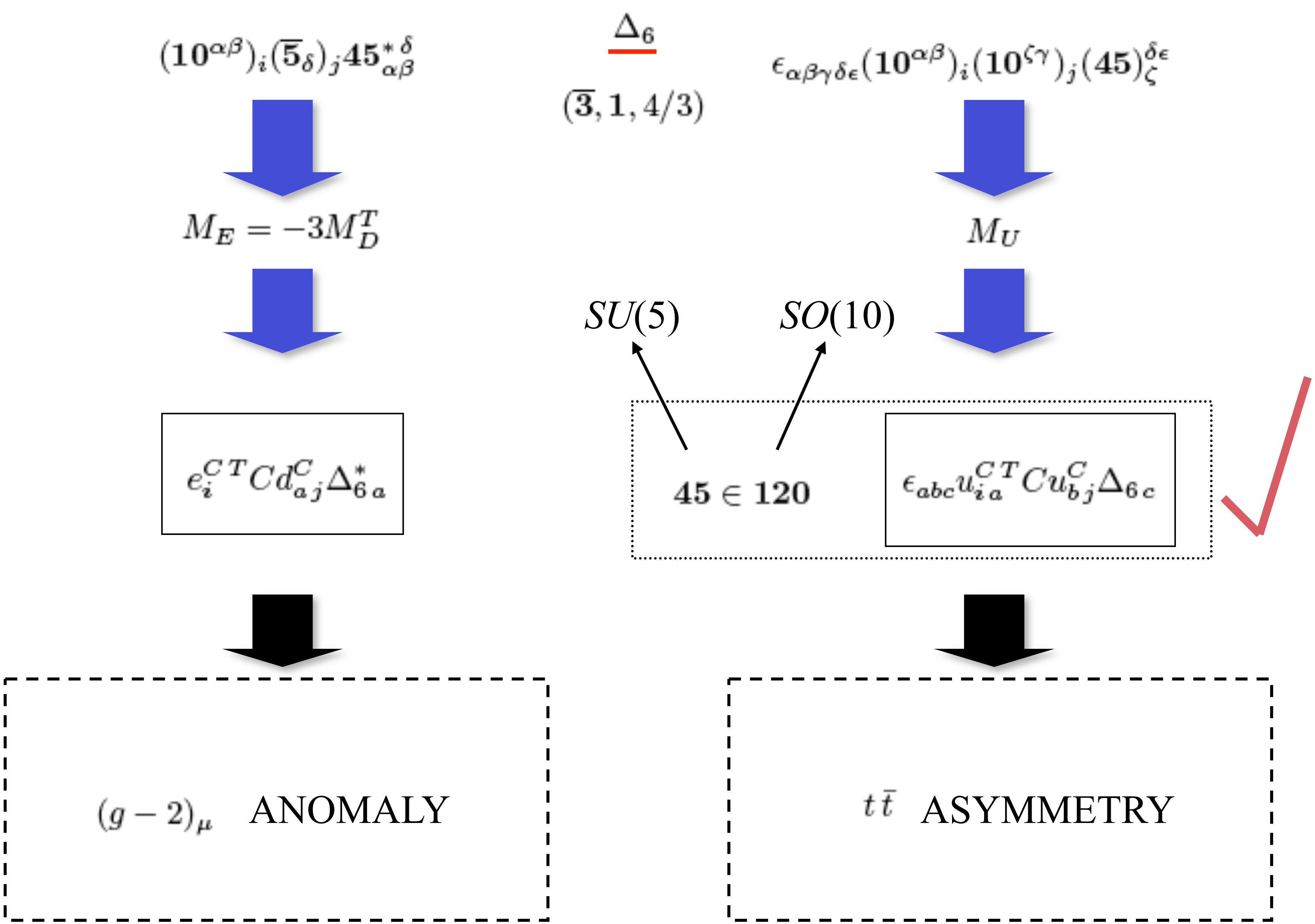
$t\,\bar{t}$ FORWARD-BACKWARD (FB)
ASYMMETRY AT TEVATRON

$|Y_{13}| \ = \ 1.9$

$|Y_{23}| \ \leq \ 0.0033$ → $D^0 - \bar{D}^0$ MIXING CONSTRAINTS

$|Y_{12}| \ \leq \ 0.042$

SINGLE t PRODUCTION CROSS-SECTION
AT TEVATRON



$\underline{\Delta_6}$

$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$

$(\mathbf{10}^{\alpha\beta})_i (\overline{\mathbf{5}}_\delta)_j \mathbf{45}^{*\,\delta}_{\alpha\beta}$

$M_E = -3 M_D^T$

$\boxed{e_i^{C\,T} C d^C_{a\,j} \Delta^*_{6\,a}}$

$(g-2)_\mu$ ANOMALY

$\epsilon_{\alpha\beta\gamma\delta\epsilon} (\mathbf{10}^{\alpha\beta})_i (\mathbf{10}^{\zeta\gamma})_j (\mathbf{45})^{\delta\epsilon}_\zeta$

M_U

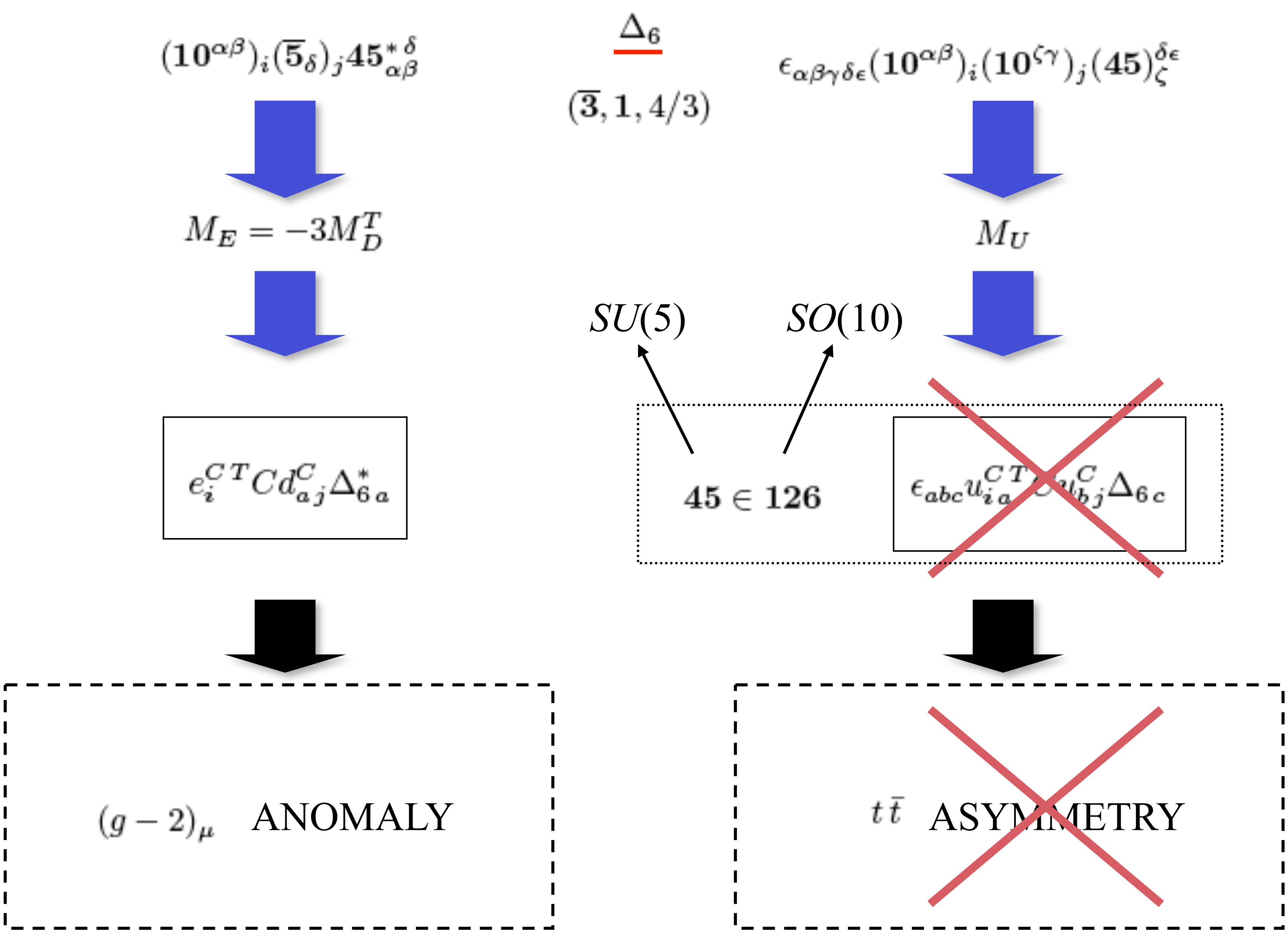
$SU(5)$ $SO(10)$

$\mathbf{45} \in \mathbf{120}$

$\boxed{\epsilon_{abc} u^{C\,T}_{i\,a} C u^C_{b\,j} \Delta_{6\,c}}$

✓

$t\,\bar{t}$ ASYMMETRY



$\underline{\Delta_6}$

$(\overline{\mathbf{3}},\mathbf{1},4/3)$

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$M_E=-3M_D^T$

$e_i^{C\,T}Cd^C_{a\,j}\Delta^*_{6\,a}$

$(g-2)_\mu$ ANOMALY

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_\zeta$

M_U

SU(5)

SO(10)

$\mathbf{45}\in\mathbf{126}$

$\xcancel{\epsilon_{abc}u^{C\,T}_{i\,a}Cu^C_{b\,j}\Delta_{6\,c}}$

$t\,\bar{t}$ ~~ASYMMETRY~~

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$\underline{\Delta_6} \in \mathbf{126}$

$(\overline{\mathbf{3}},\mathbf{1},4/3)$

$M_E = -3M_D^T$

$Y \quad \boxed{e_i^{C\,T} C d^C_{a\,j} \Delta^*_{6\,a}}$ *

$(g-2)_\mu$ ANOMALY

*I.D., Jure Drobnak, Svjetlana Fajfer, Jernej F. Kamenik and Nejc Košnik, , JHEP (2011) 1111:002.

