MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

Neuron FUND FOR SUPPORT OF SCIENCE

Portorož, April 9 2015

Minimal SO(10) GUT @ NLO

Michal Malinský

IPNP Charles University in Prague

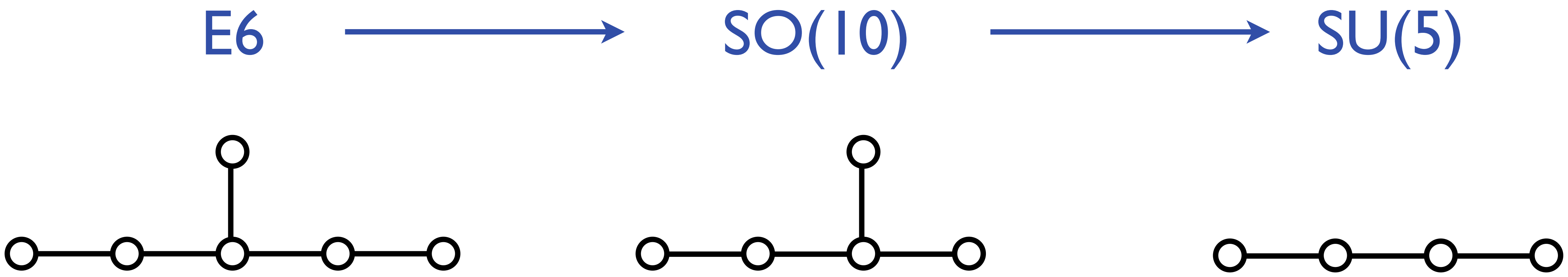
in collaboration with

S. Bertolini (SISSA & INFN Trieste), L. di Luzio (Genova U.) & H. Kolešová (IPNP Prague)

based on Phys.Rev.D 80 015013 2009
81 035015 2010
85 095014 2012
87 085020 2013
90 115001 2014

GUTs

Dynkin’s descent



E6 → SO(10) → SU(5)

Vasja Susic

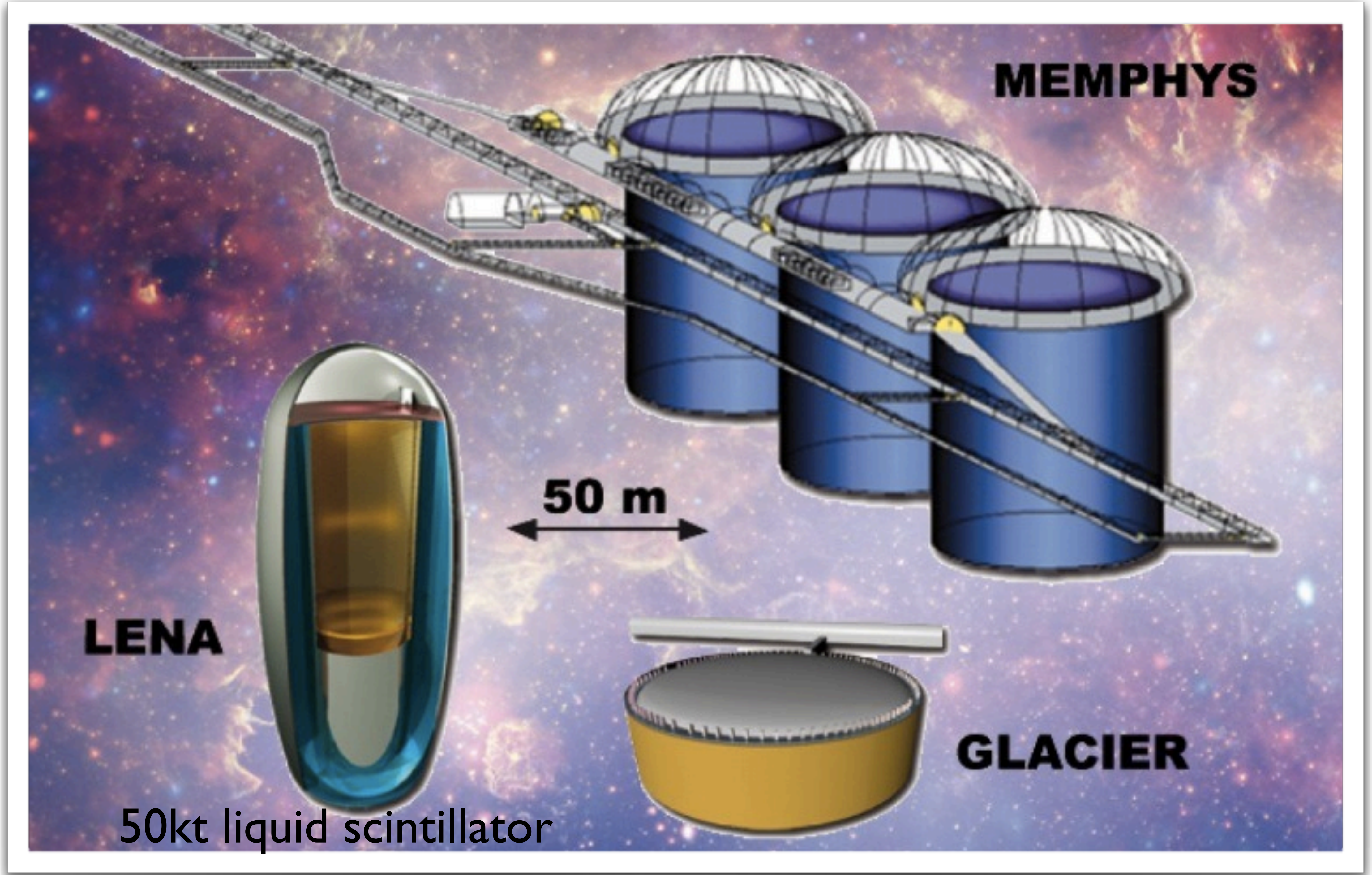
MM

Timon Mede

Few contextual remarks...

Few contextual remarks

Future p-decay searches (proposals as of 2013)



50kt liquid scintillator

Few contextual remarks

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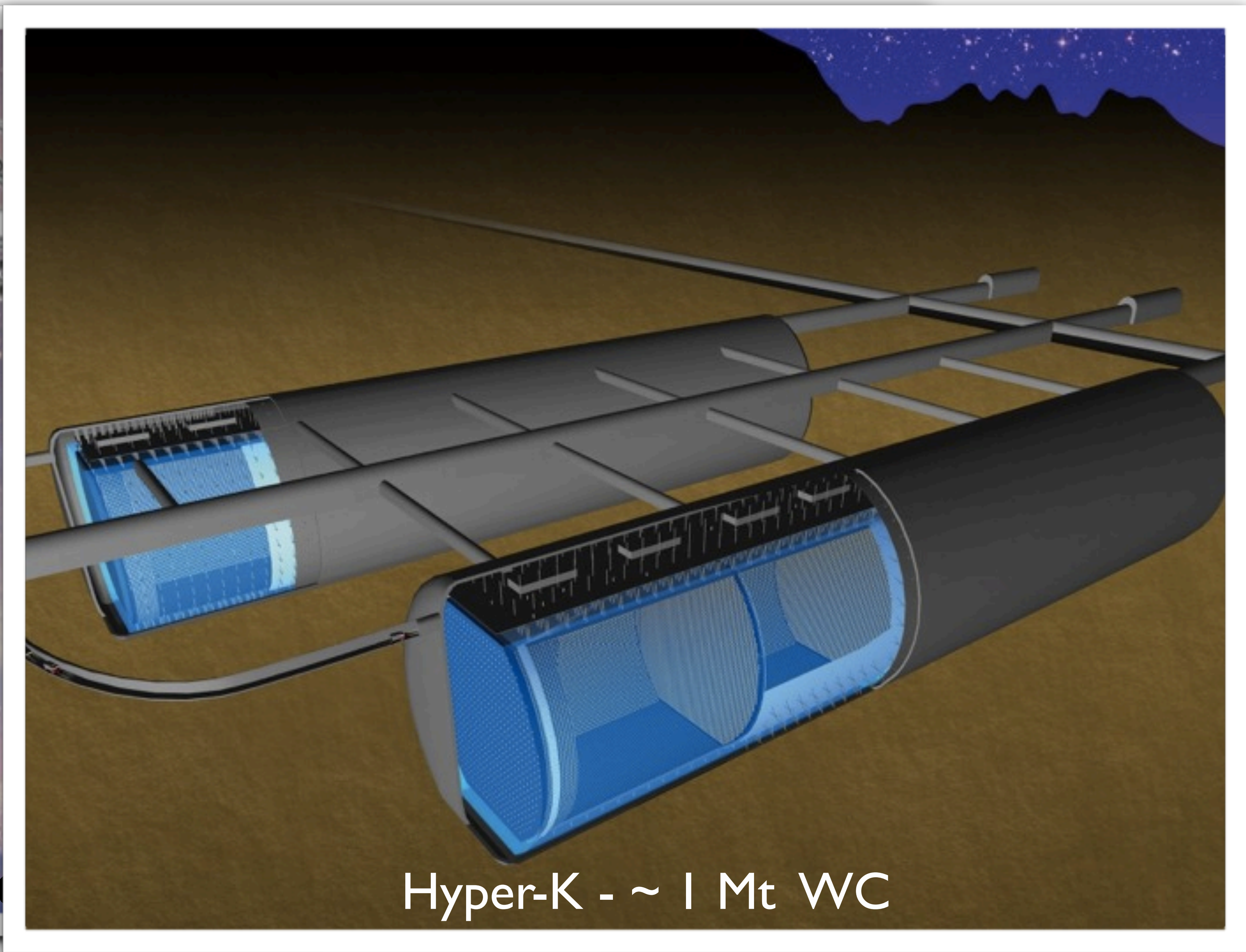
50kt liquid scintillat



Hyper-K - ~ 1 Mt WC

Few contextual remarks

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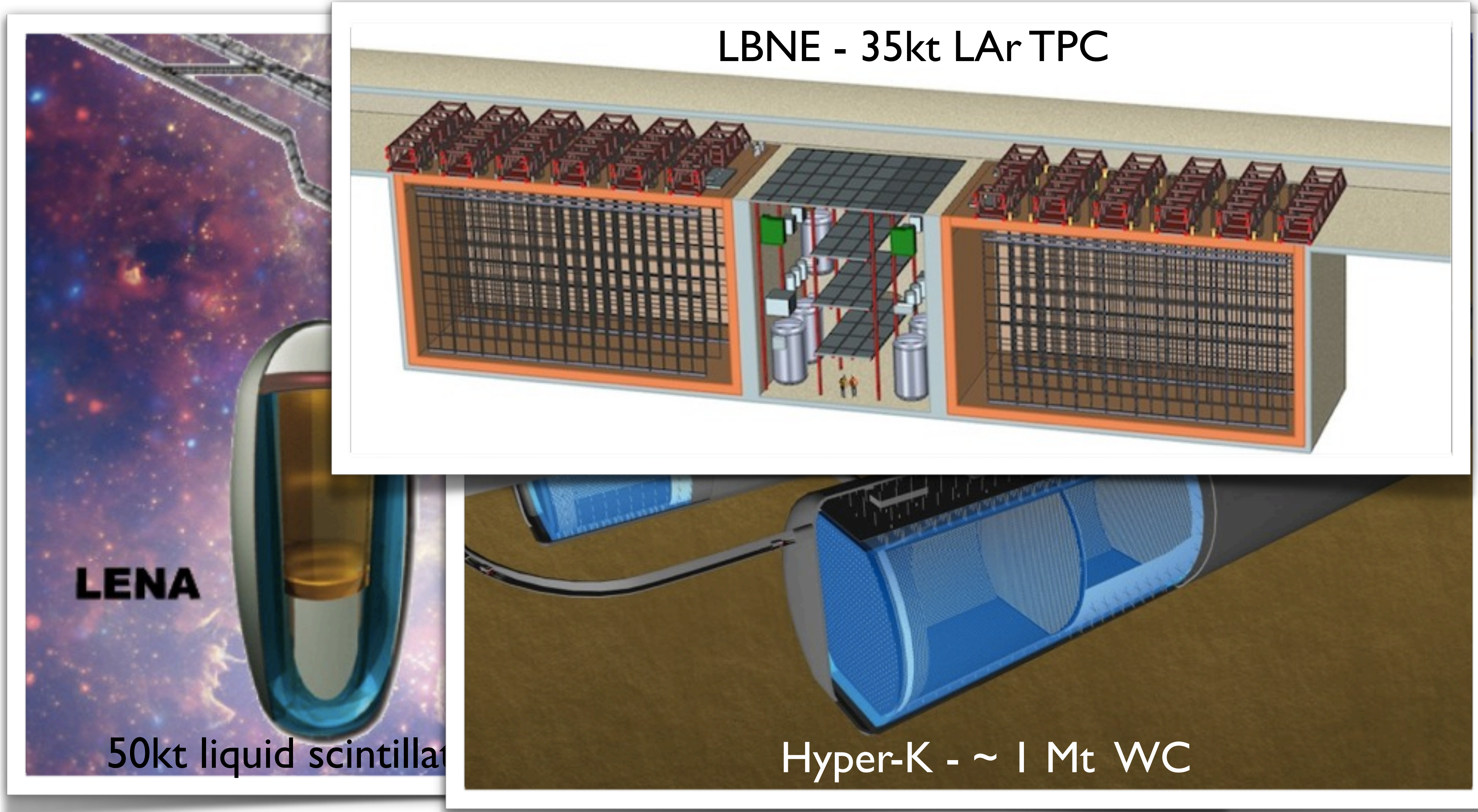