Δ_6 LEPTOQUARK: THE DOWN-QUARK AND CHARGED LEPTON SECTORS

*

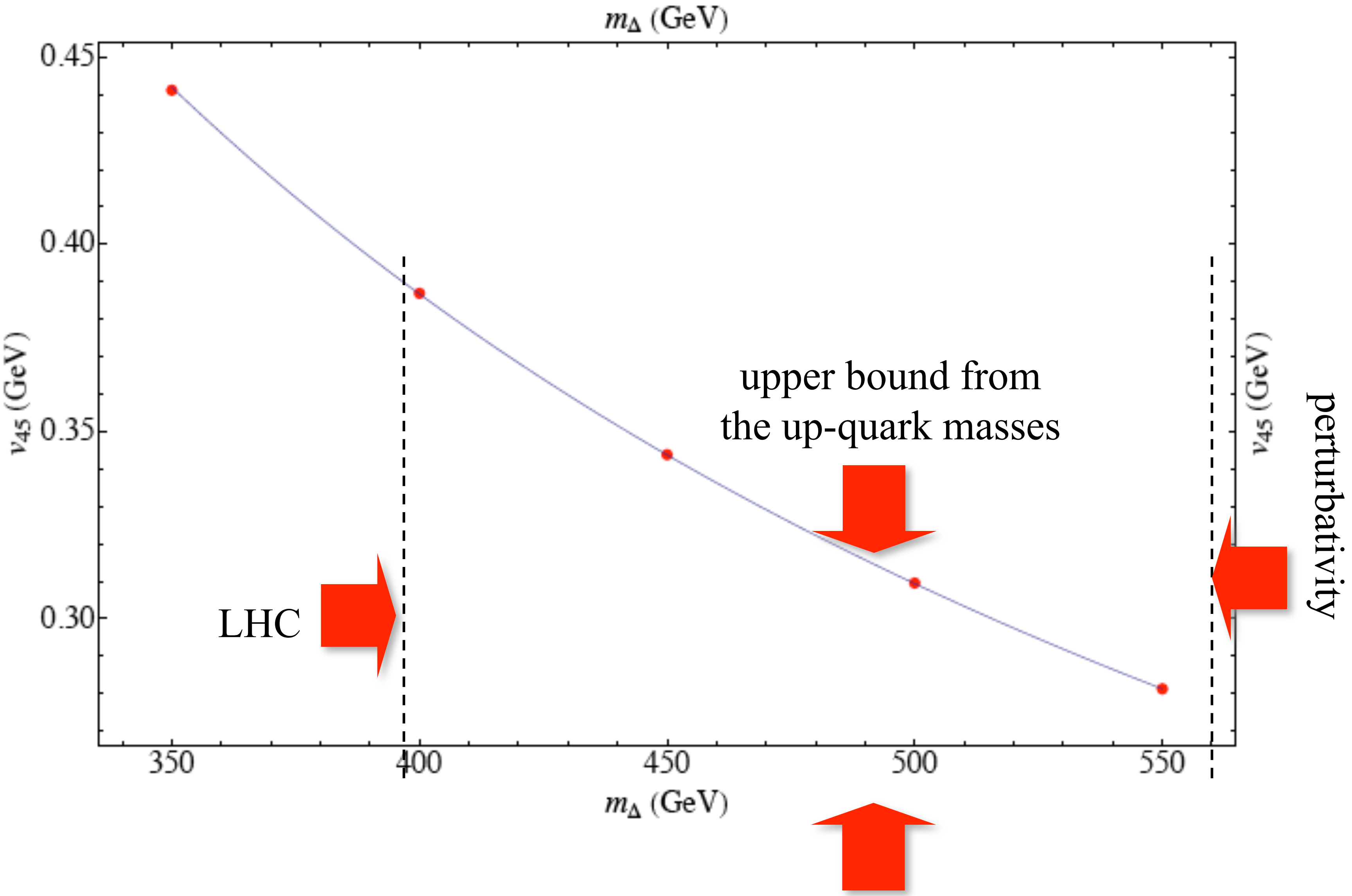
$$|Y^{(1\,\sigma)}| \;\in\; \begin{pmatrix} < 1.4\times 10^{-6} & < 8.7\times 10^{-5} & < 4.1\times 10^{-4} \\ < 3.6\times 10^{-3}\cup[2.1, 2.9] & < 3.6\times 10^{-3}\cup[2.1, 2.9] & < 6.2\times 10^{-4}\cup[2.2, 2.8] \\ < 5.6\times 10^{-3} & < 8.1\times 10^{-3} & < 9.6\times 10^{-3} \end{pmatrix}$$

⦀

$$\begin{pmatrix} 0 & 0 & 0 \\ \blacksquare & 0 & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \qquad \begin{pmatrix} 0 & 0 & 0 \\ 0 & \blacksquare & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \qquad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \blacksquare \\ \bullet & \bullet & \bullet \end{pmatrix}$$

*I.D., Jure Drobnak, Svjetlana Fajfer, Jernej F. Kamenik and Nejc Košnik, , JHEP (2011) 1111:002.

IMPLICATIONS FOR THE UP-QUARK SECTOR



LHC

upper bound from
the up-quark masses

perturbativity

lower bound from the down-quark
and charged lepton masses

CONCLUSIONS

Leptoquark states represent qualitatively new physics.

Proton decay operators induced via scalar leptoquark exchanges exhibit strong model dependence.

That feature opens up possibilities for existence of light leptoquark states with interesting phenomenological consequences without conflict with proton stability.

CONCLUSIONS

Light scalar leptoquarks can, for example address the issue of $(g-2)_\mu$ anomaly or $t\bar{t}$ asymmetry.

Scenarios that incorporate light leptoquarks could thus be directly probed at colliders.

<u>THANK YOU!</u>

CONTACT E-MAIL:

ILJA.DORSNER@IJS.SI

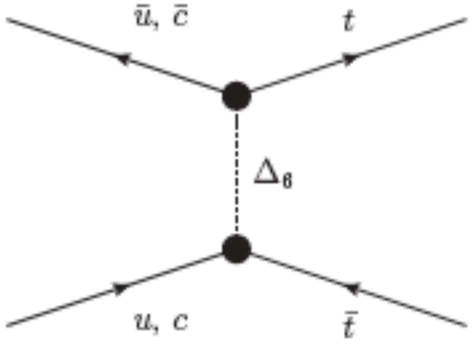
FORWARD-BACKWARD ASYMMETRY

SIMULTANEOUS FIT TO THE INTEGRATED CROSS SECTION $\sigma^{\exp}$ AND A_{FB}

$$A_{FB}^{\exp} - A_{FB}^{\mathrm{SM}} = (14.2 \pm 6.9)\%$$

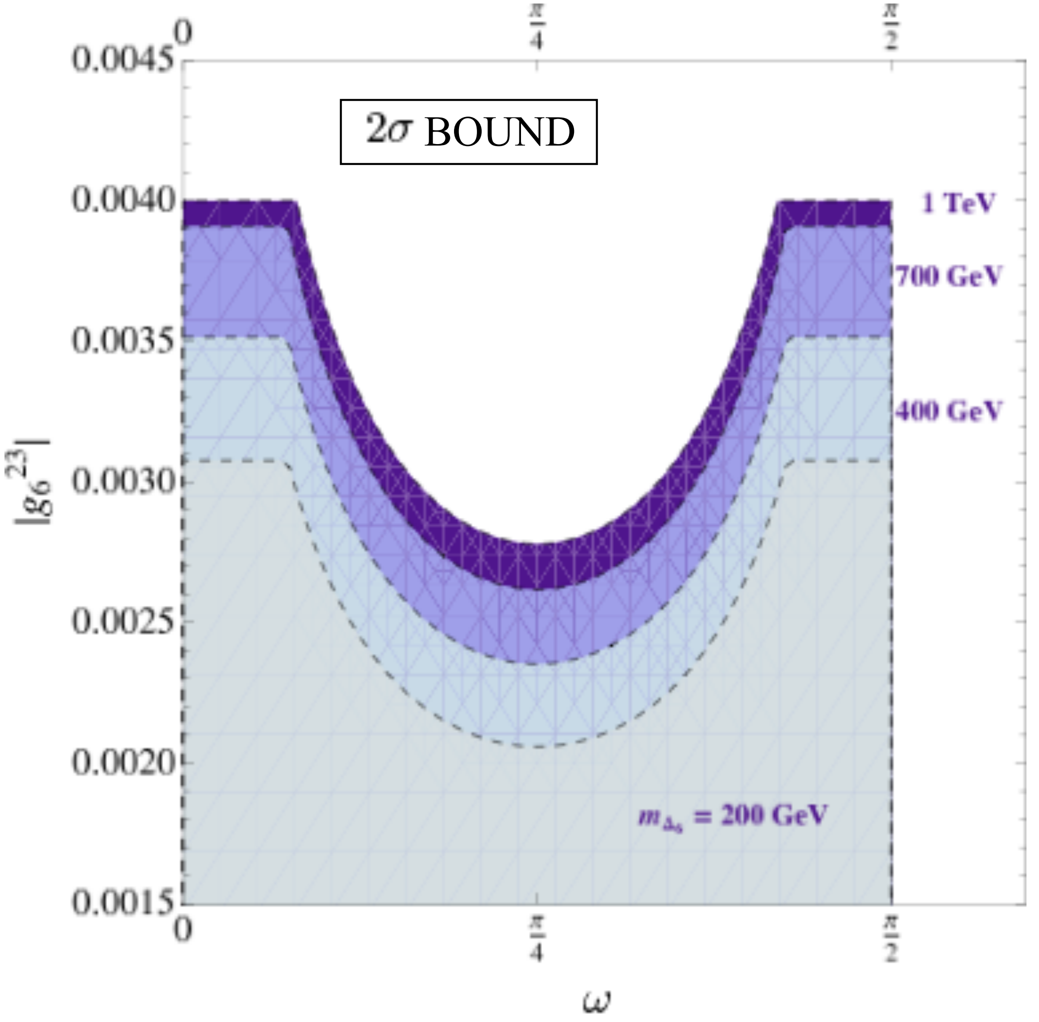
$$\sigma^{\exp} = 7.0 \pm 0.6\,\mathrm{pb}$$

$$\longrightarrow \boxed{|g_6^{13}| = 0.9(2) + 2.5(4)\frac{m_{\Delta_6}}{1\ \mathrm{TeV}}}$$



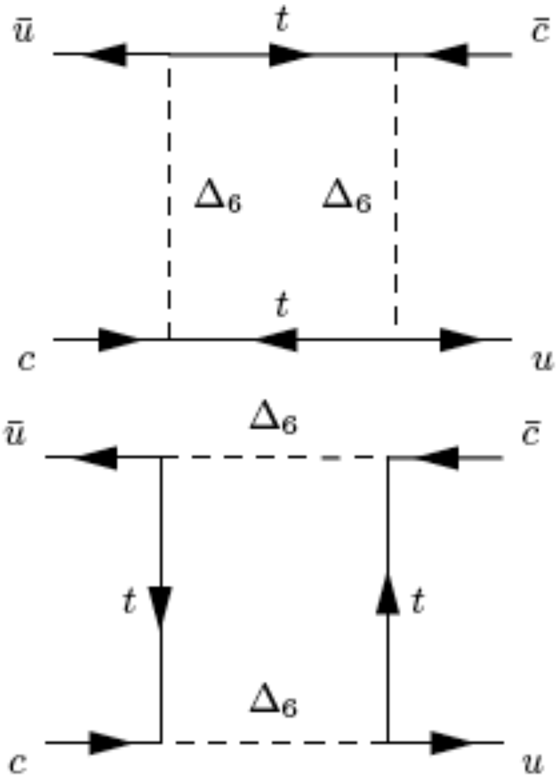
LEADING CONTRIBUTIONS TO $t\,\bar{t}$ PRODUCTION CROSS SECTION AND A_{FB} AT TEVATRON.

$D^0 - \bar{D}^0$ MIXING CONSTRAINTS



ω ≡ RELATIVE PHASE BETWEEN g_6^{13} AND g_6^{23}

$(g_6^{13} g_6^{23*})^2$ CONTRIBUTIONS TO $|\Delta C| = 2$:

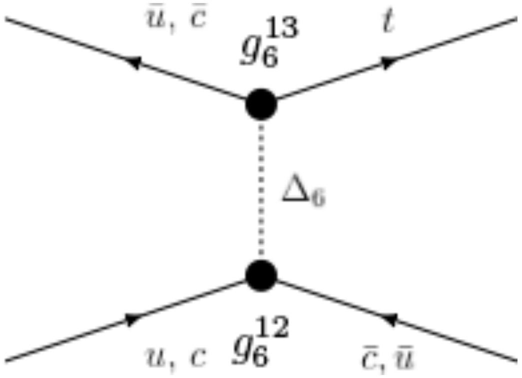


$m_{\Delta_6} = 400\,\mathrm{GeV}$

$|g_6^{23}| \leq 0.0033$

SINGLE *t* PRODUCTION CROSS-SECTION

THE SINGLE *t* PRODUCTION IS SENSITIVE TO THE PRODUCT $|g_6^{12} g_6^{13*}|$.