LBNE - 35kt LAr TPC

50kt liquid scintillat

Hyper-K - ~ 1 Mt WC

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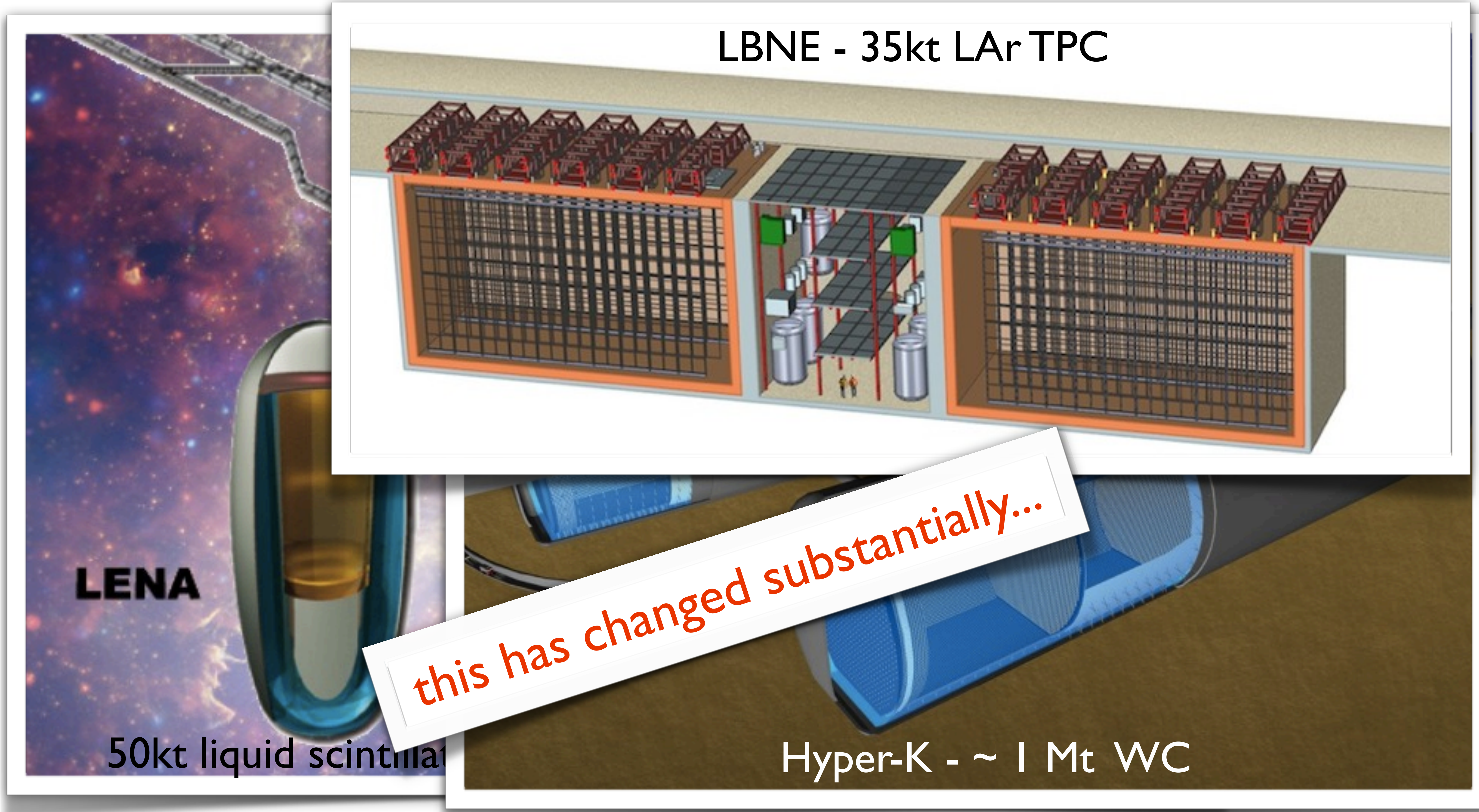

LBNE - 35kt LAr TPC

LENA

50kt liquid scintillat

Hyper-K - ~ 1 Mt WC

this has changed substantially...

Few contextual remarks

Future p-decay searches (proposals as of 2015)

The prospects of getting the Hyper-K built are improving...

提言

第22期学術の大型研究計画に関するマスタープラン
（マスタープラン2014）

平成２６年（２０１４年）２月２８日

日本学術会議

科学者委員会

学術の大型研究計画検討分科会

Japanese master plan for large scale research projects

提　言

第22期学術の大型研究計画に関する
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分野	計画番号	学術領域番号	計画名称	計画の概要	学術的な
物理学	85	23-2	大型先端検出器による核子崩壊・ニュートリノ振動実験	スーパーカミオカンデに代わる100万トン級水チェレンコフ検出器ハイパーカミオカンデを建設し、J-PARC加速器ニュートリノビームと組み合わせる事により、世界最先端の核子崩壊・ニュートリノ研究を行う。	ニュートリノにおけ (粒子・反粒子対称 探索し、ニュートリ 宙の進化論に対する る。さらに核子崩壊 せ、素粒子物理学の 超える物理の確立を
	86	23-2	高エネルギー重イオン衝突実験によるクォーク・グルーオン・プラズマ相の解明	高エネルギー重イオン衝突実験(RHIC-PHENIX/LHC-ALICE 実験)を国際協力の下で推進し、宇宙開びゃく直後の姿である新しい物質相QGP(クォーク・グルーオン・プラズマ)の物性科学を展開する。	ハドロン物質の相構 性の理解を通じて、 質相構造の理解が イラル対称性の自 クォークの閉じ込め 度場の物理、非線形 相関物性現象の解
	87	23-2	光子ビームによるクォーク核物理研究	光子ビームによるクォーク核物理研究を推進し、量子色力学真空とハドロン内クォーク相関を究明する。東北大学電子光理学研究拠点と大阪大学サブアトミック科学研究拠点との拠点間連携研究計画である。	物質の質量の99.9% 担っており、その98% けるカイラル対称性 れによって創成され ており、学術的観点 複雑な階層の研究 れない。

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Few contextual remarks

Future p-decay searches (proposals as of 2015)

The prospects of getting the Hyper-K built are improving...

- HK became a part of the Japanese "Master plan."
- The HK/T2HK collaboration is excited and active
- MOU signed on January 31 2015
- The european part of the collaboration is just forming
- R&D funding secured (both the HK and T2K/J-PARC upgrade)
- A lively discussion about the near detector
- some 2 years delay w.r. to the LOI, realistic starting date 2025(?)

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notoriously underfunded
(shared f. with beam upgrade)
total cost needed below 1 G$
admit surface variant only

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LBNE → **LBNF** → **ELBNF**

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neutrino beam + infrastructure
internationalization
LHC-like scheme

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DUNE = Deep underground neutrino experiment, 10kt in phase 1

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Convergence with the CERN activities!!!

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LAGUNA/LENA is being abandoned...

- Location issues
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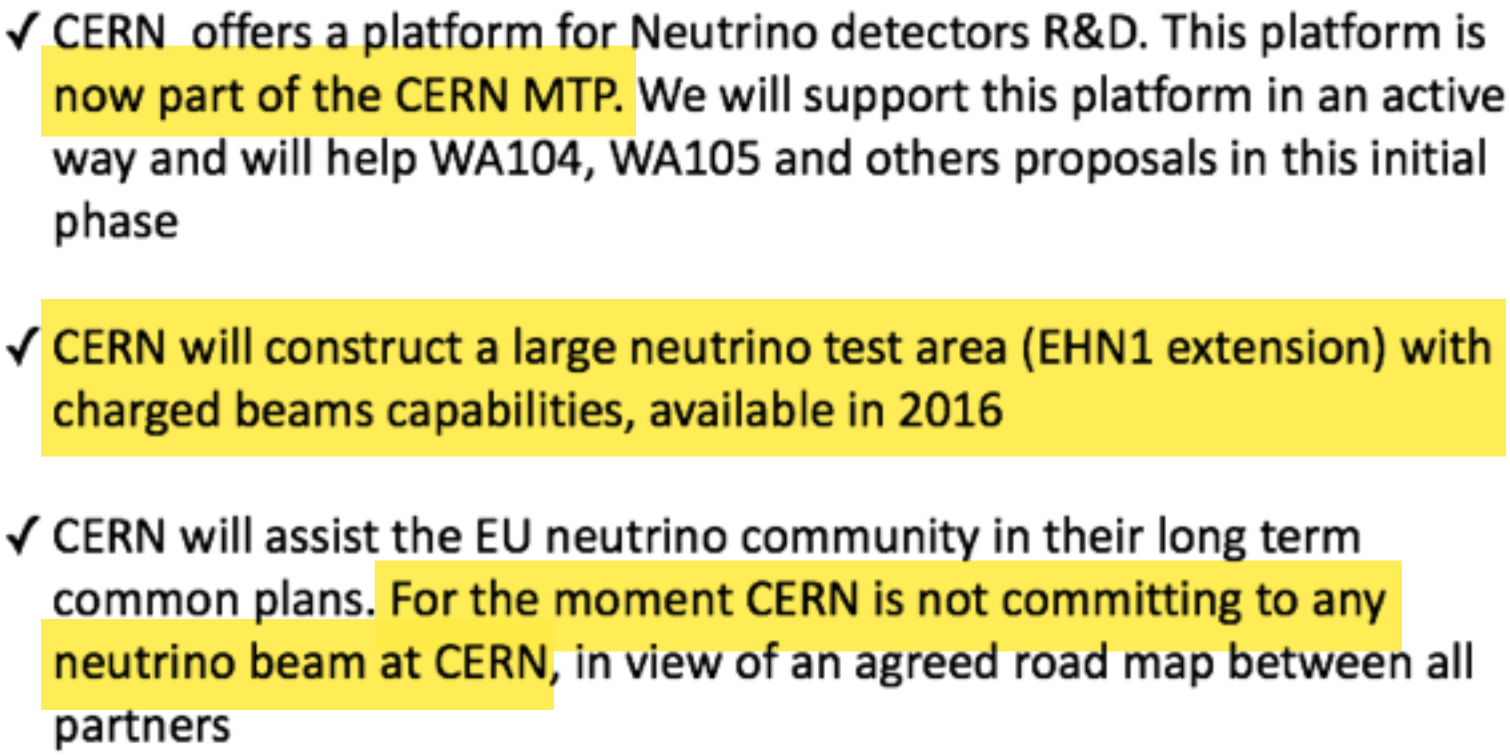
CERN neutrino platform (as a part of the Medium Term Plan)



✓ CERN offers a platform for Neutrino detectors R&D. This platform is now part of the CERN MTP. We will support this platform in an active way and will help WA104, WA105 and others proposals in this initial phase

✓ CERN will construct a large neutrino test area (EHN1 extension) with charged beams capabilities, available in 2016

✓ CERN will assist the EU neutrino community in their long term common plans. For the moment CERN is not committing to any neutrino beam at CERN, in view of an agreed road map between all partners

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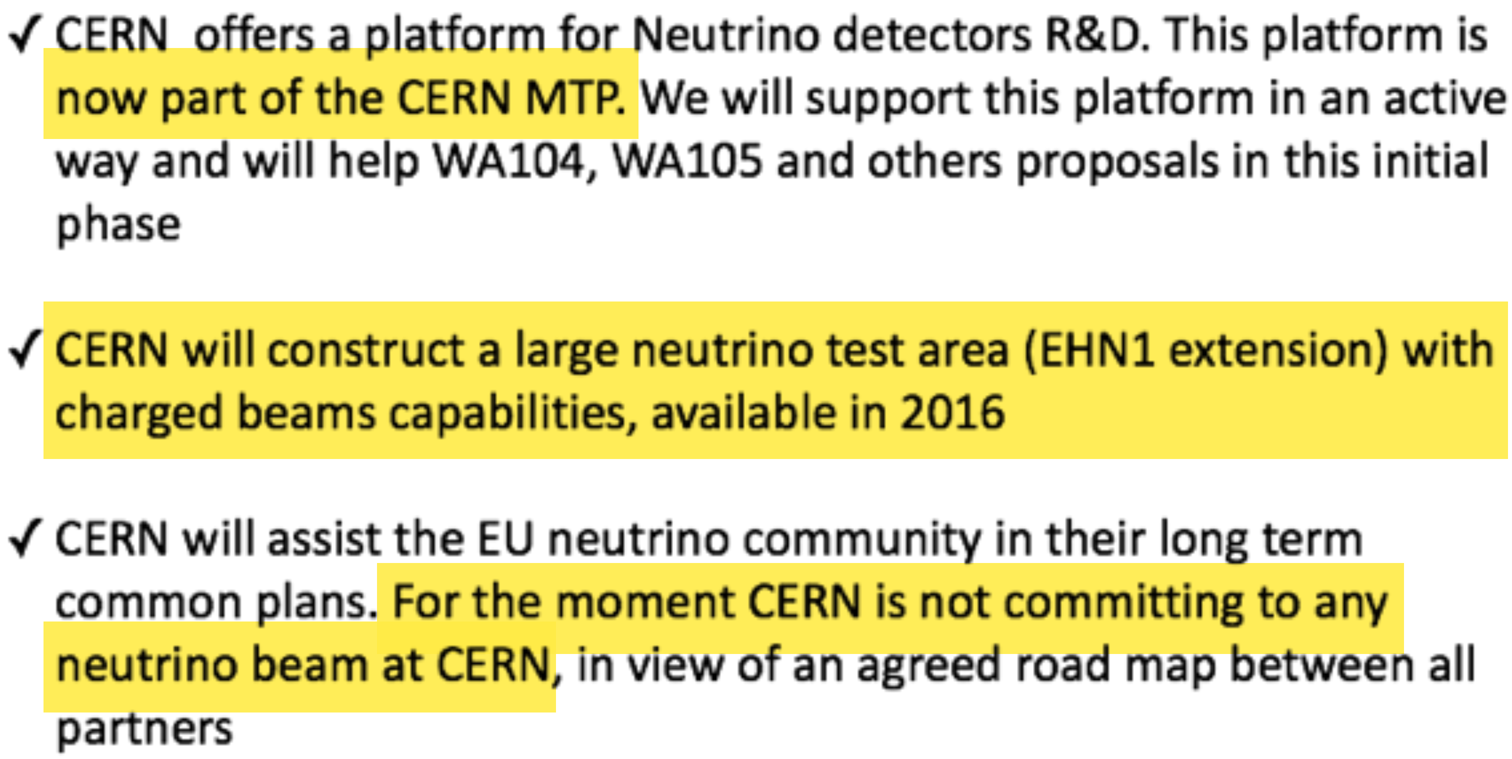

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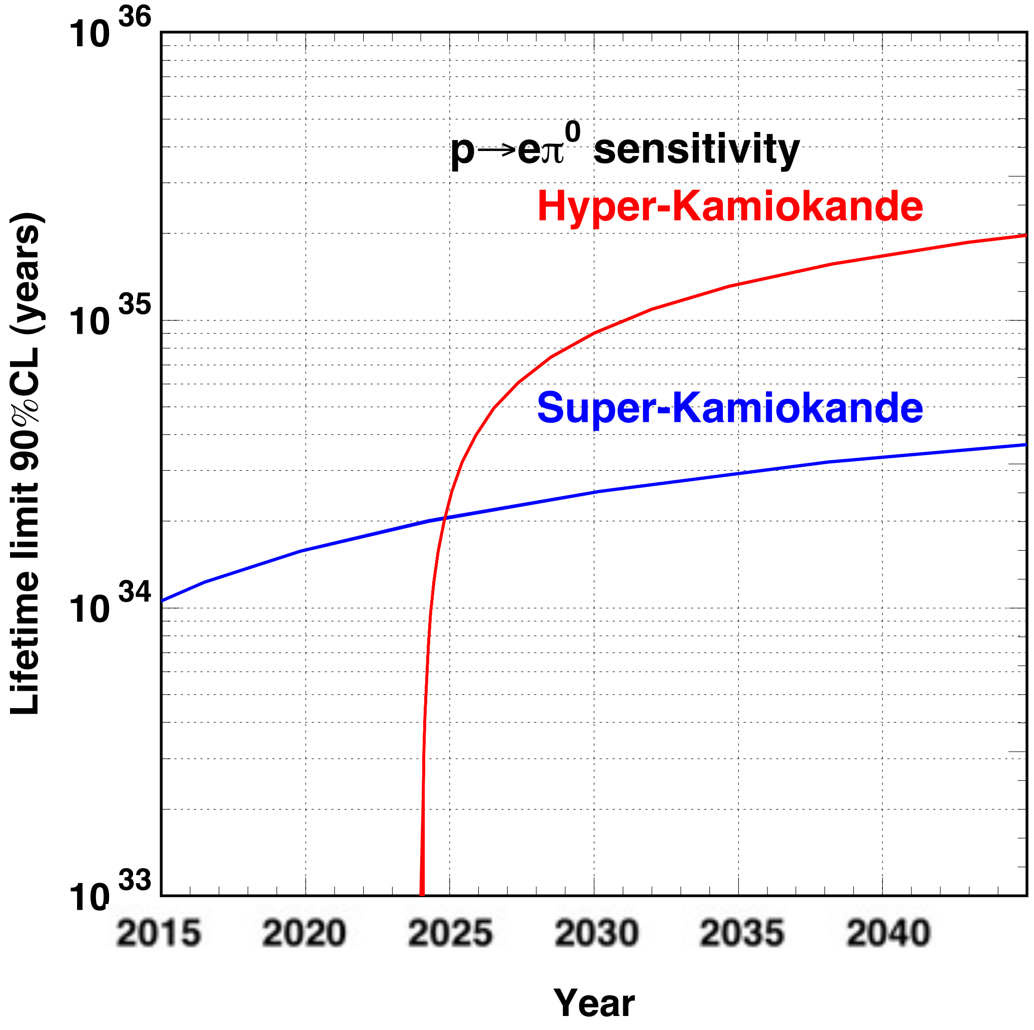
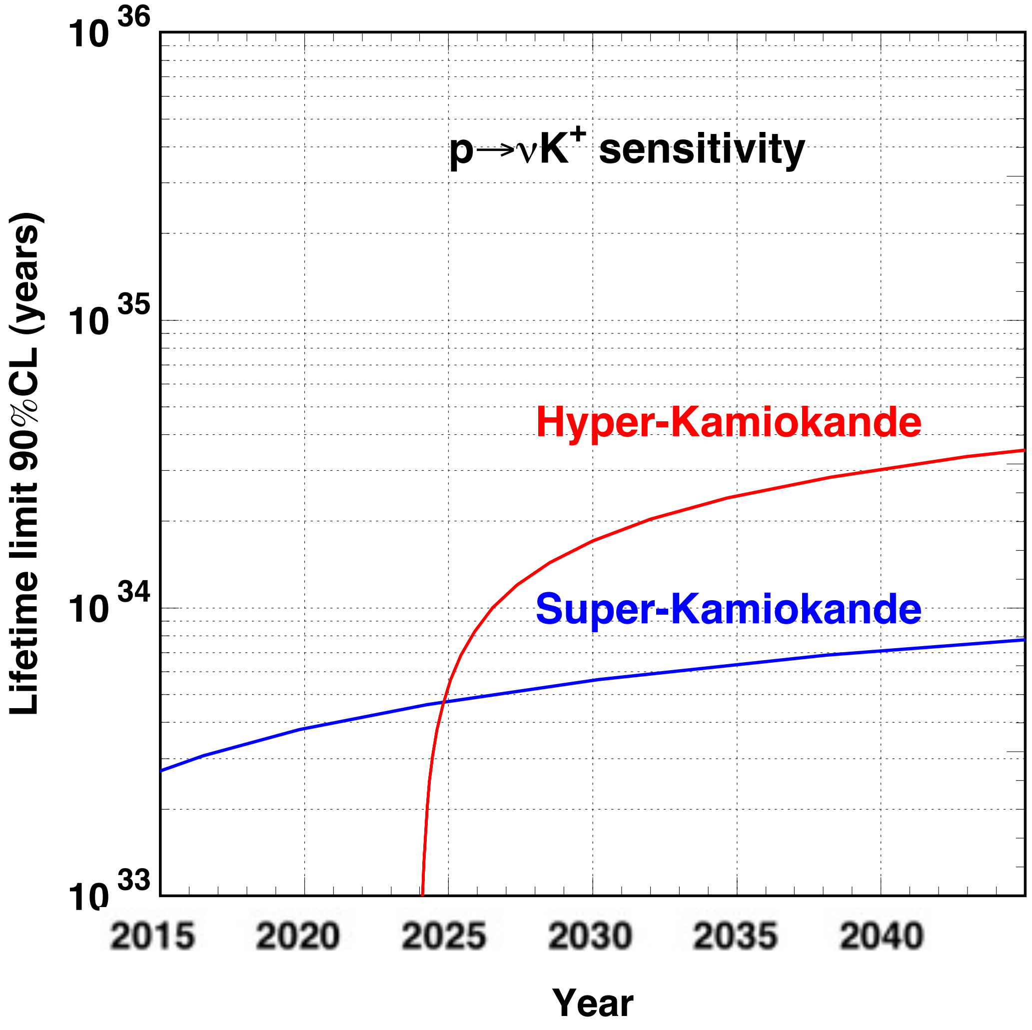
Testbed for the ELBNF LAr TPC, ICARUS moving to FNAL etc.

Regardless of what happens until Portorož 2017...

p-decay sensitivity projection (HK in 2025)

Abe et al., arXiv:1109.3262 [hep-ex]





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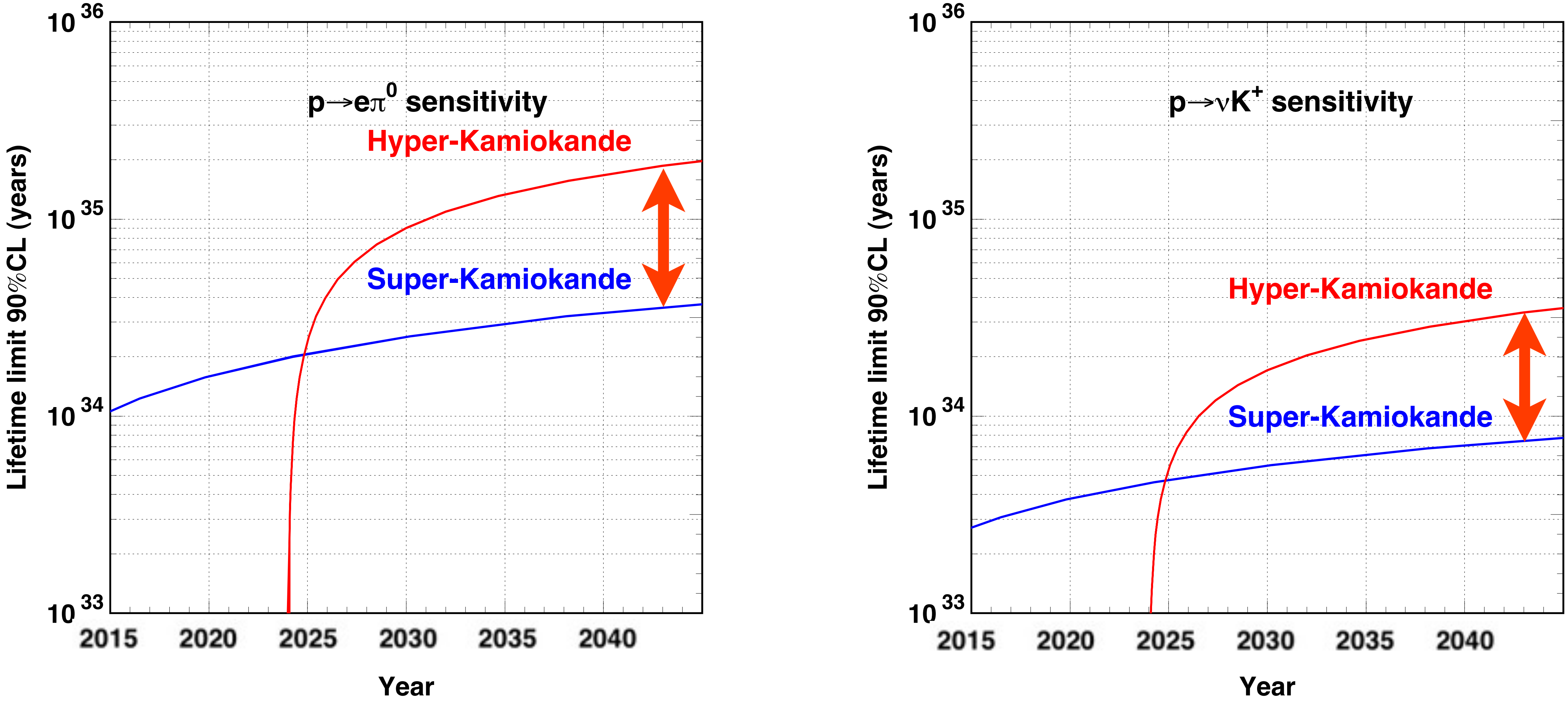
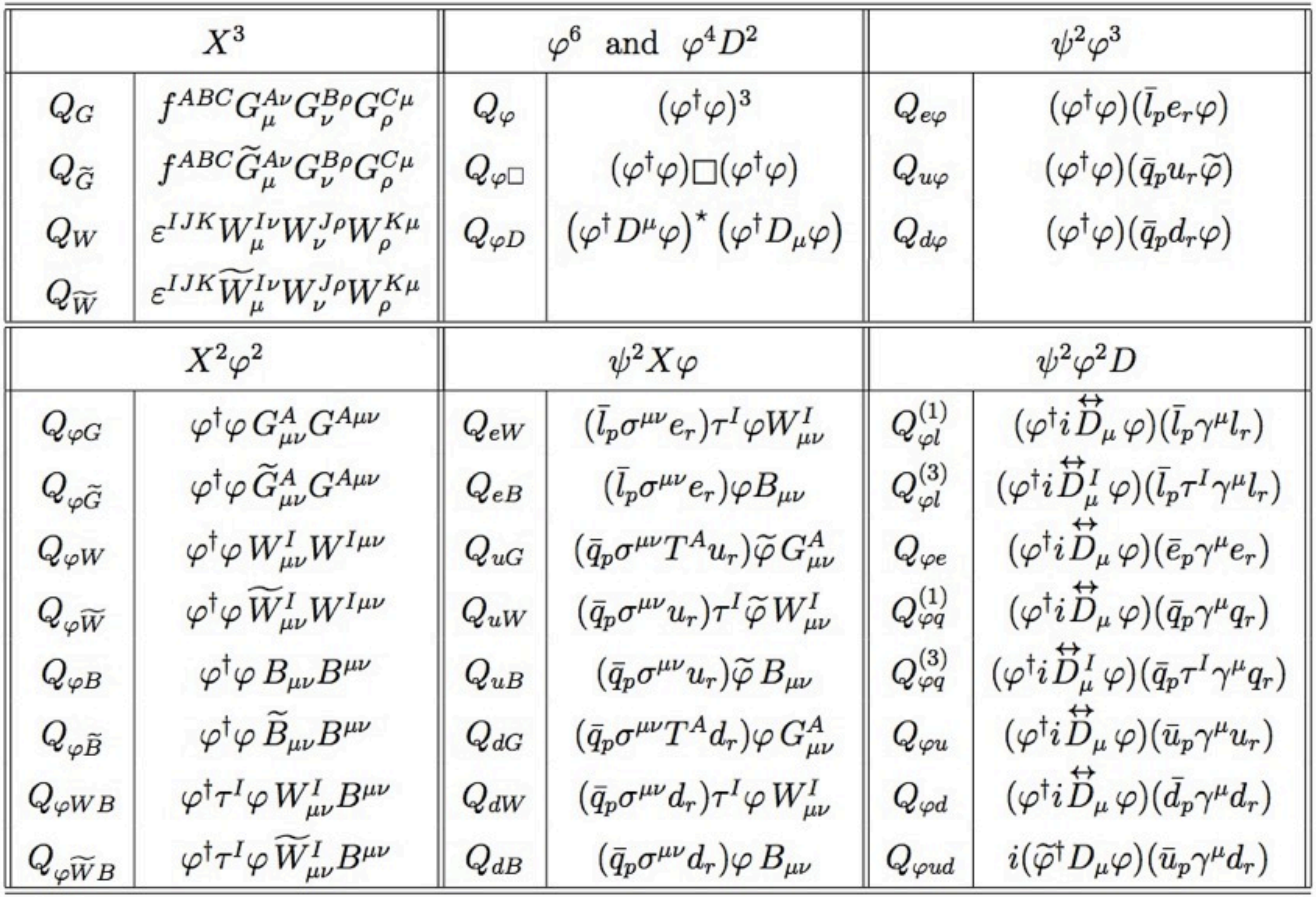


Accuracy of a **factor of few** in Γ_p needed to make a case !

Proton lifetime estimates

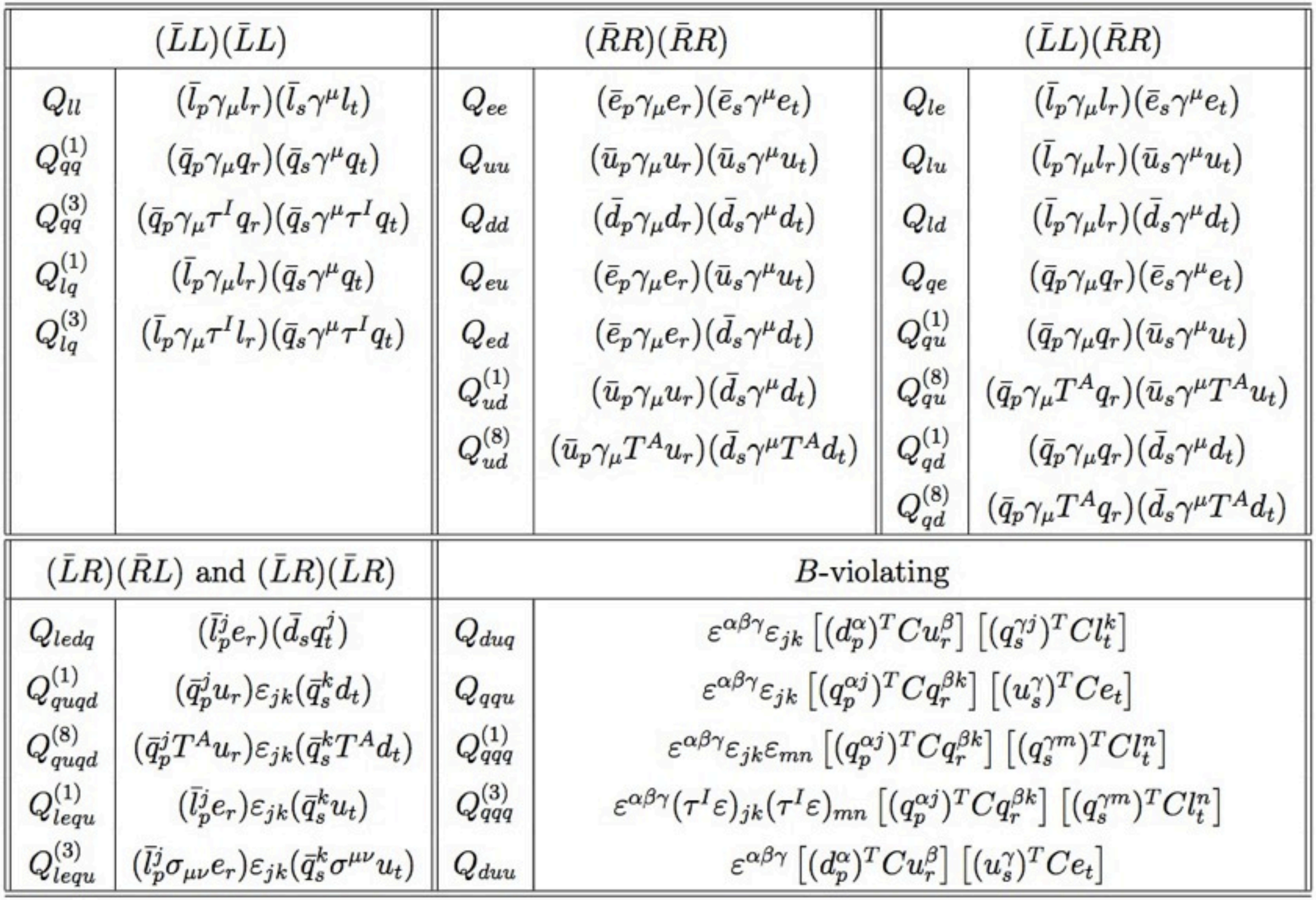
Baryon number violation from the SM perspective