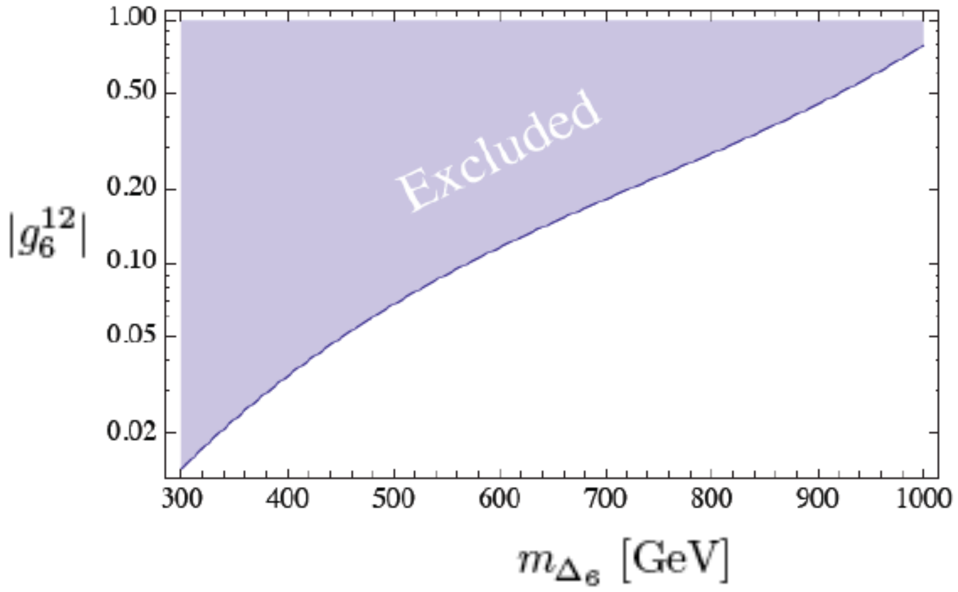


$$m_{\Delta_6} = 400\,\mathrm{GeV}$$

$$|g_6^{12}| \leq 0.042$$

TEVATRON RESULT: $\sigma_{1t} = 2.76^{+0.58}_{-0.47}\,\mathrm{pb}$

WE REQUIRE: $\sigma_{1t}^{\Delta_6} \leq 1\,\mathrm{pb}$



decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\text{ GeV})^4$
$B_d \to e^- e^+$	8.3×10^{-8}	$\lvert Y_{eb} Y^*_{ed}\rvert^2 < 4.4$
$B_d \to \mu^- \mu^+$	4.2×10^{-9}	$\lvert Y_{\mu b} Y^*_{\mu d}\rvert^2 < 5.0 \times 10^{-6}$
$B_d \to \tau^- \tau^+$	4.1×10^{-3}	$\lvert Y_{\tau b} Y^*_{\tau d}\rvert^2 < 1.3 \times 10^{-2}$
$B_s \to e^- e^+$	2.8×10^{-7}	$\lvert Y_{eb} Y^*_{es}\rvert^2 < 10.1$
$B_s \to \mu^- \mu^+$	1.2×10^{-8}	$\lvert Y_{\mu b} Y^*_{\mu s}\rvert^2 < 1.1 \times 10^{-5}$
$B_d \to e^\mp \mu^\pm$	6.4×10^{-8}	$\lvert Y_{eb} Y^*_{\mu d}\rvert^2 + \lvert Y_{\mu b} Y^*_{ed}\rvert^2 < 1.6 \times 10^{-4}$
$B_d \to \mu^\mp \tau^\pm$	2.2×10^{-5}	$\lvert Y_{\mu b} Y^*_{\tau d}\rvert^2 + \lvert Y_{\tau b} Y^*_{\mu d}\rvert^2 < 2.2 \times 10^{-4}$
$B_d \to \tau^\mp e^\pm$	2.8×10^{-5}	$\lvert Y_{\tau b} Y^*_{ed}\rvert^2 + \lvert Y_{eb} Y^*_{\tau d}\rvert^2 < 2.7 \times 10^{-4}$
$B_s \to e^\mp \mu^\pm$	2.0×10^{-7}	$\lvert Y_{eb} Y^*_{\mu s}\rvert^2 + \lvert Y_{\mu b} Y^*_{es}\rvert^2 < 3.4 \times 10^{-4}$

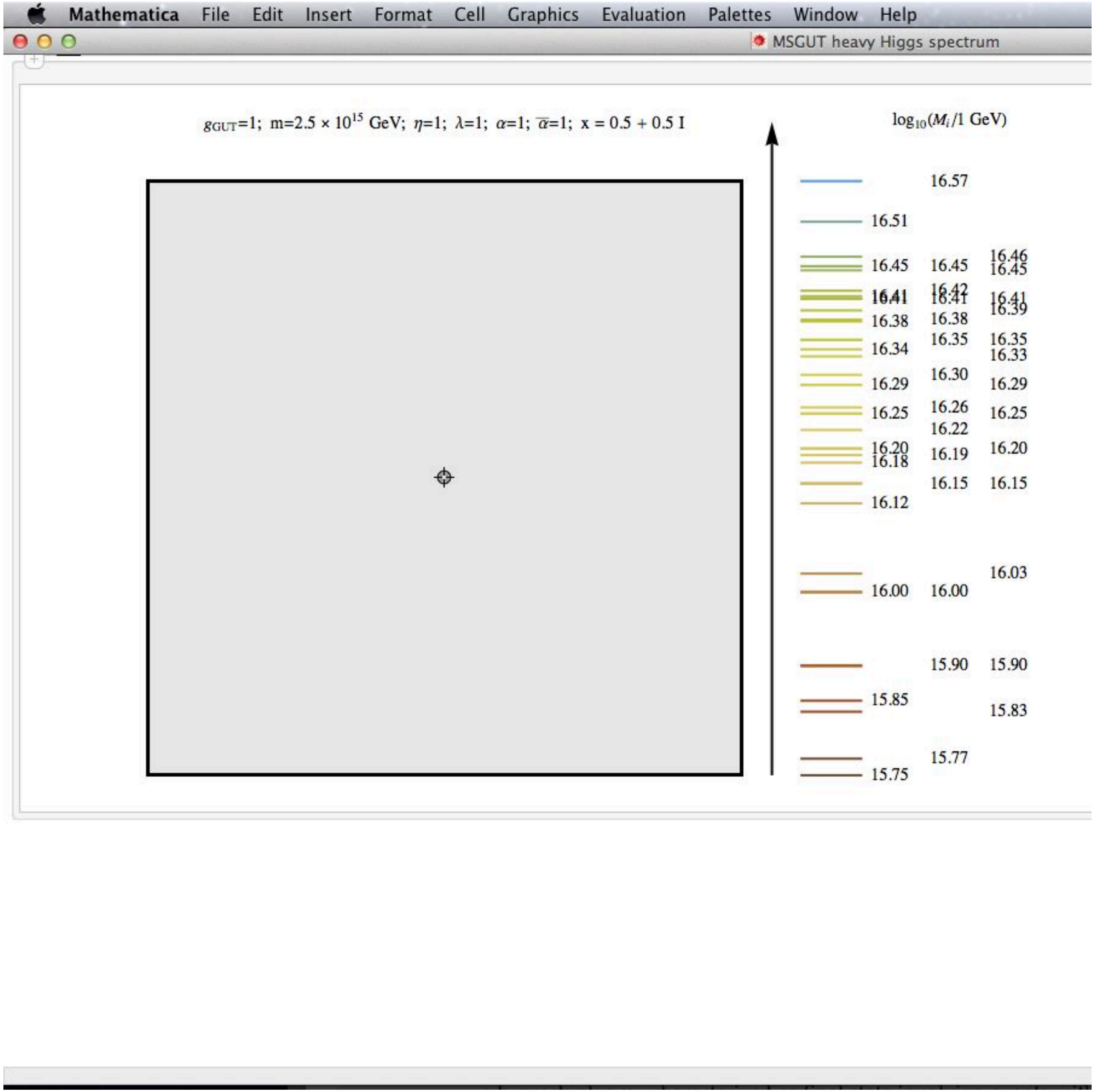
$$\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.87 \pm 0.93) \times 10^{-9}$$

$\lvert\epsilon_K\rvert$	$2.228(11) \times 10^{-3}$	[23]
Δm_K	$3.483(6) \times 10^{-15}$ GeV	[23]
ϕ_ϵ	$43.5(7)^\circ$	[23]
f_K	$0.1560(11)$ GeV	[27]
$\hat{B}_K$	$0.725(26)$	[27]
κ_ϵ	$0.94(2)$	[48]
η_1	$1.31(^{+25}_{-22})$	[49]
η_2	$0.57(1)$	[46, 50]
η_3	$0.496(47)$	[51]

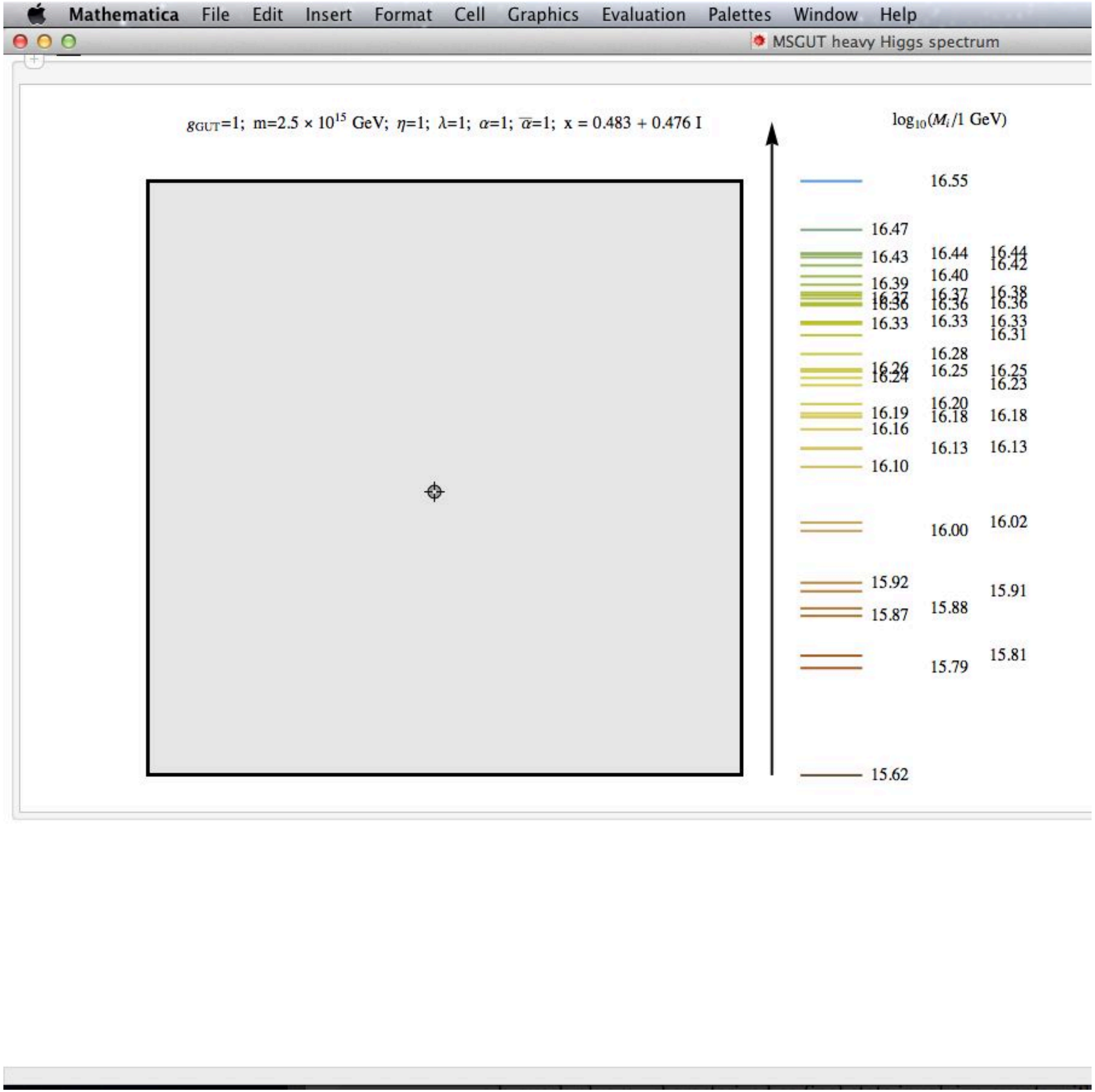
decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\text{ GeV})^4$
$B^+ \to \pi^+\ell^-\ell^+$	4.9×10^{-8}	$\left\lvert Y_{eb}Y^*_{ed}\right\rvert^2 + \left\lvert Y_{\mu b}Y^*_{\mu d}\right\rvert^2 < 3.0 \times 10^{-7}$
$B^+ \to \pi^+e^\pm\mu^\mp$	1.7×10^{-7}	$\left\lvert Y_{eb}Y^*_{\mu d}\right\rvert^2 + \lvert Y_{\mu b}Y^*_{ed}\rvert^2 < 1.1 \times 10^{-6}$
$B^+ \to K^+e^\pm\mu^\mp$	9.1×10^{-8}	$\left\lvert Y_{eb}Y^*_{\mu s}\right\rvert^2 + \lvert Y_{\mu b}Y^*_{es}\rvert^2 < 4.3 \times 10^{-7}$
$B^+ \to K^+\tau^\pm\mu^\mp$	7.7×10^{-5}	$\left\lvert Y_{\tau b}Y^*_{\mu s}\right\rvert^2 + \lvert Y_{\mu b}Y^*_{\tau s}\rvert^2 < 5.7 \times 10^{-4}$

decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\text{ GeV})^4$
$\tau \to e\pi^0$	8.0×10^{-8}	$\lvert Y_{ed}Y^*_{\tau d}\rvert^2 < 1.9 \times 10^{-4}$
$\tau \to \mu\pi^0$	1.1×10^{-7}	$\lvert Y_{\mu d}Y^*_{\tau d}\rvert^2 < 2.7 \times 10^{-4}$
$\tau \to eK_S$	3.3×10^{-8}	$\lvert Y_{ed}Y^*_{\tau s} - Y_{es}Y^*_{\tau d}\rvert^2 < 3.2 \times 10^{-5}$
$\tau \to \mu K_S$	4.0×10^{-8}	$\lvert Y_{\mu d}Y^*_{\tau s} - Y_{\mu s}Y^*_{\tau d}\rvert^2 < 4.0 \times 10^{-5}$
$\tau \to \mu\eta$	6.5×10^{-8}	$\lvert 0.69\, Y_{\mu d}Y^*_{\tau d} - Y_{\mu s}Y^*_{\tau s}\rvert^2 < 1.3 \times 10^{-4}$

decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\text{ GeV})^4$
$\mu \to e\gamma$	2.4×10^{-12}	$\lvert \sum_{i=d,s,b} Y_{ei}Y^*_{\mu i}\rvert^2 < 4.6 \times 10^{-8}$
$\tau \to \mu\gamma$	4.4×10^{-8}	$\lvert \sum_{i=d,s,b} Y_{\mu i}Y^*_{\tau i}\rvert^2 < 4.8 \times 10^{-3}$
$\tau \to e\gamma$	3.3×10^{-8}	$\lvert \sum_{i=d,s,b} Y_{ei}Y^*_{\tau i}\rvert^2 < 3.6 \times 10^{-3}$



$g_{\mathrm{GUT}}=1$; m=2.5×10^{15} GeV; $\eta=1$; $\lambda=1$; $\alpha=1$; $\overline{\alpha}=1$; x = 0.5 + 0.5 I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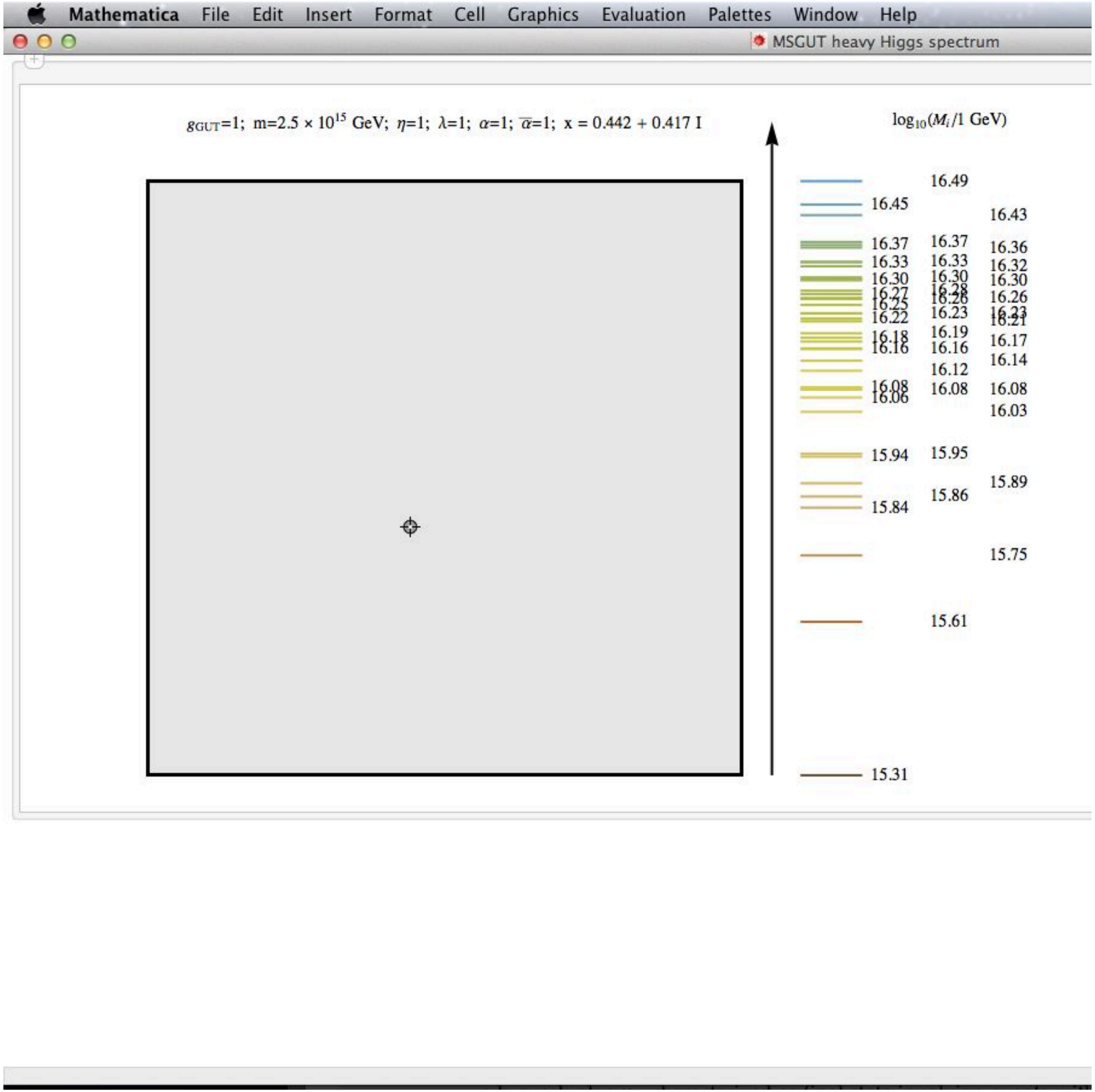
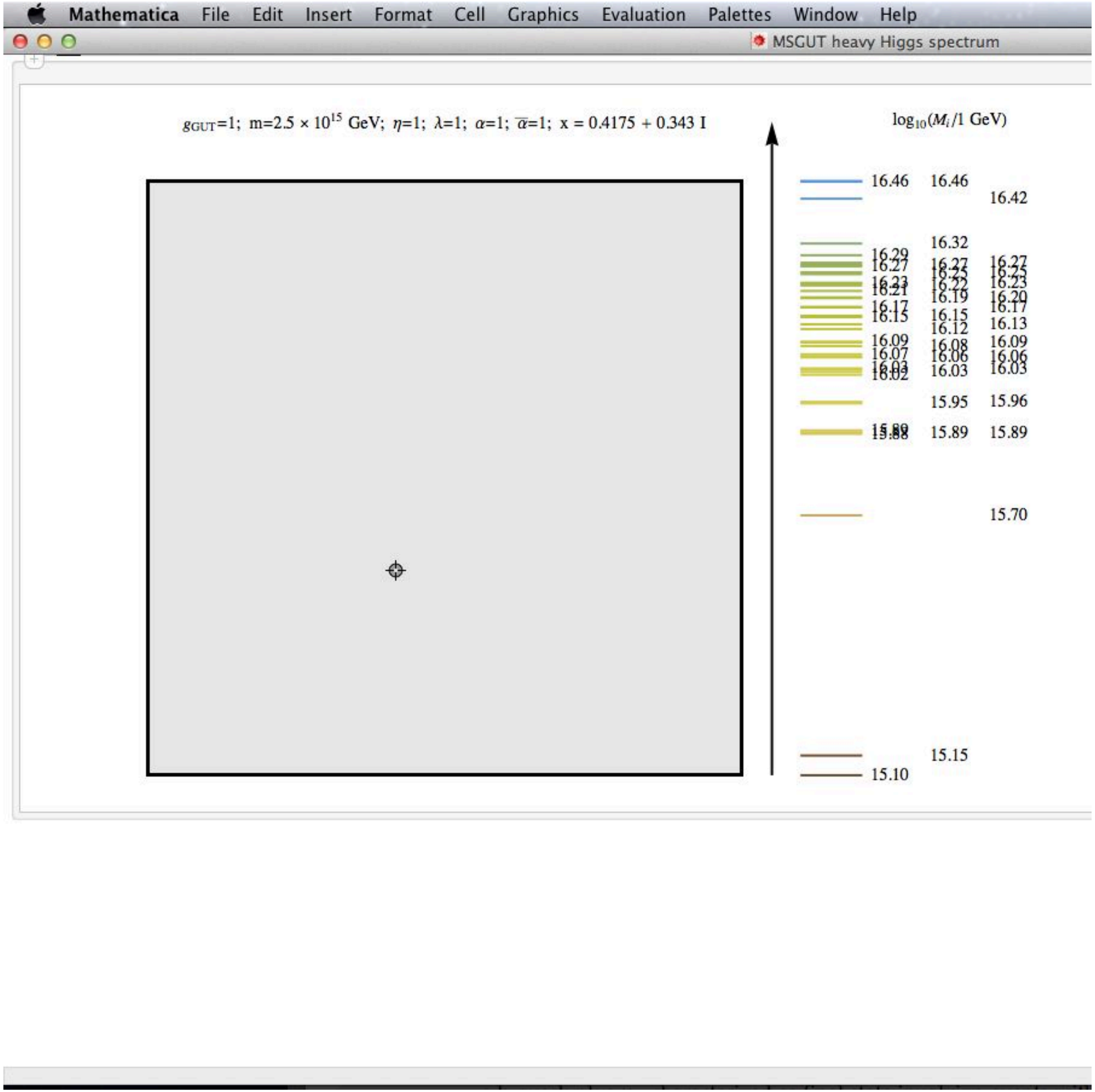
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.483 + 0.476 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
16.55
16.47
16.43
16.44
16.44
16.42
16.40
16.39
16.37
16.36
16.37
16.36
16.38
16.36
16.33
16.33
16.33
16.31
16.28
16.26
16.24
16.25
16.25
16.23
16.20
16.19
16.18
16.18
16.16
16.13
16.13
16.10
16.00
16.02
15.92
15.91
15.87
15.88
15.79
15.81
15.62



g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.442 + 0.417 I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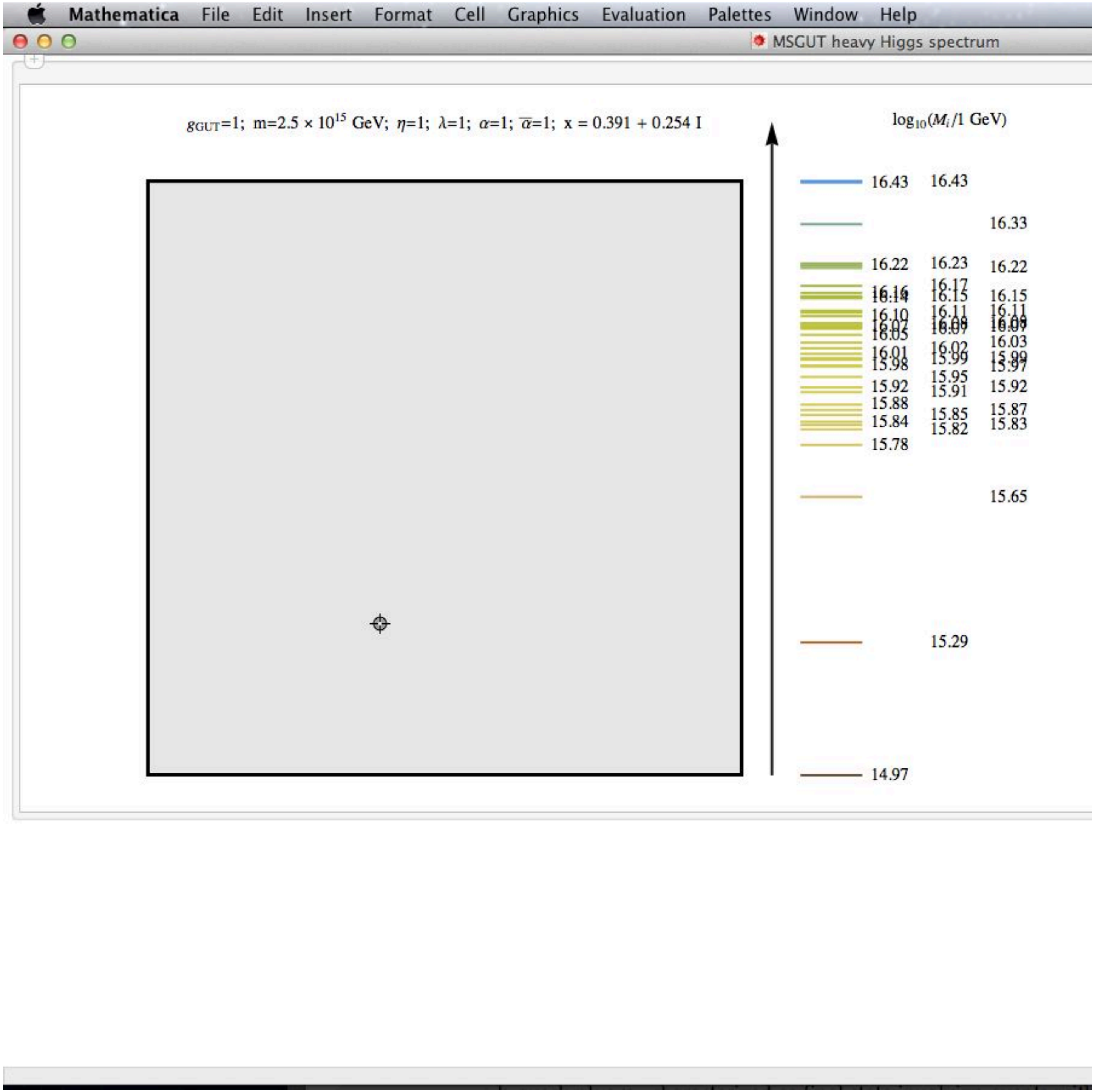
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.4175 + 0.343 I
$\log_{10}(M_i/1$ GeV)
16.46
16.29
16.27
16.23
16.21
16.17
16.15
16.09
16.07
16.03
16.02
15.89
15.88
15.10
16.46
16.32
16.27
16.25
16.22
16.19
16.15
16.12
16.08
16.06
16.03
15.95
15.89
15.15
16.42
16.27
16.25
16.23
16.20
16.17
16.13
16.09
16.06
16.03
15.96
15.89
15.70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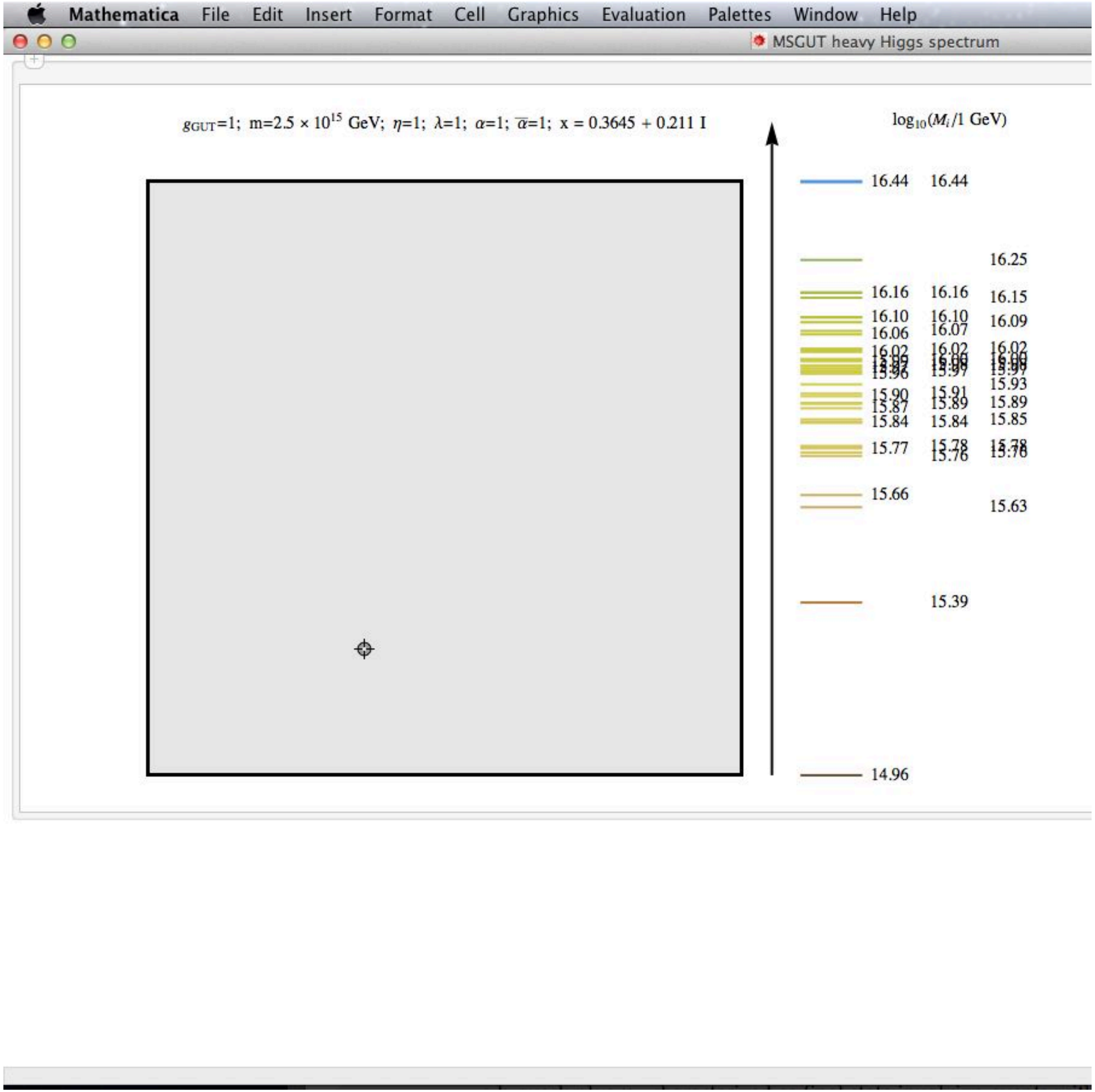
MSGUT heavy Higgs spectrum
$g_{\rm GUT}$=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.391 + 0.254 I
$\log_{10}(M_i/1\ {\rm GeV})$
16.43
16.22
16.16
16.14
16.10
16.07
16.05
16.01
15.98
15.92
15.88
15.84
15.78
14.97
16.43
16.23
16.17
16.15
16.11
16.08
16.07
16.02
15.99
15.95
15.91
15.85
15.82
15.29
16.33
16.22
16.15
16.11
16.09
16.07
16.03
15.99
15.97
15.92
15.87
15.83
15.65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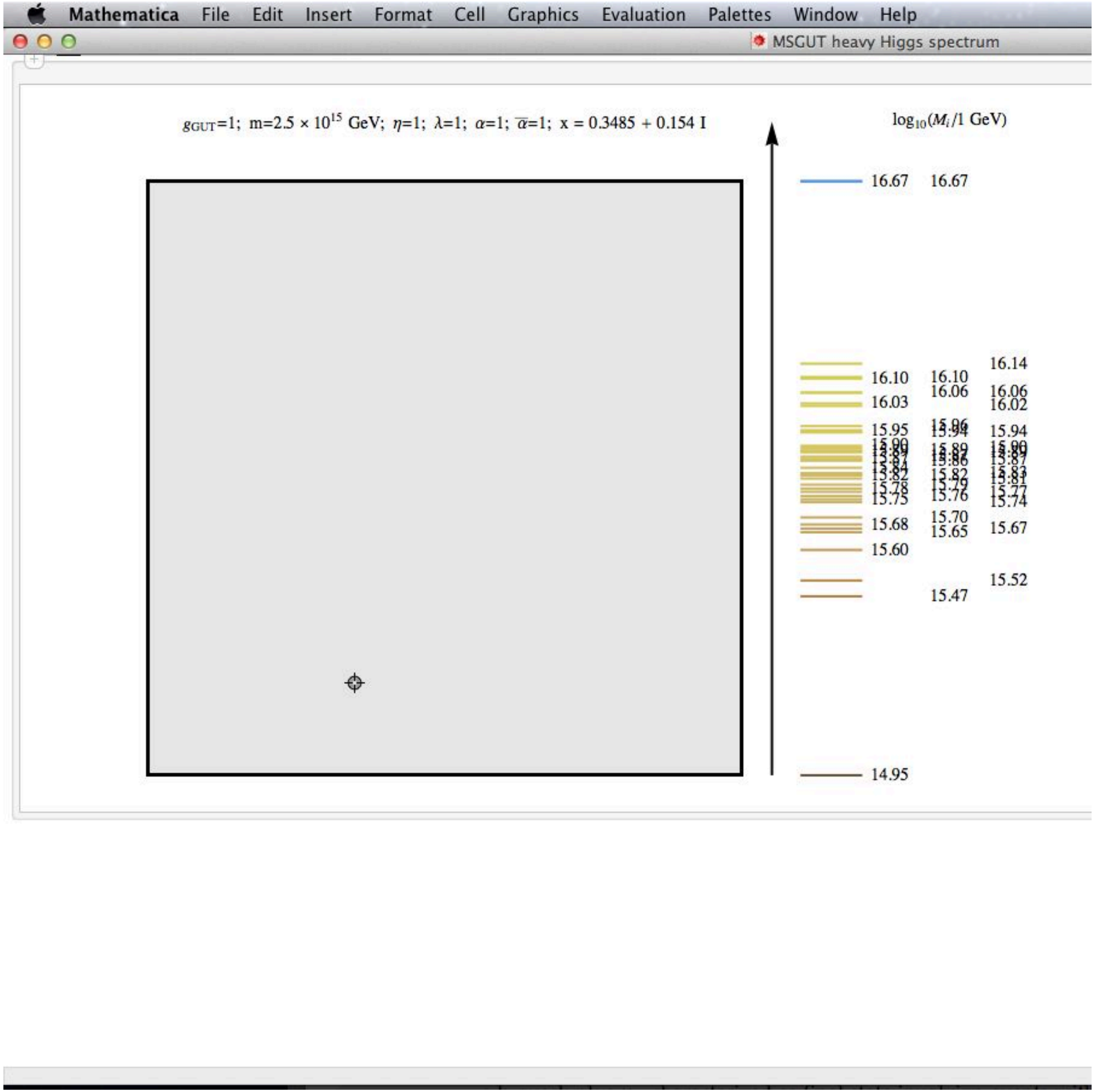
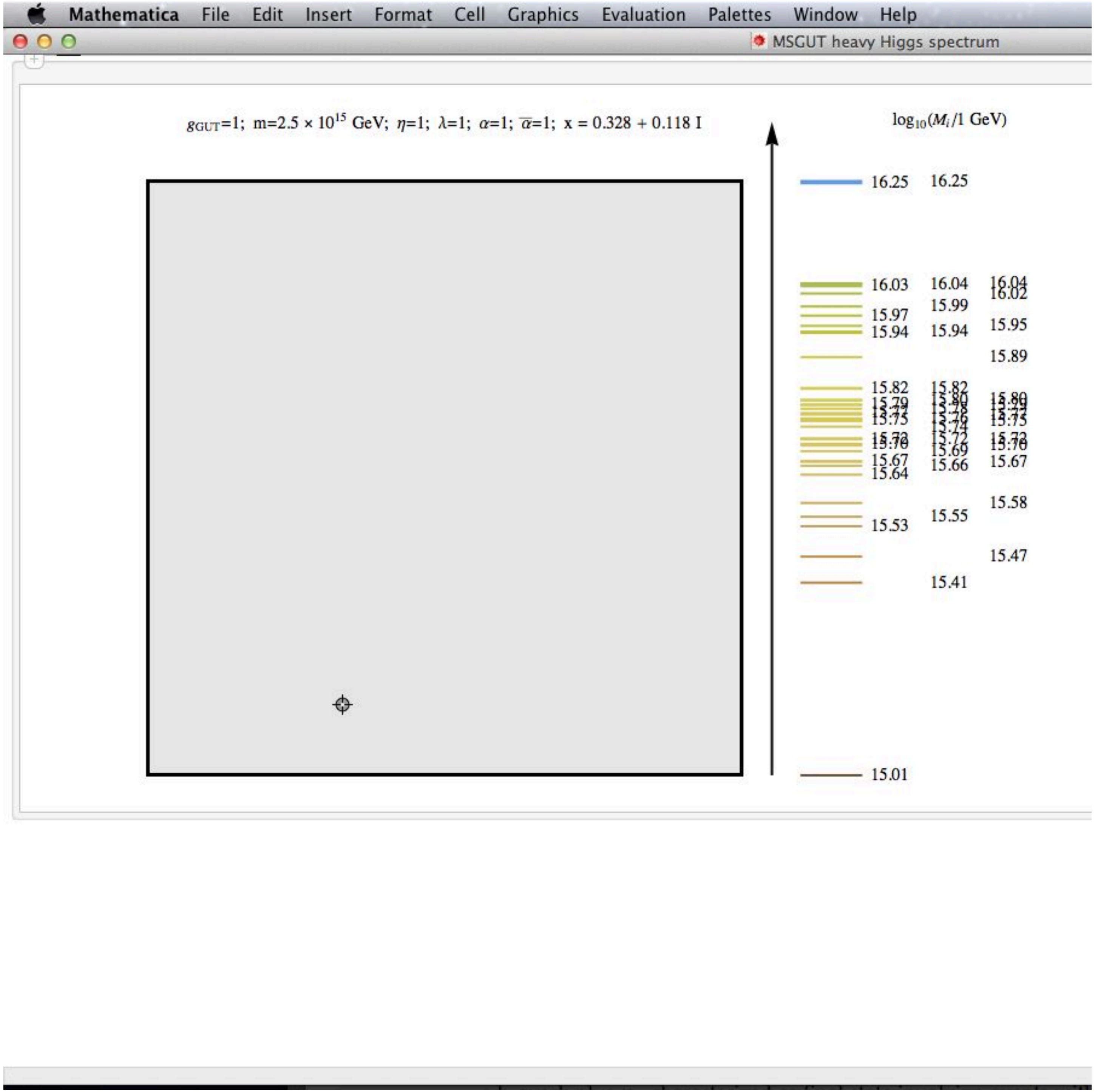
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.3645 + 0.211 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
16.44 16.44
16.25
16.16 16.16 16.15
16.10 16.10 16.09
16.06 16.07
16.02 16.02 16.02
15.96 15.97 15.97
15.93
15.90 15.91
15.87 15.89 15.89
15.84 15.84 15.85
15.77 15.78 15.78
15.76 15.76
15.66
15.63
15.39
14.96