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

B. Grzadkowski et al., JHEP 10 (2010) 085, arXiv: 1008.4884

Baryon number violation from the SM perspective



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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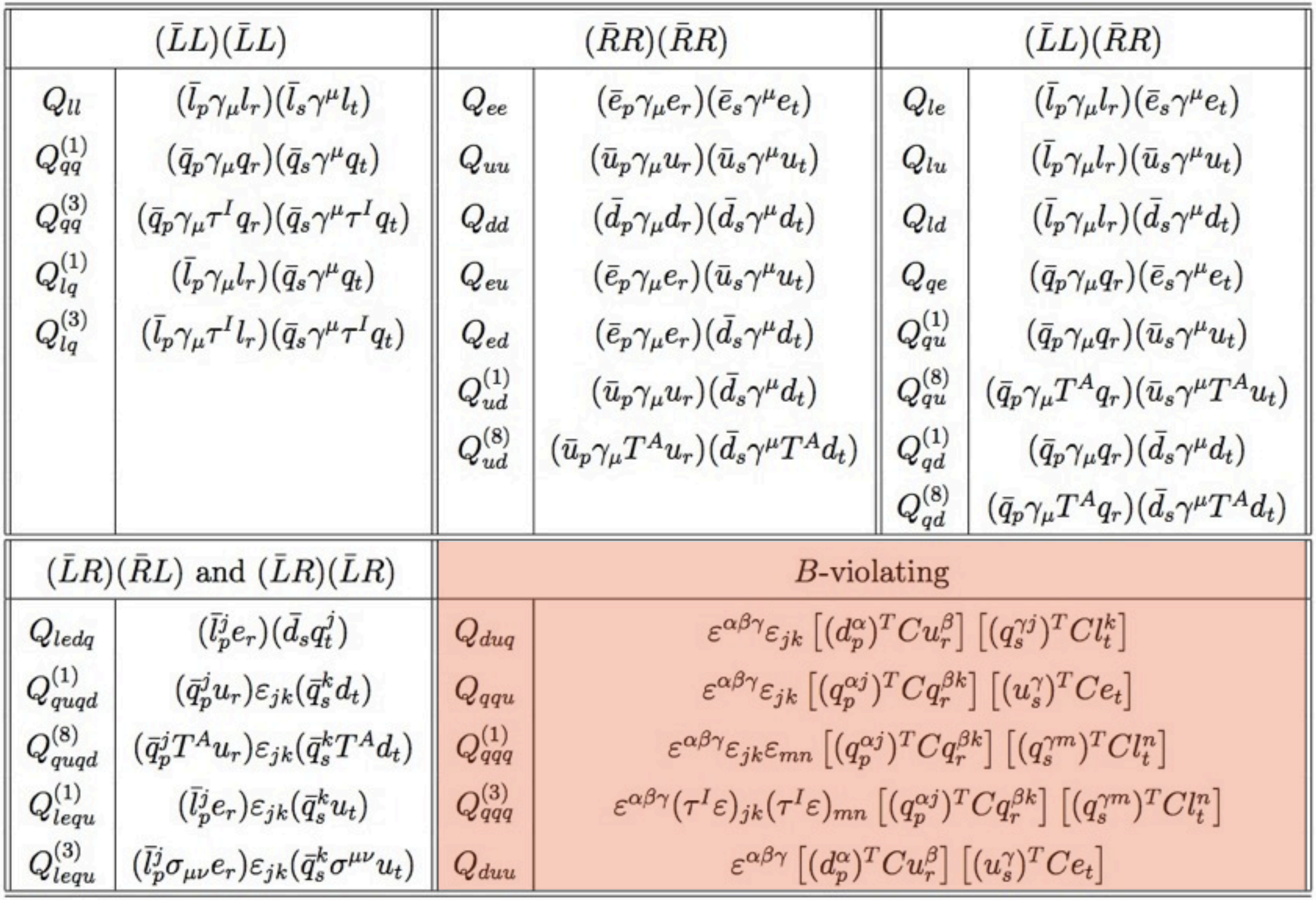

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
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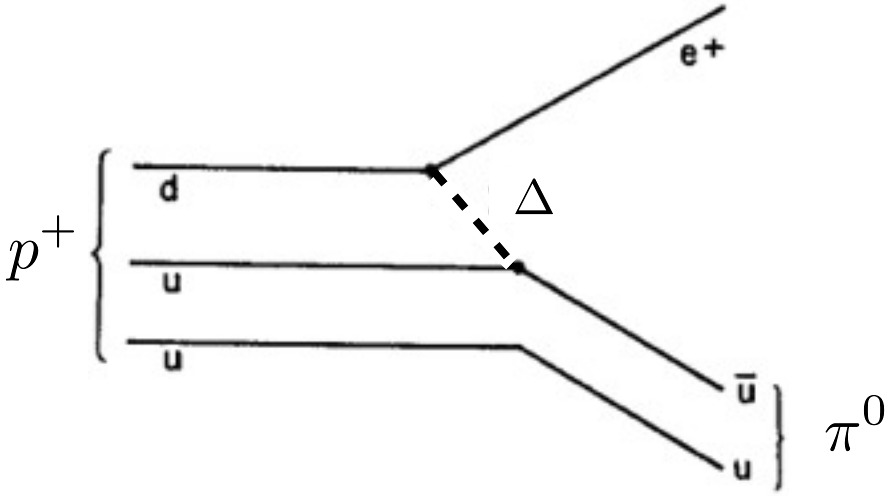
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		*B*-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

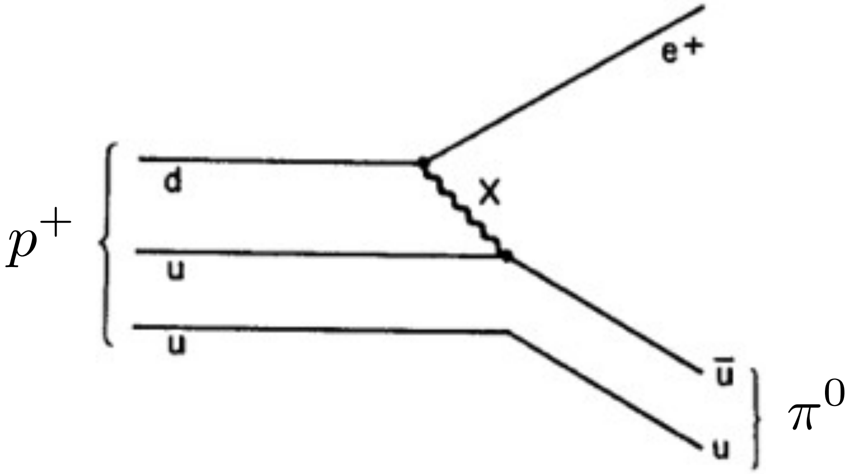
B. Grzadkowski et al., JHEP 10 (2010) 085, arXiv: 1008.4884

d=6 baryon number violation mediators

new Yukawa interactions?



new gauge interactions?



$$\Gamma_p \sim \frac{m_p^5}{M^4} < (10^{34}\mathrm{y})^{-1}$$

d=6 baryon number violation mediators

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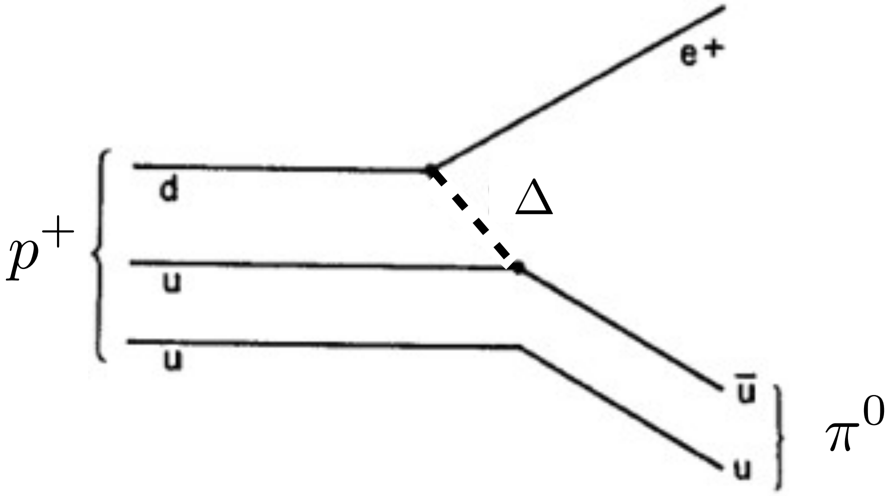
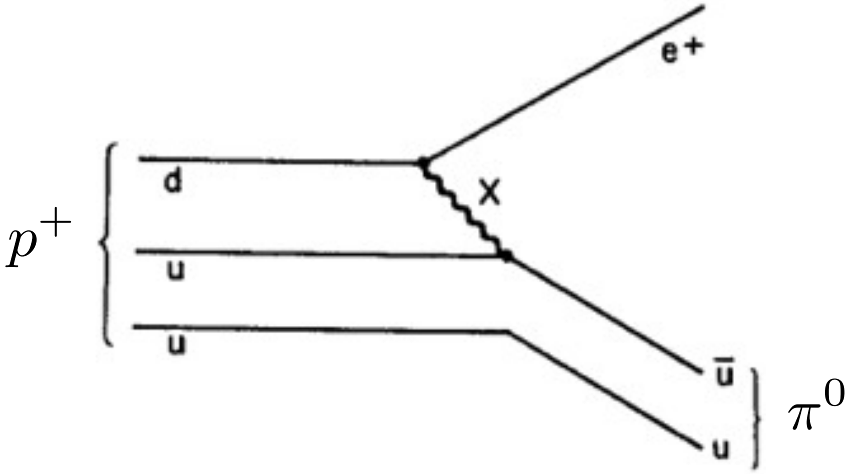


new gauge interactions?



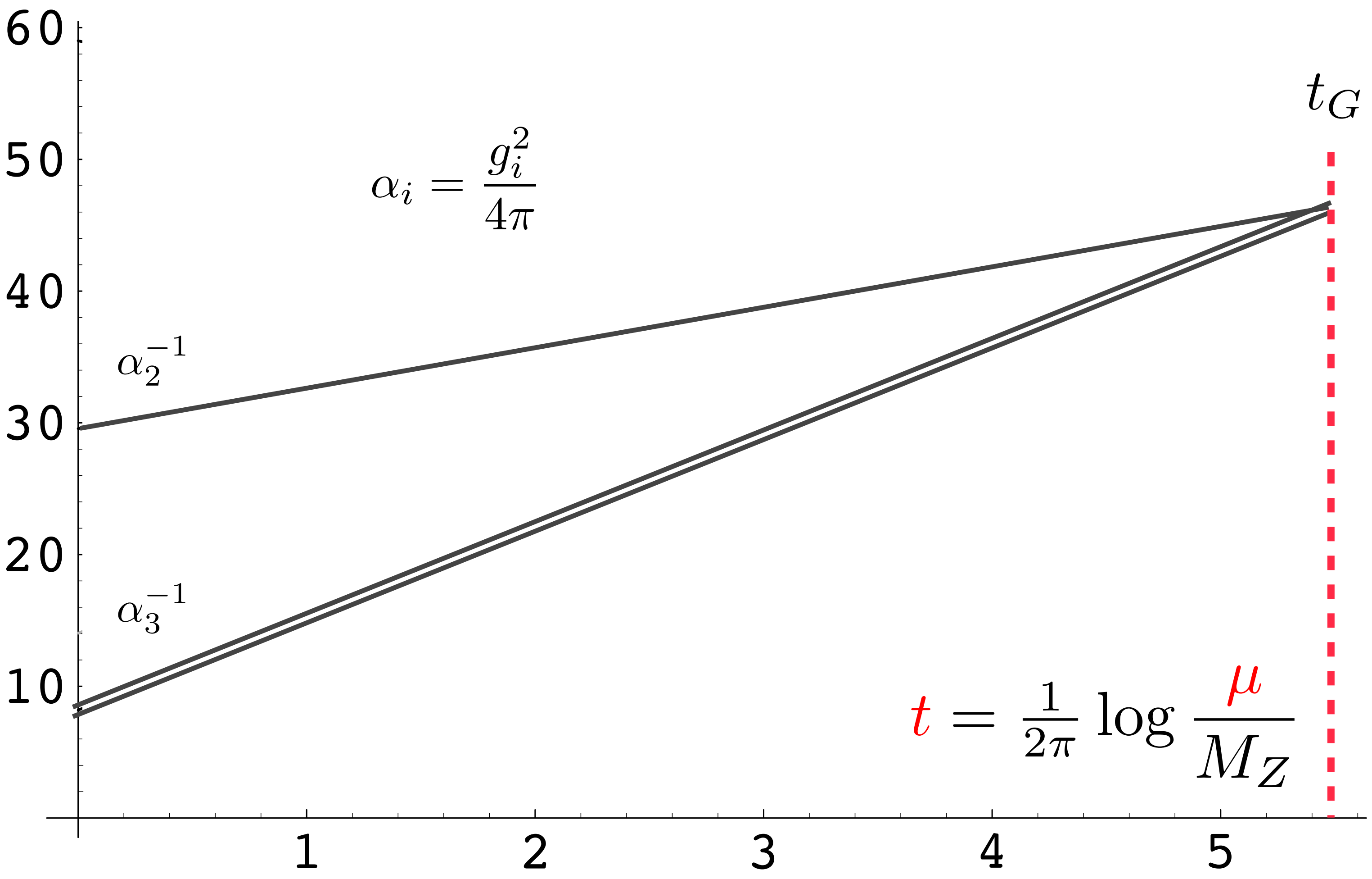
$$\Gamma_p \sim \frac{m_p^5}{M^4} < (10^{34}\mathrm{y})^{-1}$$

Such a new physics should be above 10^{15} GeV !??

Can SM tell us anything about such a huge-scale dynamics?