g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.3485 + 0.154 I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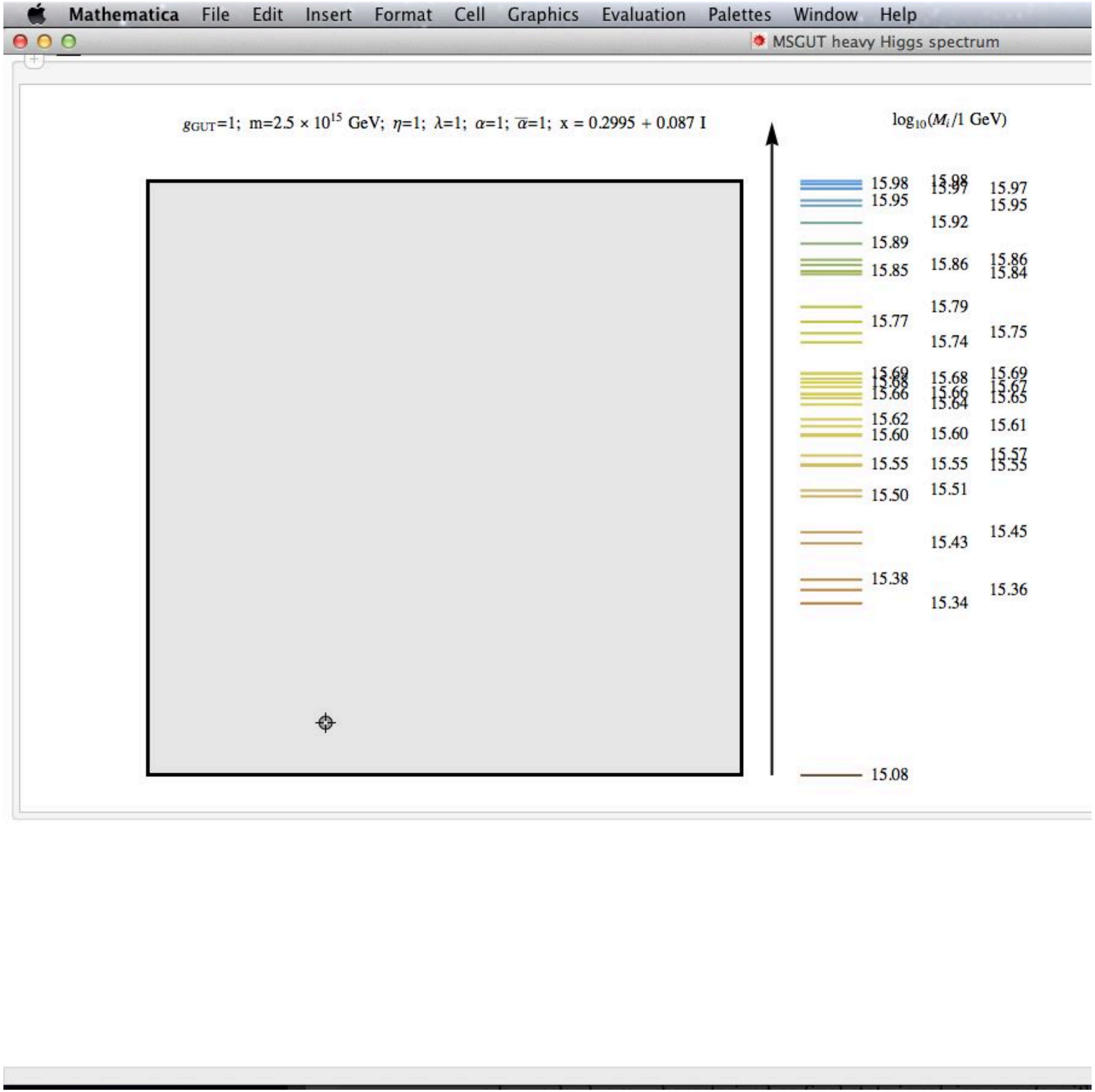
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.328 + 0.118 I
$\log_{10}(M_i/1$ GeV)
16.25
16.25
16.03
16.04
16.04
16.02
15.99
15.97
15.94
15.94
15.95
15.89
15.82
15.82
15.80
15.79
15.78
15.76
15.75
15.75
15.74
15.72
15.70
15.70
15.69
15.67
15.66
15.67
15.64
15.58
15.55
15.53
15.47
15.41
15.01


Mathematica
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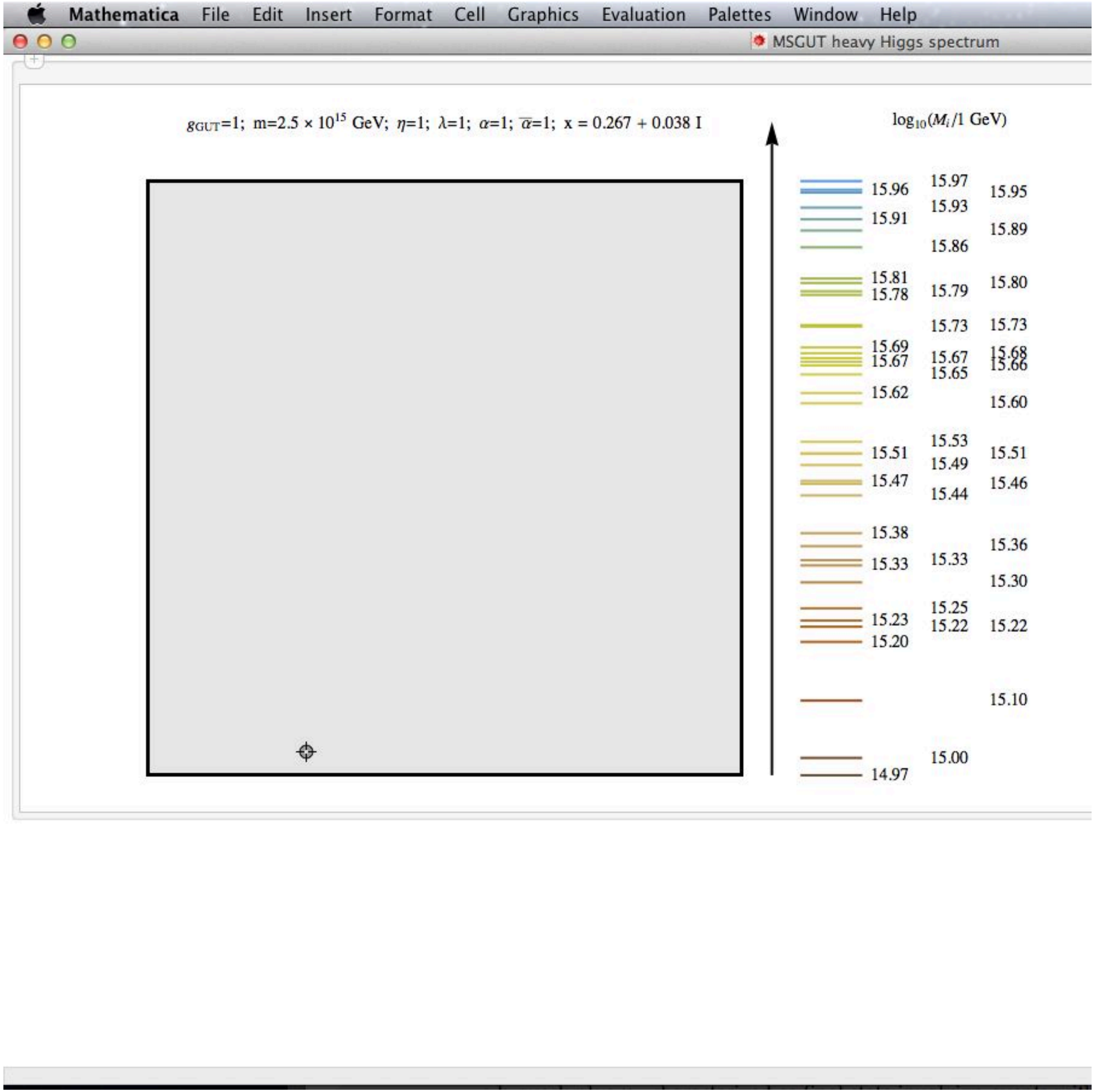
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.2995 + 0.087 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
15.98
15.95
15.89
15.85
15.77
15.69
15.68
15.66
15.62
15.60
15.55
15.50
15.38
15.08
15.98
15.97
15.92
15.86
15.79
15.74
15.68
15.66
15.64
15.60
15.55
15.51
15.43
15.34
15.97
15.95
15.86
15.84
15.75
15.69
15.67
15.65
15.61
15.57
15.55
15.45
15.36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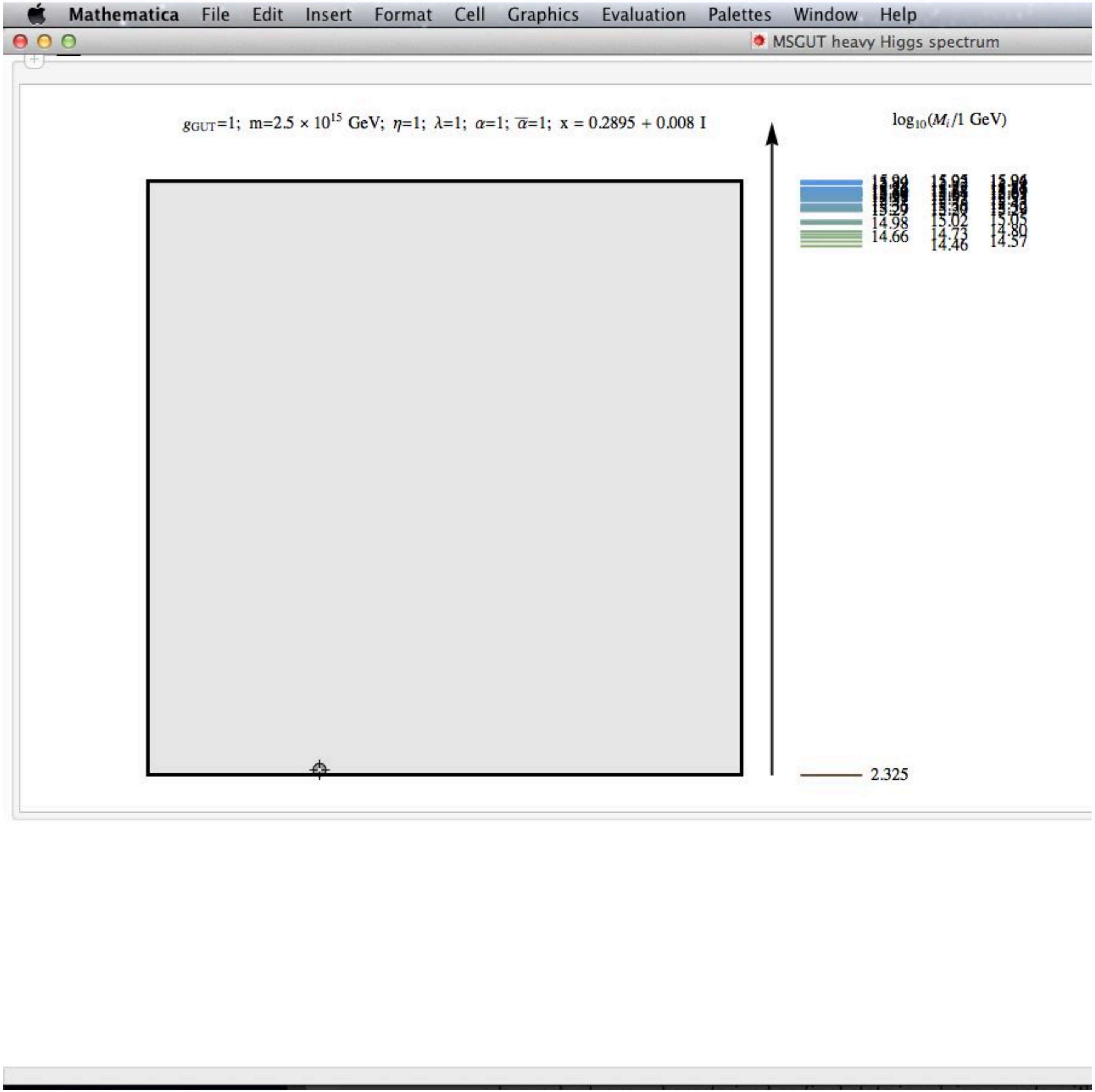
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.267 + 0.038 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
15.96
15.91
15.81
15.78
15.69
15.67
15.62
15.51
15.47
15.38
15.33
15.23
15.20
14.97
15.97
15.93
15.86
15.79
15.73
15.67
15.65
15.53
15.49
15.44
15.33
15.25
15.22
15.00
15.95
15.89
15.80
15.73
15.68
15.66
15.60
15.51
15.46
15.36
15.30
15.22
15.10

Mathematica
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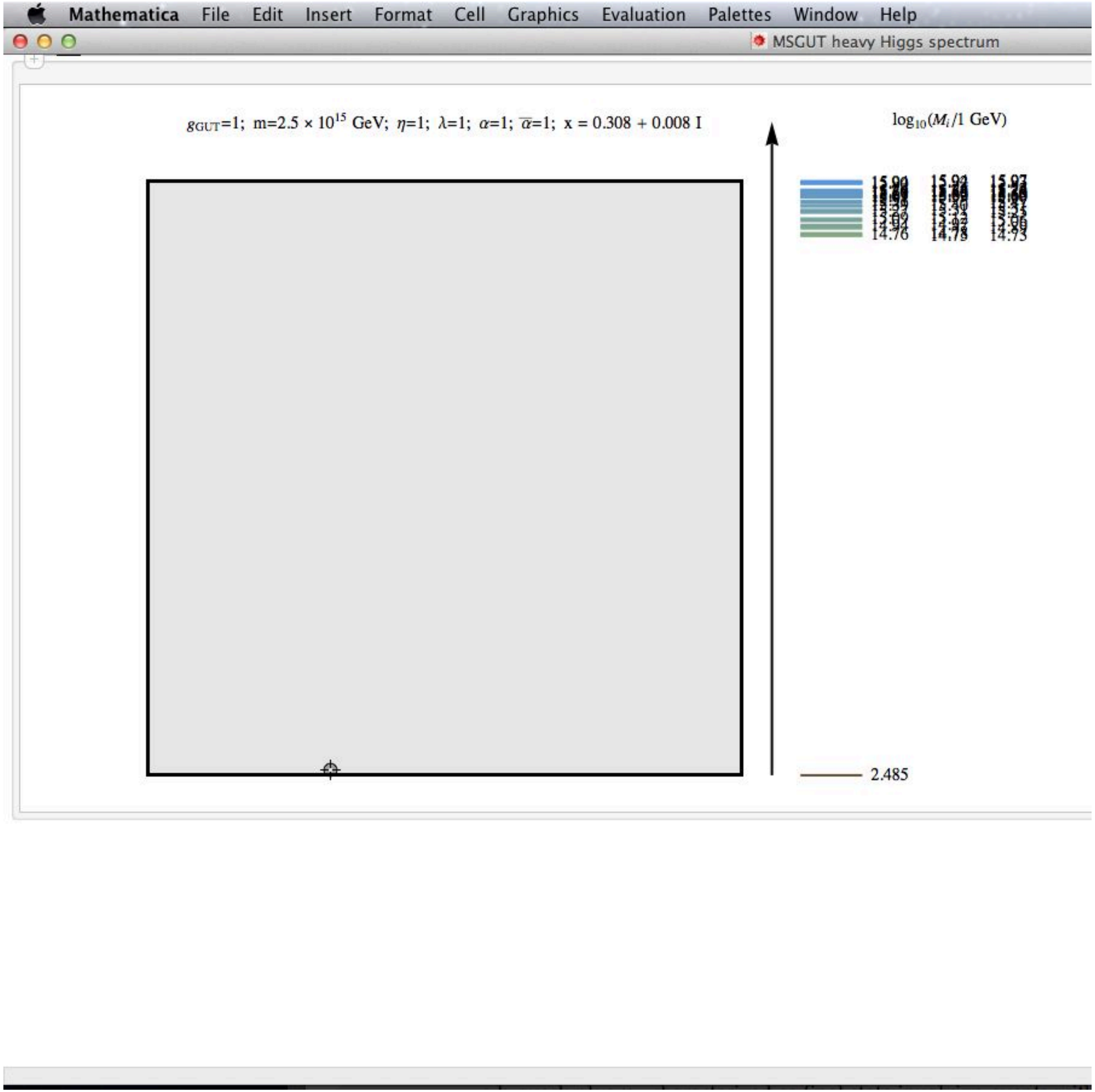
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.2895 + 0.008 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
15.94
15.29
14.98
14.66
15.95
15.30
15.02
14.73
14.46
15.96
15.29
15.05
14.80
14.57
2.325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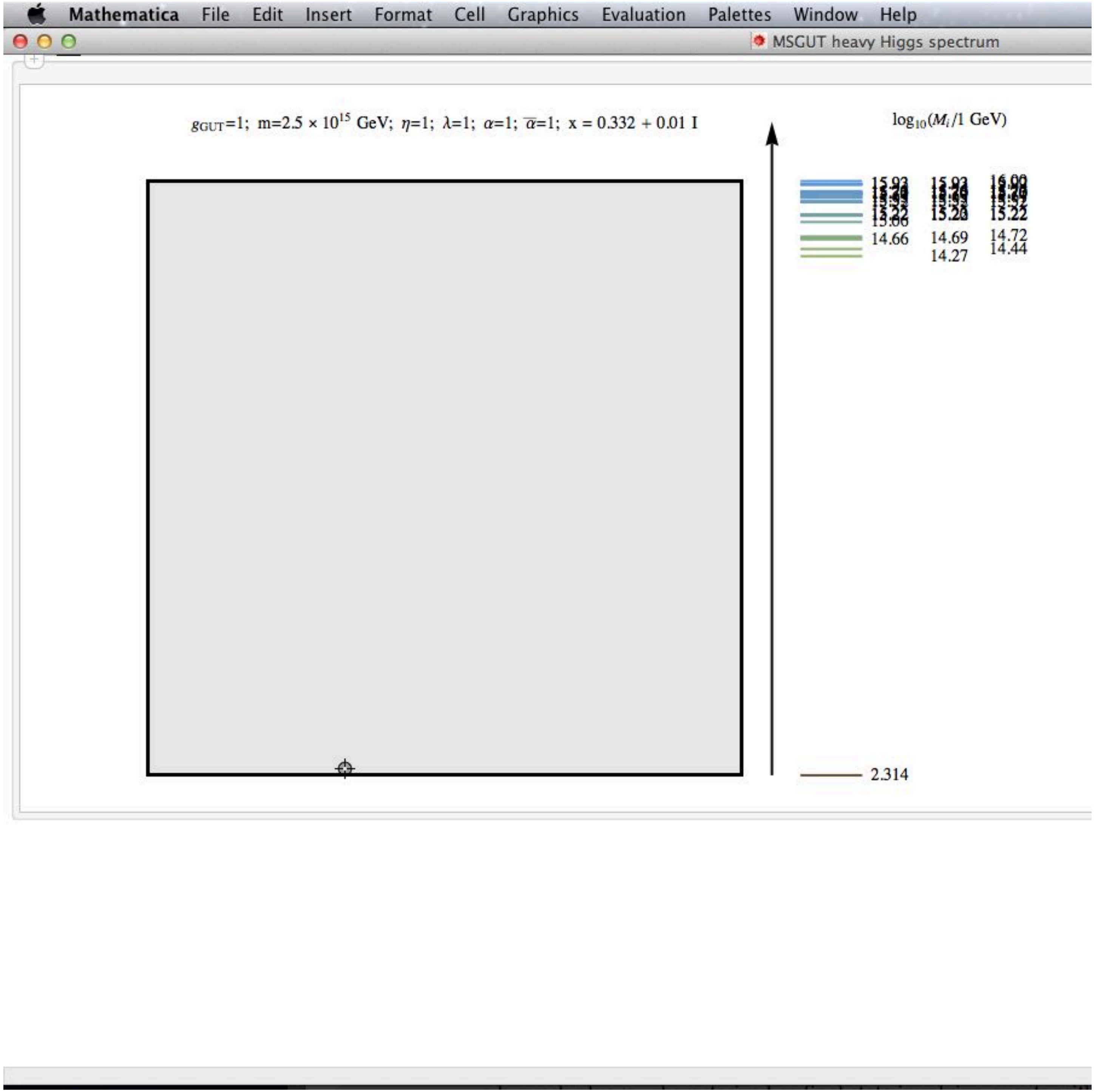
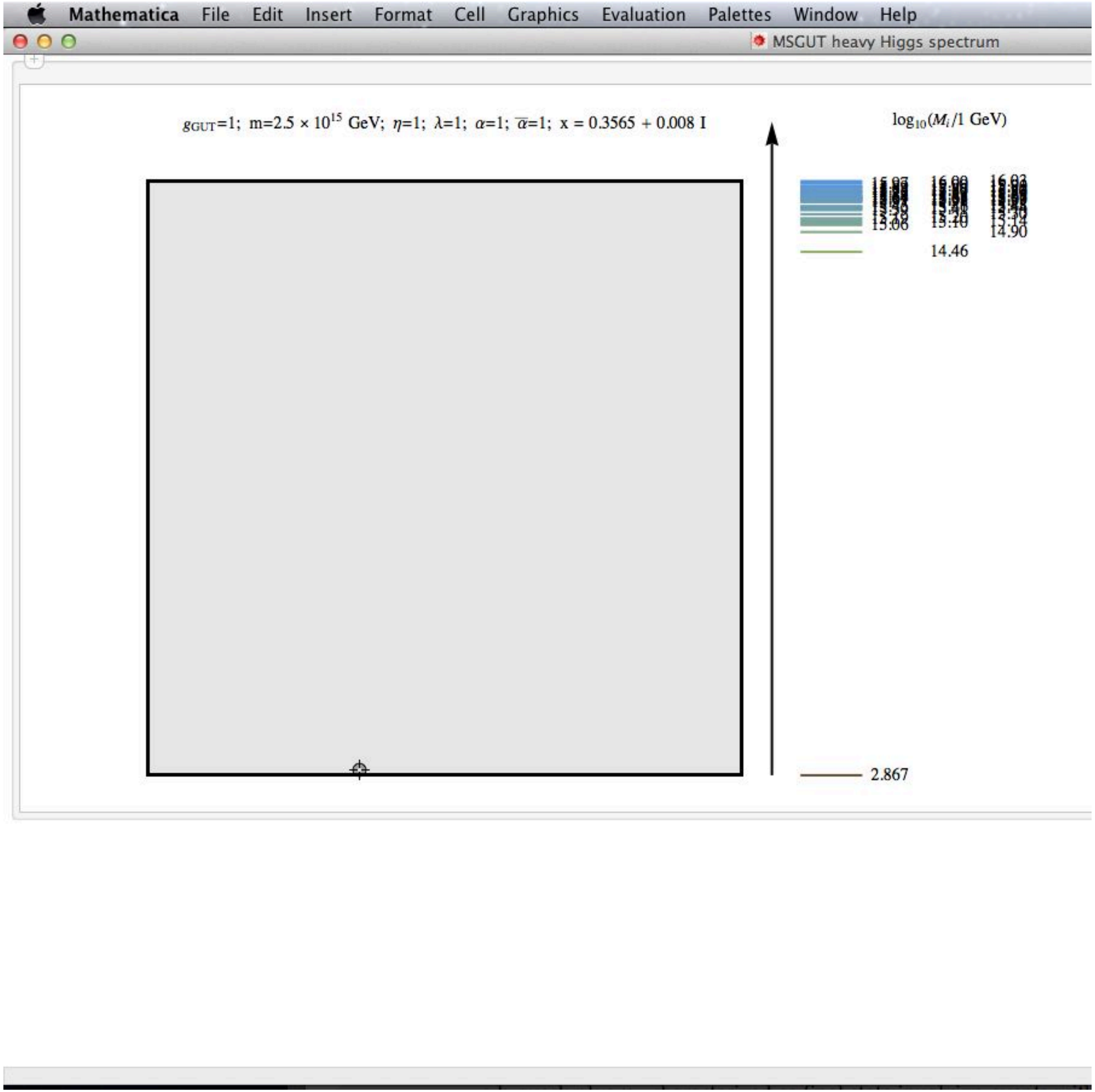
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.308 + 0.008 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
15.90
15.92
15.97
14.76
14.78
14.73
2.485