Running gauge couplings in the SM

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = -\frac{11}{3}\begin{pmatrix} 0 \\ 2 \\ 3 \end{pmatrix}_{gauge} + 2\begin{pmatrix} \frac{10}{3} \\ 2 \\ 2 \end{pmatrix}_{ferm.} + \frac{1}{3}\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ 0 \end{pmatrix}_{scal.}$$

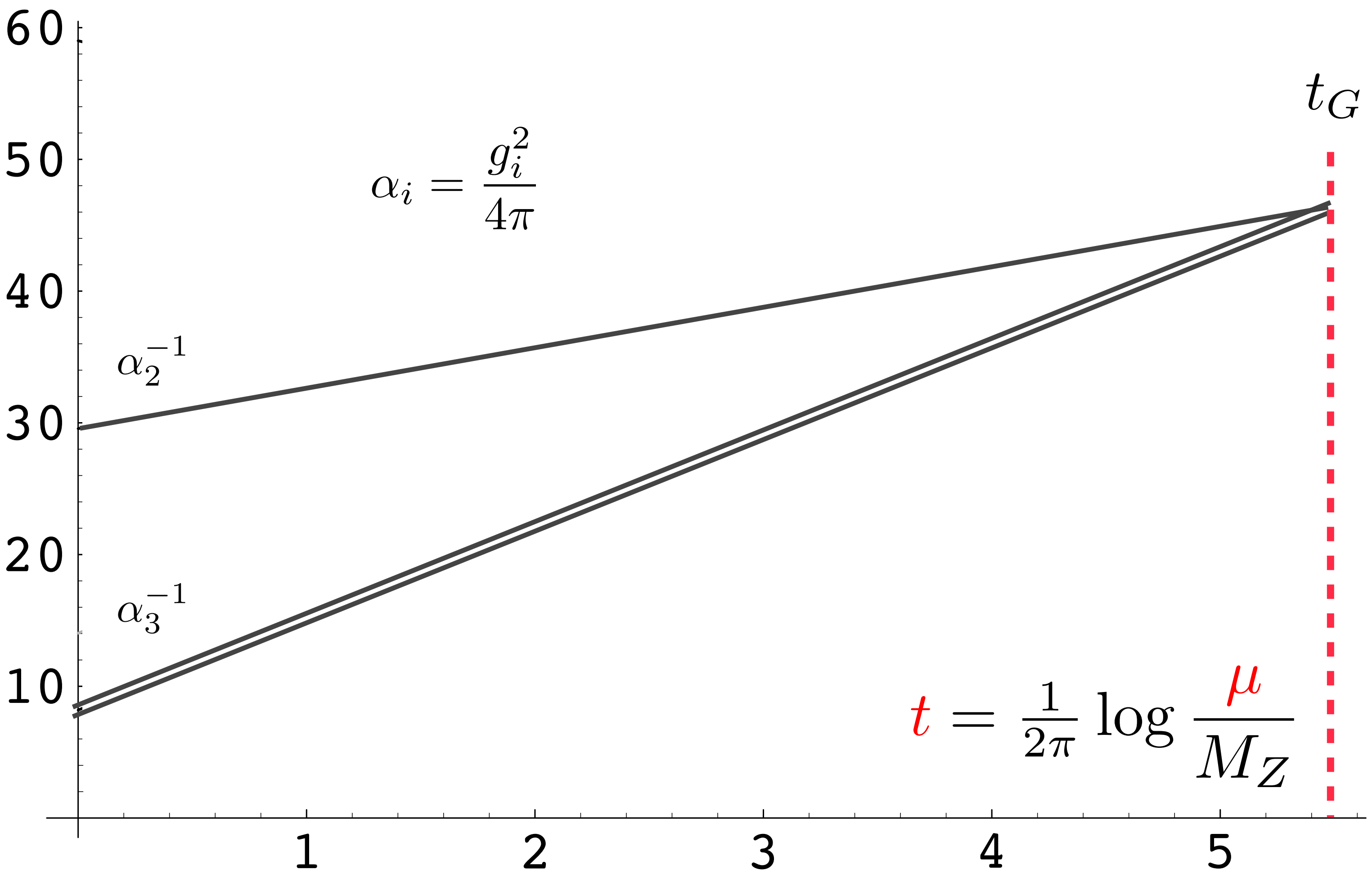


$$M_G \sim 10^{16}\mathrm{GeV}$$

Can SM tell us anything about such a huge-scale dynamics?

Running gauge couplings in the SM $+X+\Delta$

$$\begin{pmatrix} \frac{3}{5}b_1 \\ b_2 \\ b_3 \end{pmatrix} = -\frac{11}{3}\begin{pmatrix} 5 \\ 5 \\ 5 \end{pmatrix}_{gauge} + 2\begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix}_{ferm.} + \frac{1}{3}\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ \frac{1}{2} \end{pmatrix}_{scal.}$$



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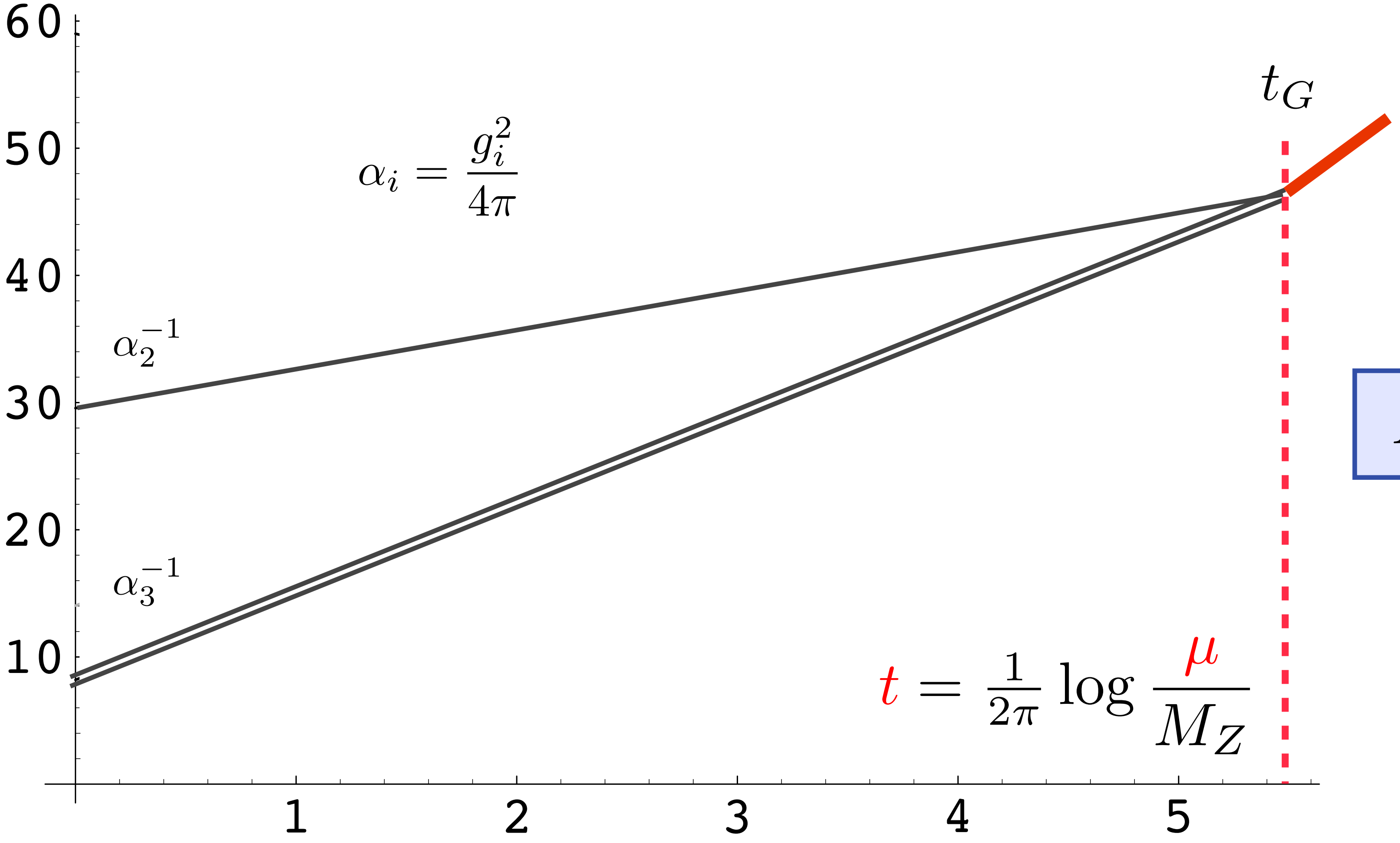
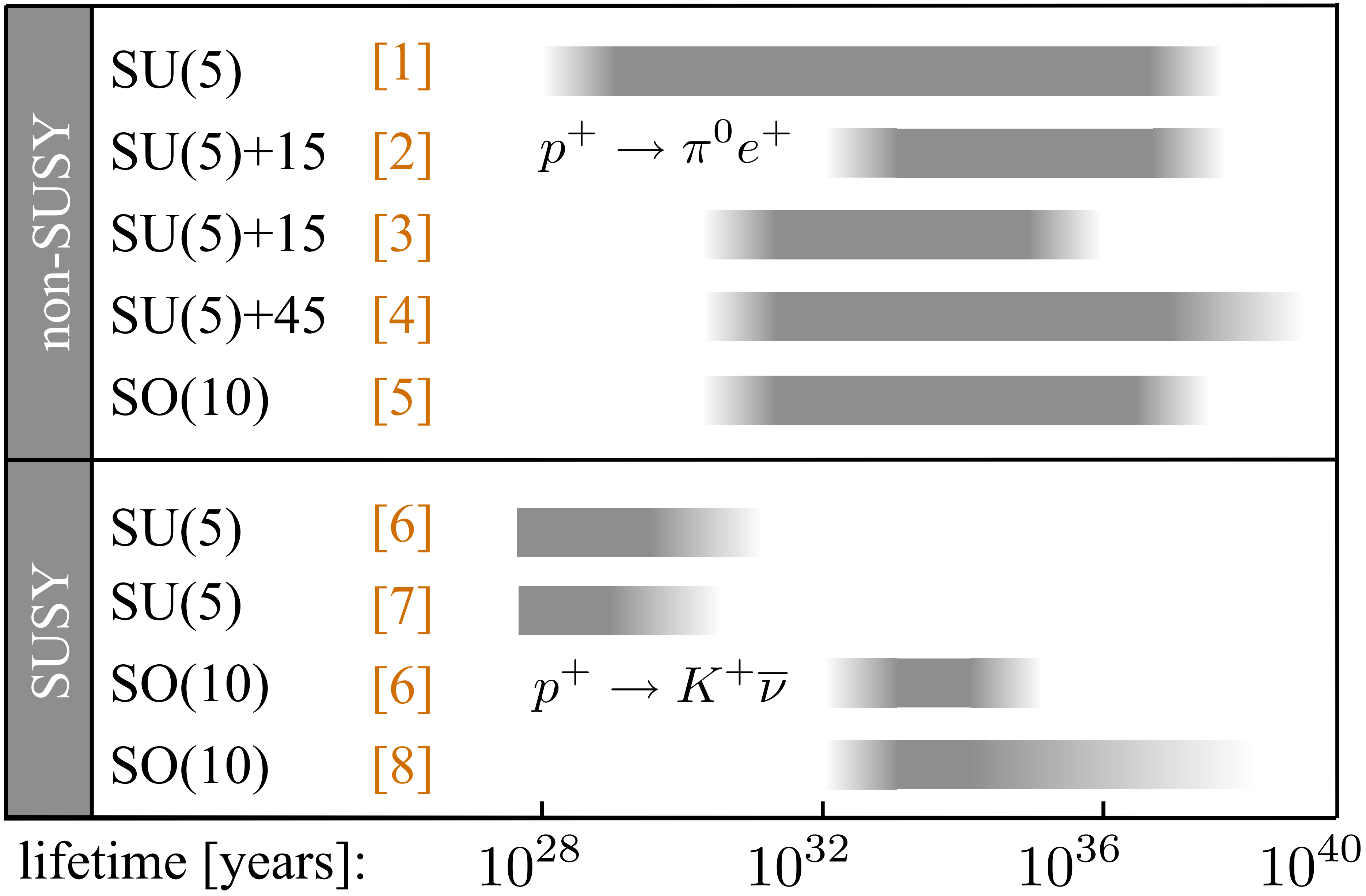


single gauge coupling like in an asymptotically free gauge theory with a simple gauge group

$$\boxed{M_G \sim 10^{16}\mathrm{GeV}}$$

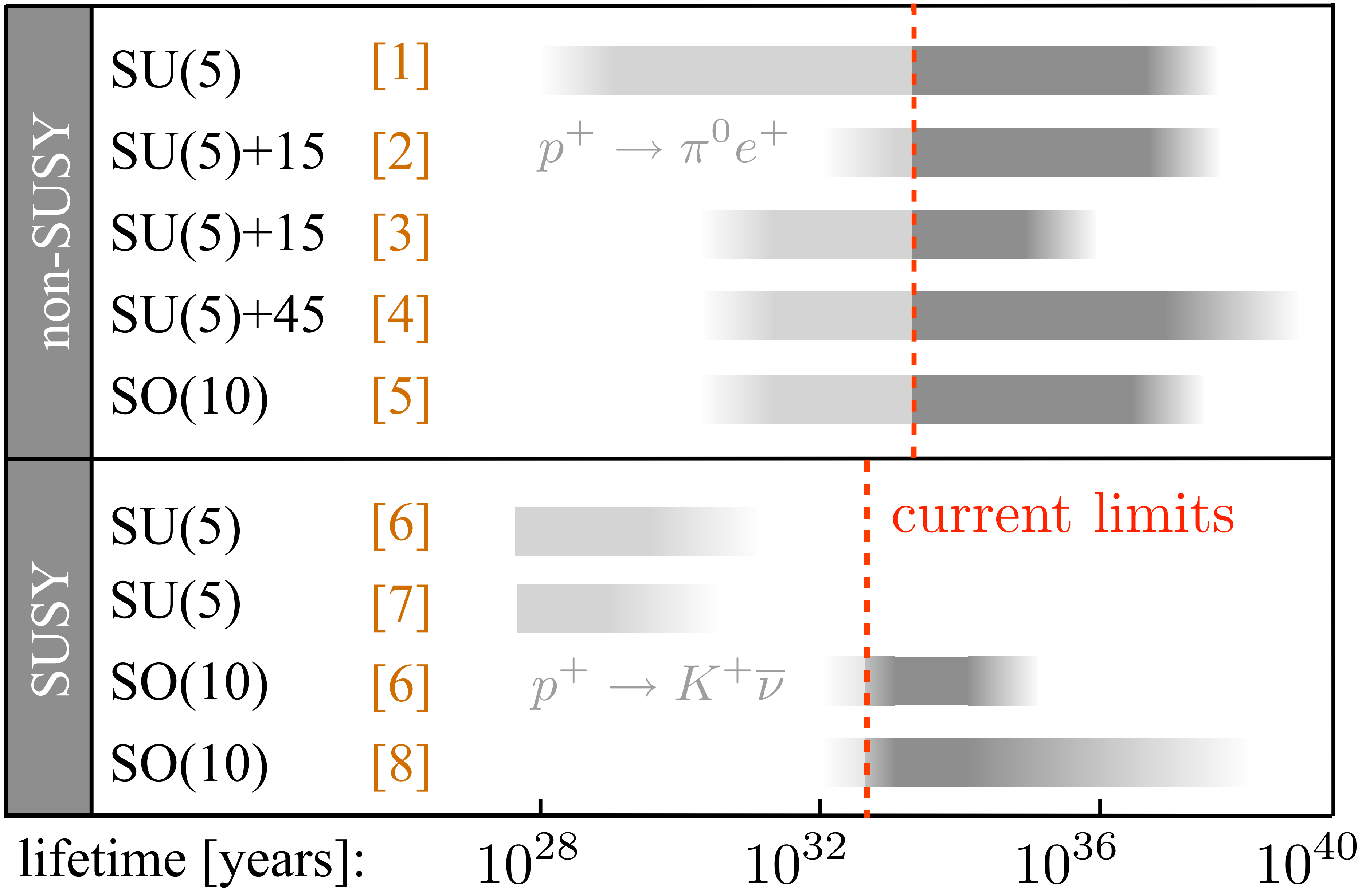
tells us the BNV scale and also the gauge coupling

Proton lifetime estimates in GUTs



[1] Georgi, Quinn, Weinberg, PRL 33, 451 (1974)
[2] Dorsner, Fileviez Perez, NPB 723, 53 (2005)
[3] Dorsner, Fileviez Perez, Rodrigo, PRD75, 125007 (2007)
[4] Dorsner, Fileviez Perez, PLB 642, 248 (2006)
[5] Lee, Mohapatra, Parida, Rani, PRD 51 (1995)
[6] Pati, hep-ph/0507307
[7] Murayama, Pierce, PRD 65. 055009 (2002)
[8] Dutta, Mimura, Mohapatra, PRL 94, 091804 (2005)
... and many more.

Proton lifetime estimates in GUTs



[1] Georgi, Quinn, Weinberg, PRL 33, 451 (1974)
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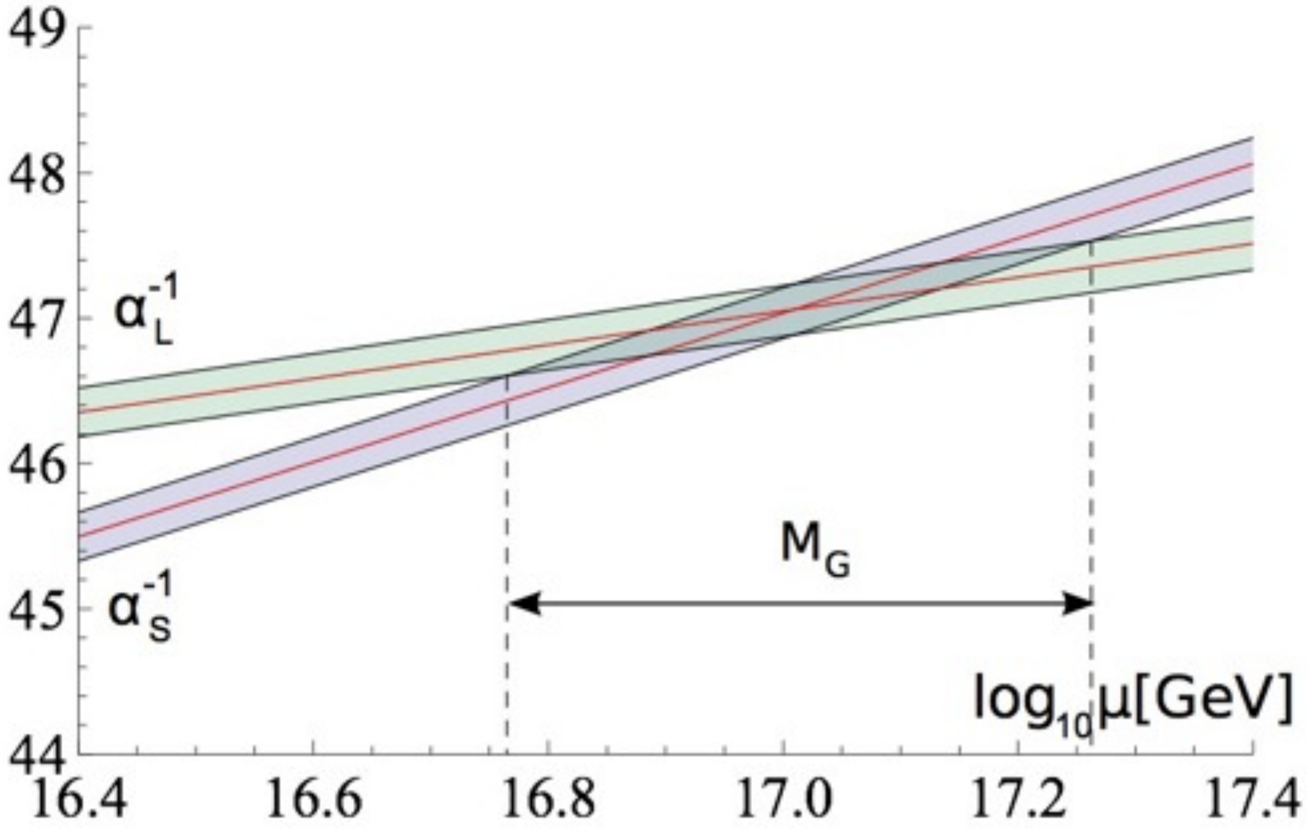
... and many more.

Main theoretical uncertainties in p-decay estimates

GUT scale determination

- at least two-loop running necessary!



Credit: H. Kolesova

- requires a **very good** understanding of the **whole** spectrum

SUSY is “schizophrenic” in this respect...

Main theoretical uncertainties in p-decay estimates

Flavour structure of the BLV currents

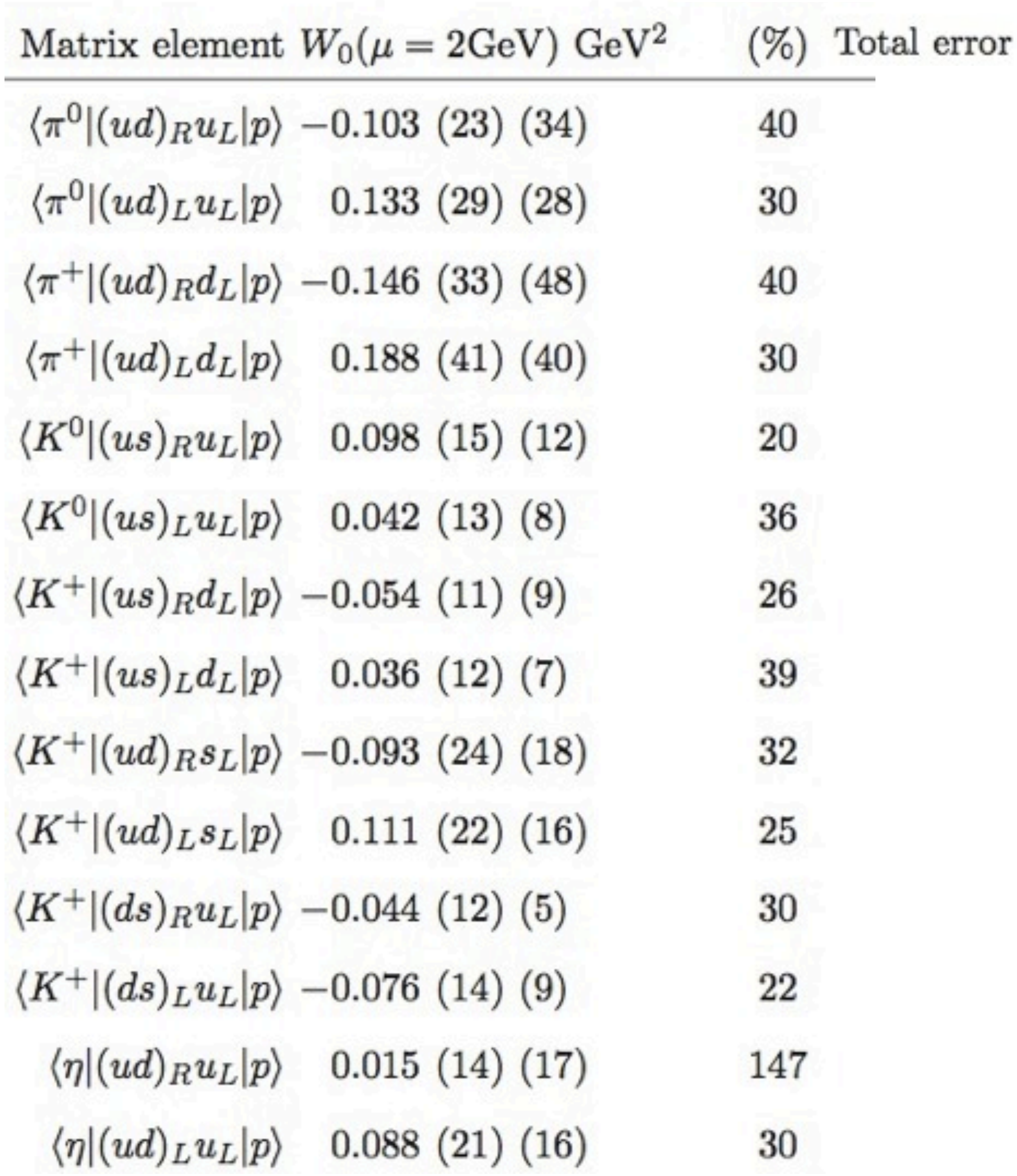
Example: $\frac{g^2}{M_{1/6}^2} C_{ijk}\, \overline{u^c}\gamma^\mu d_i\, \overline{d^c_j}\gamma_\mu \nu_k$ $\qquad C_{ijk} = (V_{d^c}^\dagger V_d)_{ji}(V_{u^c}^\dagger V_\nu)_{1k}$

- RH rotations enter here

- simple Yukawa sector desirable!

Main theoretical uncertainties in p-decay estimates

Hadronic matrix elements



Matrix element	$W_0(\mu = 2\text{GeV})$ GeV^2	(%) Total error
$\langle\pi^0\|(ud)_R u_L\|p\rangle$	-0.103 (23) (34)	40
$\langle\pi^0\|(ud)_L u_L\|p\rangle$	0.133 (29) (28)	30
$\langle\pi^+\|(ud)_R d_L\|p\rangle$	-0.146 (33) (48)	40
$\langle\pi^+\|(ud)_L d_L\|p\rangle$	0.188 (41) (40)	30
$\langle K^0\|(us)_R u_L\|p\rangle$	0.098 (15) (12)	20
$\langle K^0\|(us)_L u_L\|p\rangle$	0.042 (13) (8)	36
$\langle K^+\|(us)_R d_L\|p\rangle$	-0.054 (11) (9)	26
$\langle K^+\|(us)_L d_L\|p\rangle$	0.036 (12) (7)	39
$\langle K^+\|(ud)_R s_L\|p\rangle$	-0.093 (24) (18)	32
$\langle K^+\|(ud)_L s_L\|p\rangle$	0.111 (22) (16)	25
$\langle K^+\|(ds)_R u_L\|p\rangle$	-0.044 (12) (5)	30
$\langle K^+\|(ds)_L u_L\|p\rangle$	-0.076 (14) (9)	22
$\langle\eta\|(ud)_R u_L\|p\rangle$	0.015 (14) (17)	147
$\langle\eta\|(ud)_L u_L\|p\rangle$	0.088 (21) (16)	30

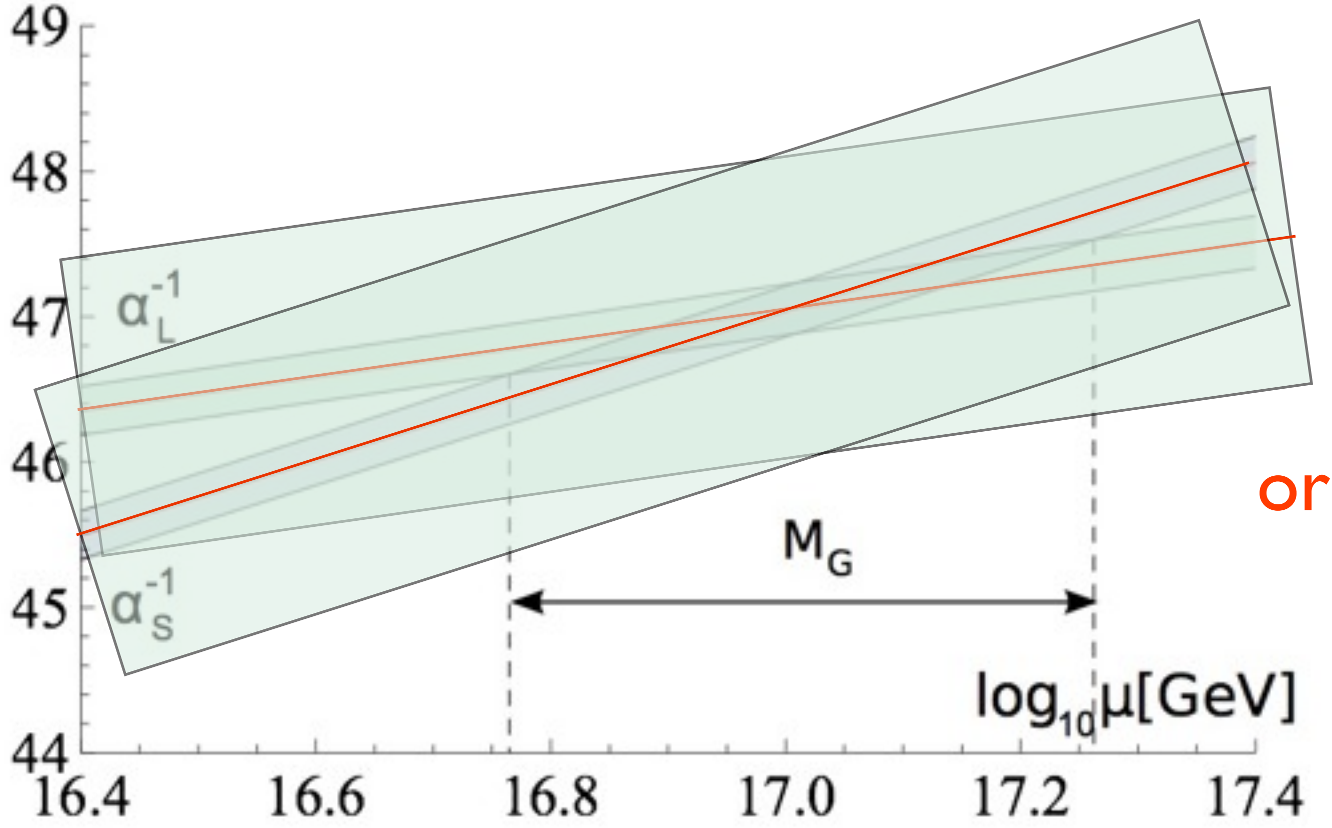
Y. Aoki, E. Shintani, A. Soni, Phys.Rev. D89 (2014) 014505 (lattice)

Main theoretical uncertainties in p-decay estimates

Planck scale effects

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle \Phi \rangle F_{\mu\nu}$$

- finite shifts in the gauge matching, can be as large as $\Delta\alpha_i^{-1} \sim 1$



Larsen, Wilczek, NPB 458, 249 (1996)
G. Veneziano, JHEP 06 (2002) 051
Calmet, Hsu, Reeb, PRD 77, 125015 (2008)
G. Dvali, Fortsch. Phys. 58 (2010) 528-536

order of magnitude uncertainty in M_G !