$g_{\rm GUT}$=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.332 + 0.01 I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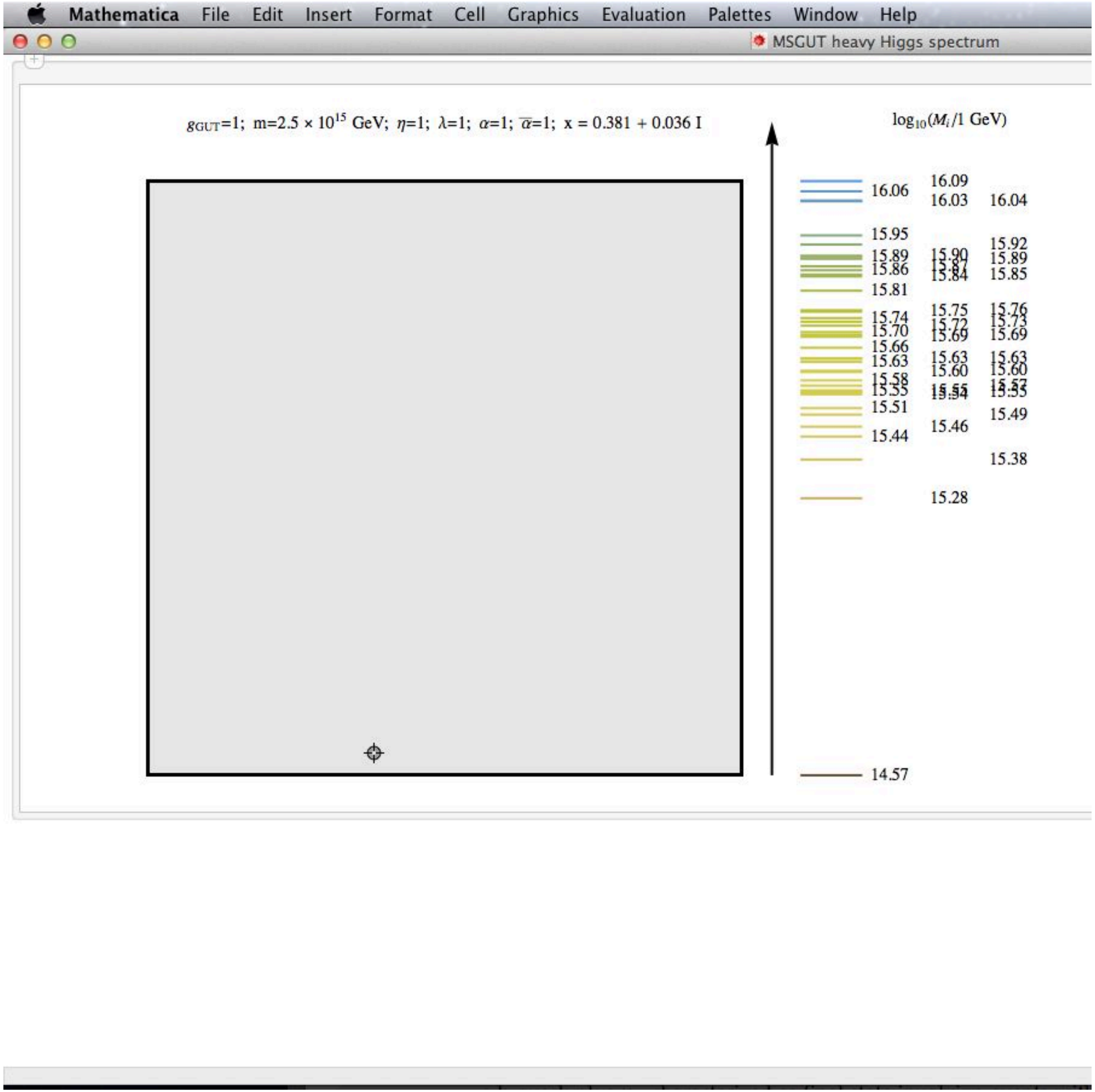
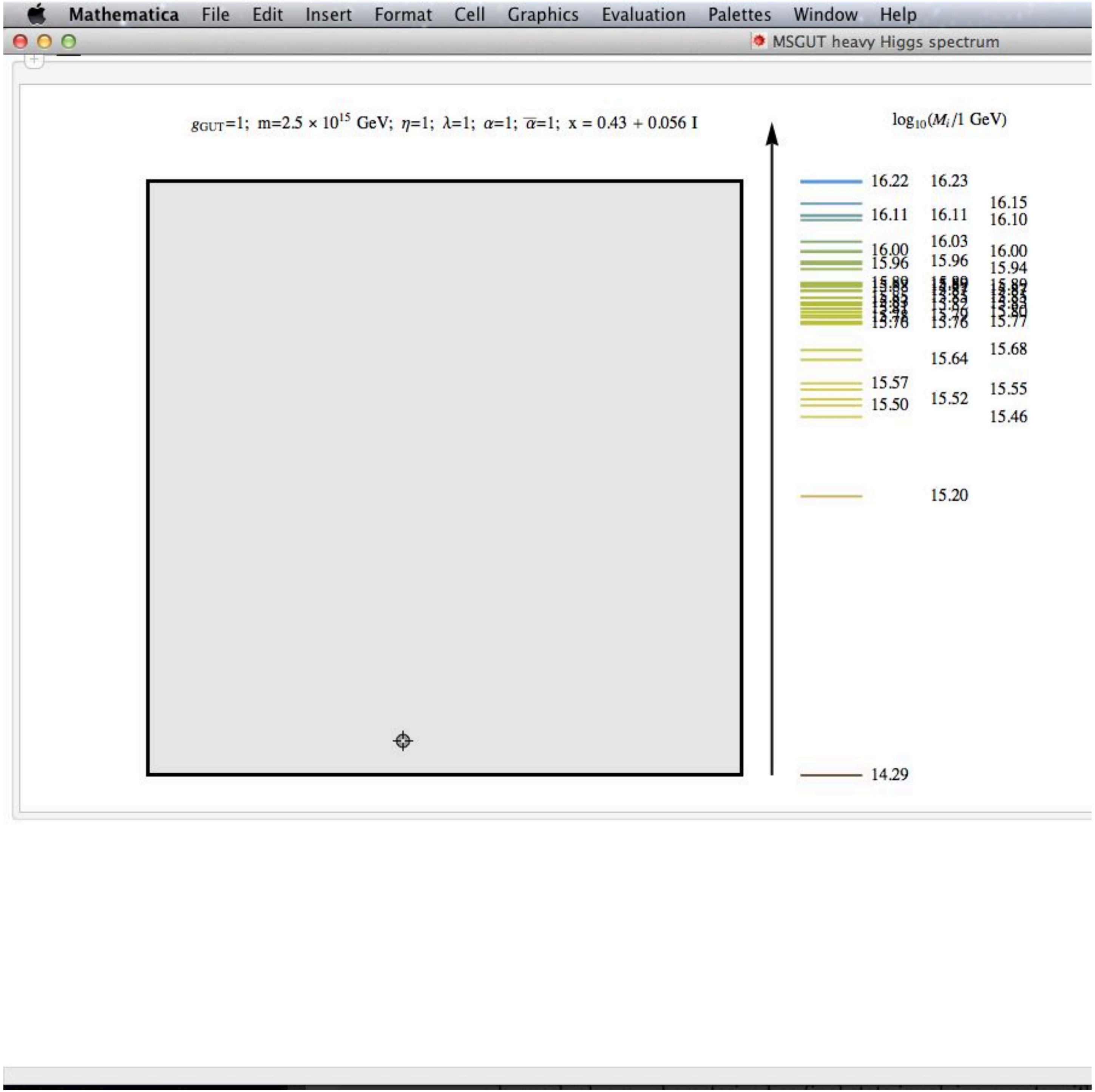
MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.3565 + 0.008 I
$\log_{10}(M_i/1\ \text{GeV})$
15.06
14.90
14.46
2.867



g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.381 + 0.036 I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MSGUT heavy Higgs spectrum
g_{GUT}=1; m=2.5 × 10^{15} GeV; η=1; λ=1; α=1; $\overline{\alpha}$=1; x = 0.43 + 0.056 I
$\log_{10}(M_i/1\ \mathrm{GeV})$
16.22
16.23
16.15
16.11
16.11
16.10
16.03
16.00
16.00
15.96
15.96
15.94
15.89
15.89
15.89
15.76
15.76
15.77
15.68
15.64
15.57
15.55
15.50
15.52
15.46
15.20
14.29