NO POINT IN EVER TRYING NLO WITHOUT TAMING THESE!

What to do about the Planck-scale effects?

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle \Phi \rangle F_{\mu\nu}$$

- absent @ d=5 if, e.g., Φ is not in $(Adj. \otimes Adj.)_{sym}$

SU(5) GUTs:

$$(24 \otimes 24)_{sym} = 24 \oplus 75 \oplus 200$$

not many options - the rank should not get reduced...

SO(10) GUTs:

$$(45 \otimes 45)_{sym} = 54 \oplus 210 \oplus 770$$

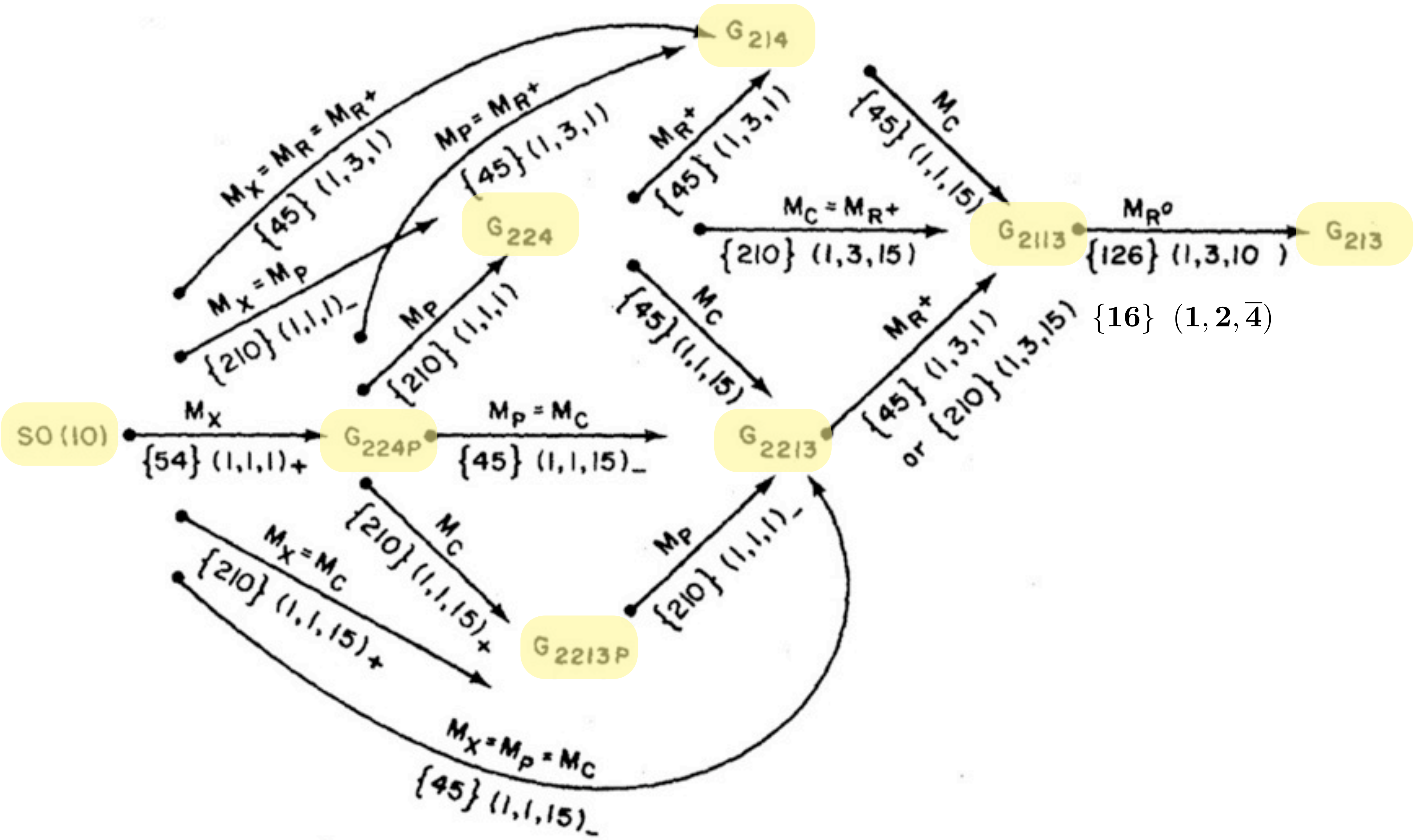
these, however, are the "usual" choices (**though not minimal**)...

Minimal SO(10) GUT

The minimal SO(10) unification

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted

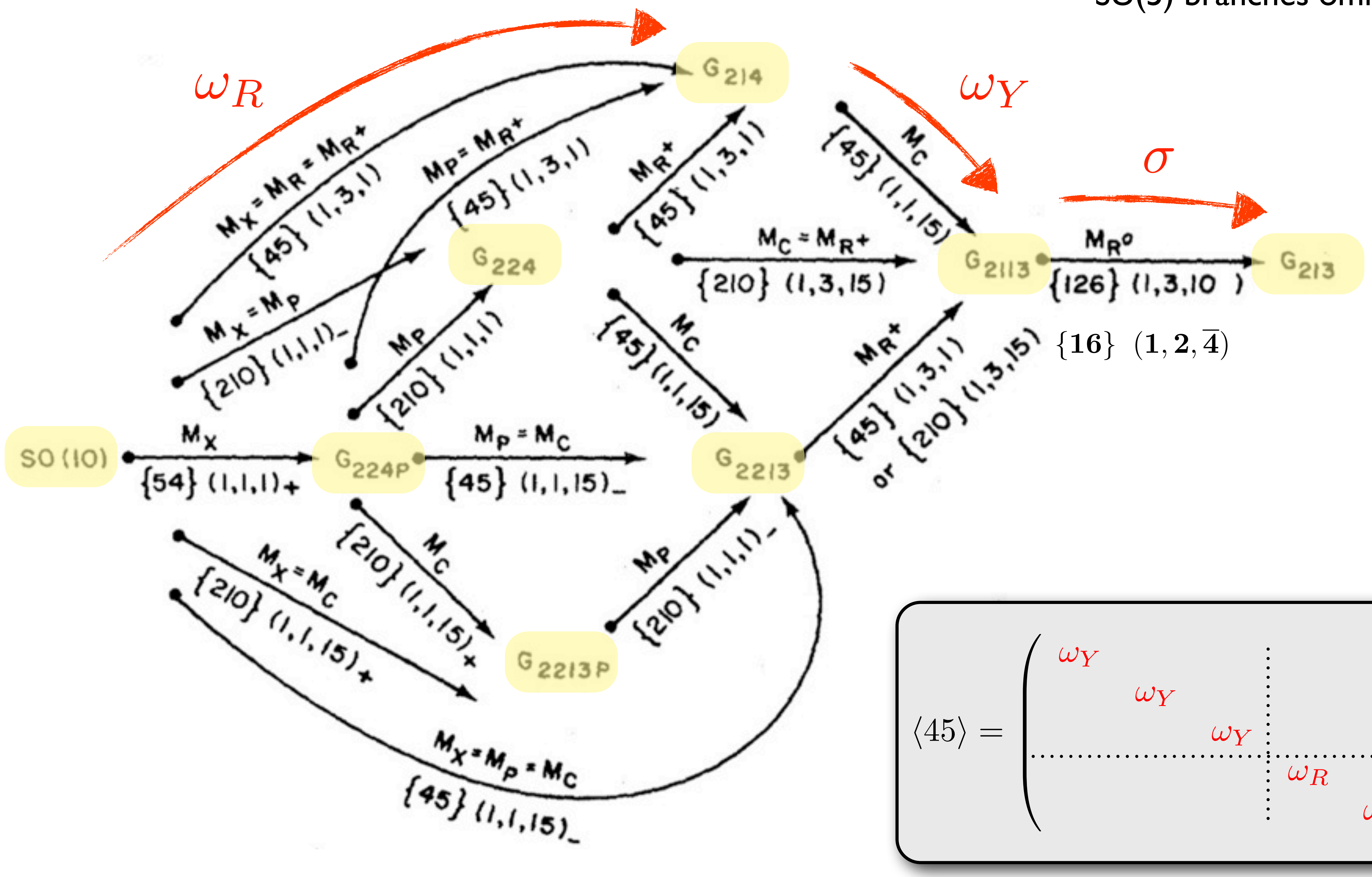


$\{16\}$ $(\mathbf{1}, \mathbf{2}, \overline{\mathbf{4}})$

The minimal SO(10) unification

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



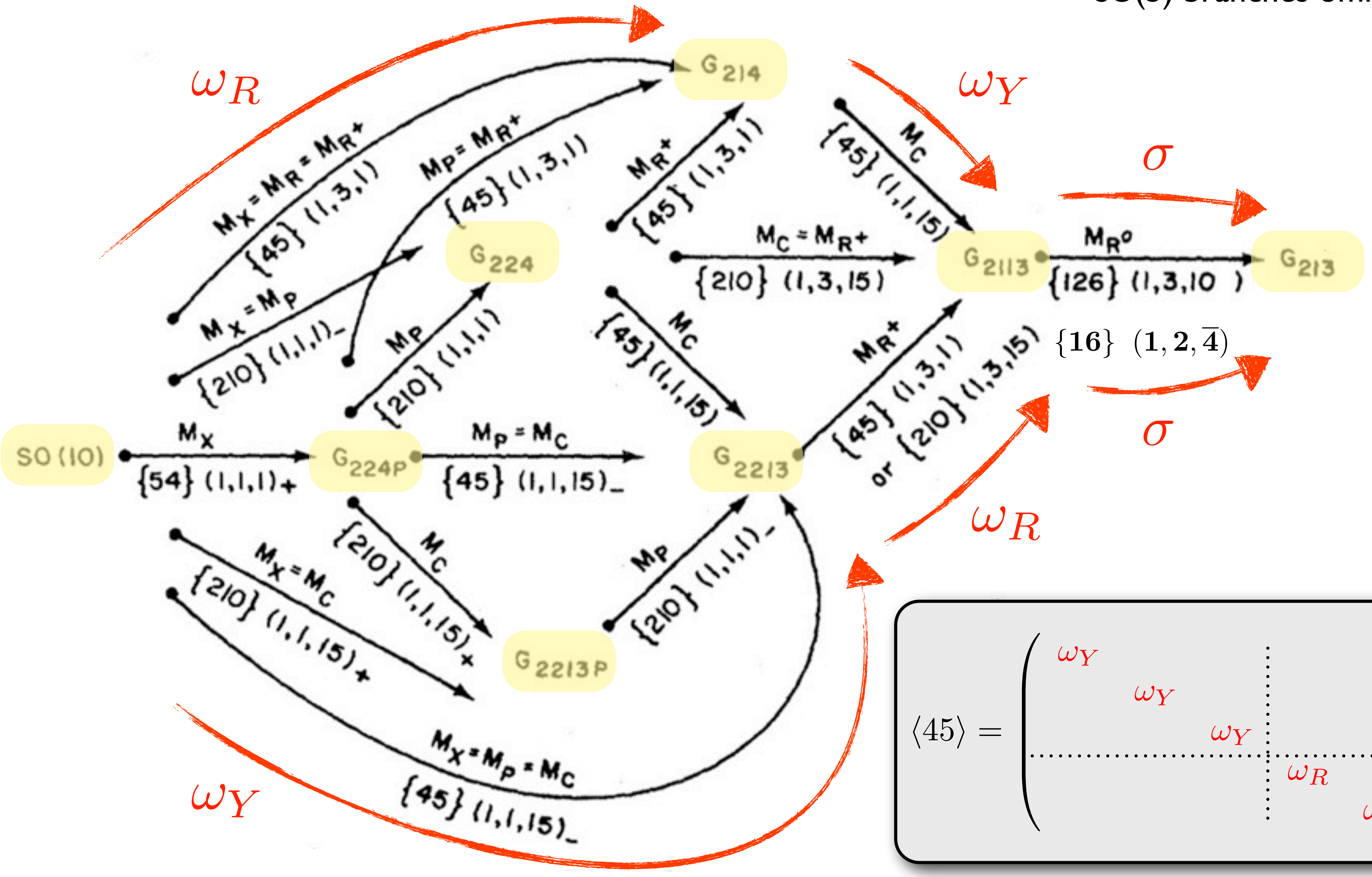
$\{\mathbf{16}\}\quad(\mathbf{1},\mathbf{2},\overline{\mathbf{4}})$

$$\langle 45\rangle = \left(\begin{array}{ccc|cc} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ \hline & & & \omega_R & \\ & & & & \omega_R \end{array}\right) \otimes \tau_2$$

The minimal SO(10) unification

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



$$\langle 45\rangle = \begin{pmatrix} \begin{array}{ccc:cc} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ \hdashline & & & \omega_R & \\ & & & & \omega_R \end{array} \end{pmatrix} \otimes \tau_2$$

Taming the Planck-scale effects in the minimal SO(10)

The leading Planck-scale effects absent in SO(10) GUTs broken by 45!

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle 45 \rangle F_{\mu\nu} = 0$$

The minimal SO(10) unification

SO(10) broken by 45, rank reduced by 126

Scalar potential: $V = V_{45} + V_{126} + V_{\mathrm{mix}}$

$$V_{45} = -\frac{\mu^2}{2}(\phi\phi)_0 + \frac{a_0}{4}(\phi\phi)_0(\phi\phi)_0 + \frac{a_2}{4}(\phi\phi)_2(\phi\phi)_2\,,$$

$$\begin{aligned} V_{126} = &-\frac{\nu^2}{5!}(\Sigma\Sigma^*)_0 \\ &+ \frac{\lambda_0}{(5!)^2}(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 + \frac{\lambda_2}{(4!)^2}(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \\ &+ \frac{\lambda_4}{(3!)^2(2!)^2}(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 + \frac{\lambda_4'}{(3!)^2}(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \\ &+ \frac{\eta_2}{(4!)^2}(\Sigma\Sigma)_2(\Sigma\Sigma)_2 + \frac{\eta_2^*}{(4!)^2}(\Sigma^*\Sigma^*)_2(\Sigma^*\Sigma^*)_2\,, \end{aligned}$$

$$\begin{aligned} V_{\mathrm{mix}} = &\frac{i\tau}{4!}(\phi)_2(\Sigma\Sigma^*)_2 + \frac{\alpha}{2\cdot 5!}(\phi\phi)_0(\Sigma\Sigma^*)_0 \\ &+ \frac{\beta_4}{4\cdot 3!}(\phi\phi)_4(\Sigma\Sigma^*)_4 + \frac{\beta_4'}{3!}(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \\ &+ \frac{\gamma_2}{4!}(\phi\phi)_2(\Sigma\Sigma)_2 + \frac{\gamma_2^*}{4!}(\phi\phi)_2(\Sigma^*\Sigma^*)_2\,. \end{aligned}$$

$$(\phi\phi)_0(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}\phi_{kl}\phi_{kl}$$

$$(\phi\phi)_2(\phi\phi)_2 \equiv \phi_{ij}\phi_{ik}\phi_{lj}\phi_{lk}$$

$$(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}, \quad (\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}$$

$$(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}\Sigma_{nopqr}\Sigma^*_{nopqr}$$

$$(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \equiv \Sigma_{ijklm}\Sigma^*_{ijkln}\Sigma_{opqrm}\Sigma^*_{opqrn}$$

$$(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrlm}\Sigma^*_{pqrno}$$

$$(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrln}\Sigma^*_{pqrmo}$$

$$(\Sigma\Sigma)_2(\Sigma\Sigma)_2 \equiv \Sigma_{ijklm}\Sigma_{ijkln}\Sigma_{opqrm}\Sigma_{opqrn}$$

$$(\phi)_2(\Sigma\Sigma^*)_2 \equiv \phi_{ij}\Sigma_{klmni}\Sigma^*_{klmnj}$$

$$(\phi\phi)_0(\Sigma\Sigma^*)_0 \equiv \phi_{ij}\phi_{ij}\Sigma_{klmno}\Sigma^*_{klmno}$$

$$(\phi\phi)_4(\Sigma\Sigma^*)_4 \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoij}\Sigma^*_{mnokl}$$

$$(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoik}\Sigma^*_{mnojl}$$

$$(\phi\phi)_2(\Sigma\Sigma)_2 \equiv \phi_{ij}\phi_{ik}\Sigma_{lmnoj}\Sigma_{lmnok}$$

$$(\phi\phi)_2(\Sigma^*\Sigma^*)_2 \equiv \phi_{ij}\phi_{ik}\Sigma^*_{lmnoj}\Sigma^*_{lmnok}$$

The minimal SO(10) ~~unification~~ nightmare

SO(10) broken by 45, rank reduced by 126

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$$\begin{aligned} V_{126} = &-\frac{\nu^2}{5!}(\Sigma\Sigma^*)_0 \\ &+ \frac{\lambda_0}{(5!)^2}(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 + \frac{\lambda_2}{(4!)^2}(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \\ &+ \frac{\lambda_4}{(3!)^2(2!)^2}(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 + \frac{\lambda_4'}{(3!)^2}(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \\ &+ \frac{\eta_2}{(4!)^2}(\Sigma\Sigma)_2(\Sigma\Sigma)_2 + \frac{\eta_2^*}{(4!)^2}(\Sigma^*\Sigma^*)_2(\Sigma^*\Sigma^*)_2\,, \end{aligned}$$

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$$(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \Sigma_{ijklm}\Sigma^*_{ijkno}\Sigma_{pqrln}\Sigma^*_{pqrmo}$$

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$$(\phi)_2(\Sigma\Sigma^*)_2 \equiv \phi_{ij}\Sigma_{klmni}\Sigma^*_{klmnj}$$

$$(\phi\phi)_0(\Sigma\Sigma^*)_0 \equiv \phi_{ij}\phi_{ij}\Sigma_{klmno}\Sigma^*_{klmno}$$

$$(\phi\phi)_4(\Sigma\Sigma^*)_4 \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoij}\Sigma^*_{mnokl}$$

$$(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \equiv \phi_{ij}\phi_{kl}\Sigma_{mnoik}\Sigma^*_{mnojl}$$

$$(\phi\phi)_2(\Sigma\Sigma)_2 \equiv \phi_{ij}\phi_{ik}\Sigma_{lmnoj}\Sigma_{lmnok}$$

$$(\phi\phi)_2(\Sigma^*\Sigma^*)_2 \equiv \phi_{ij}\phi_{ik}\Sigma^*_{lmnoj}\Sigma^*_{lmnok}$$

The minimal SO(10) ~~unification~~ nightmare

“Ruled out” in 1980’s

$$\begin{aligned} m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\ m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R) \end{aligned}$$

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

The minimal SO(10) ~~unification~~ nightmare

“Ruled out” in 1980’s

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Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

Aaarrrggh... tachyonic spectrum unless $\frac{1}{2} < |\omega_Y/\omega_R| < 2$

The minimal SO(10) ~~unification~~ nightmare

"Ruled out" in 1980's

$$
\begin{aligned}
m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\
m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R)
\end{aligned}
$$

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

Aaarrrggh... tachyonic spectrum unless $\frac{1}{2} < |\omega_Y/\omega_R| < 2$

$$
\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2
$$

SU(5)-like vacua only, not far from the "SM running"!

The minimal SO(10) ~~unification~~ nightmare

"Ruled out" in 1980's

$$
\begin{aligned}
m^2_{(8,1,0)} &= 2a_2(\omega_R-\omega_Y)(\omega_R+2\omega_Y)\\
m^2_{(1,3,0)} &= 2a_2(\omega_Y-\omega_R)(\omega_Y+2\omega_R)
\end{aligned}
$$

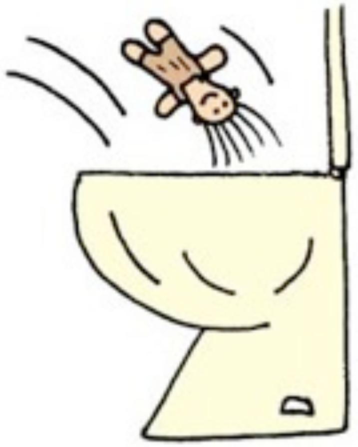
???

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

Aaarrrggh... tachyonic spectrum unless $\frac{1}{2}<|\omega_Y/\omega_R|<2$

$$
\langle 45\rangle=\begin{pmatrix}\omega_Y &&&&\\ &\omega_Y&&&\\ &&\omega_Y&&\\ &&&\omega_R&\\ &&&&\omega_R\end{pmatrix}\otimes\tau_2
$$

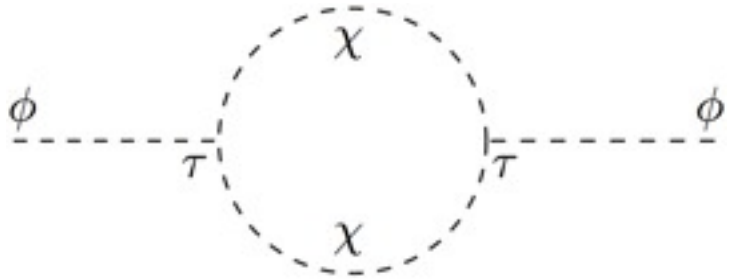
SU(5)-like vacua only, not far from the "SM running"!

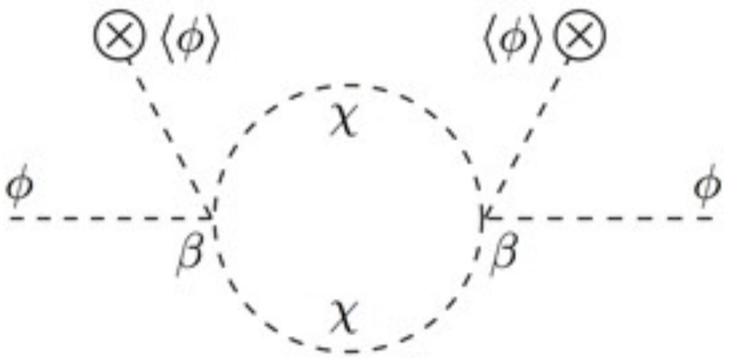


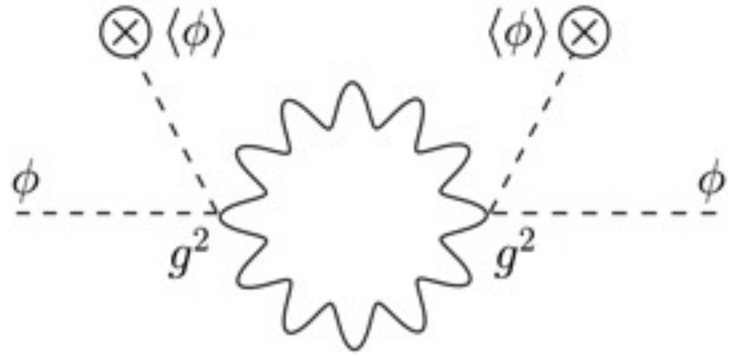
The minimal SO(10) ~~unification~~ nightmare

Quantum salvation in 2010

One-loop effective potential:







$$\Delta m^2_{(1,3,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(2\omega_R^2 - \omega_R\omega_Y + 2\omega_Y^2) + g^4\left(16\omega_R^2 + \omega_Y\omega_R + 19\omega_Y^2\right)\right] + \text{logs}\,,$$

$$\Delta m^2_{(8,1,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(\omega_R^2 - \omega_R\omega_Y + 3\omega_Y^2) + g^4\left(13\omega_R^2 + \omega_Y\omega_R + 22\omega_Y^2\right)\right] + \text{logs}\,,$$

Bertolini, Di Luzio, MM, PRD 81, 035015 (2010)

The minimal consistent SO(10) unification

**“Consistency is the last refuge
of people without imagination”**

Oscar Wilde

The minimal consistent SO(10) unification

Chang, Mohapatra, Gipson, Marshak, Parida (1985)
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Simple estimates: $M_{\rm seesaw} \sim 10^{10}\,{\rm GeV}$ $\Longrightarrow$ too heavy LH neutrinos!?

multiple Yukawa finetuning?

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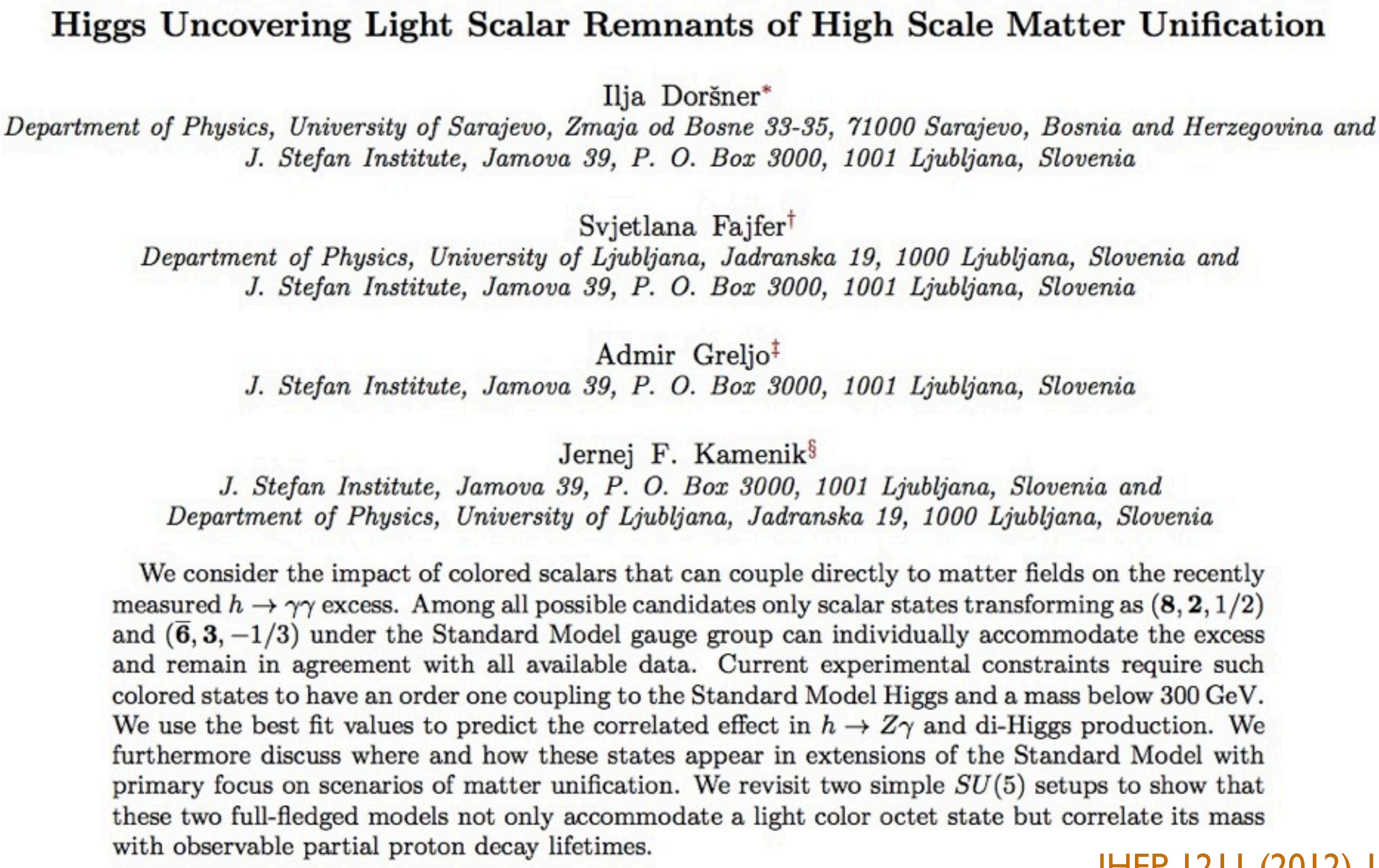
Two other potentially realistic minimally fine-tuned & consistent scenarios with “light” scalars:

$(8,2,+\frac{1}{2})$ $(6,3,+\frac{1}{3})$

Bertolini, Di Luzio, MM, PRD85 095014 2012

A funny coincidence :-)



Higgs Uncovering Light Scalar Remnants of High Scale Matter Unification

Ilja Doršner[*]
Department of Physics, University of Sarajevo, Zmaja od Bosne 33-35, 71000 Sarajevo, Bosnia and Herzegovina and
J. Stefan Institute, Jamova 39, P. O. Box 3000, 1001 Ljubljana, Slovenia

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Department of Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia and
J. Stefan Institute, Jamova 39, P. O. Box 3000, 1001 Ljubljana, Slovenia

Admir Greljo[‡]
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Jernej F. Kamenik[§]
J. Stefan Institute, Jamova 39, P. O. Box 3000, 1001 Ljubljana, Slovenia and
Department of Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia

We consider the impact of colored scalars that can couple directly to matter fields on the recently measured $h \to \gamma\gamma$ excess. Among all possible candidates only scalar states transforming as $(\mathbf{8}, \mathbf{2}, 1/2)$ and $(\overline{\mathbf{6}}, \mathbf{3}, -1/3)$ under the Standard Model gauge group can individually accommodate the excess and remain in agreement with all available data. Current experimental constraints require such colored states to have an order one coupling to the Standard Model Higgs and a mass below 300 GeV. We use the best fit values to predict the correlated effect in $h \to Z\gamma$ and di-Higgs production. We furthermore discuss where and how these states appear in extensions of the Standard Model with primary focus on scenarios of matter unification. We revisit two simple $SU(5)$ setups to show that these two full-fledged models not only accommodate a light color octet state but correlate its mass with observable partial proton decay lifetimes.

JHEP 1211 (2012) 130

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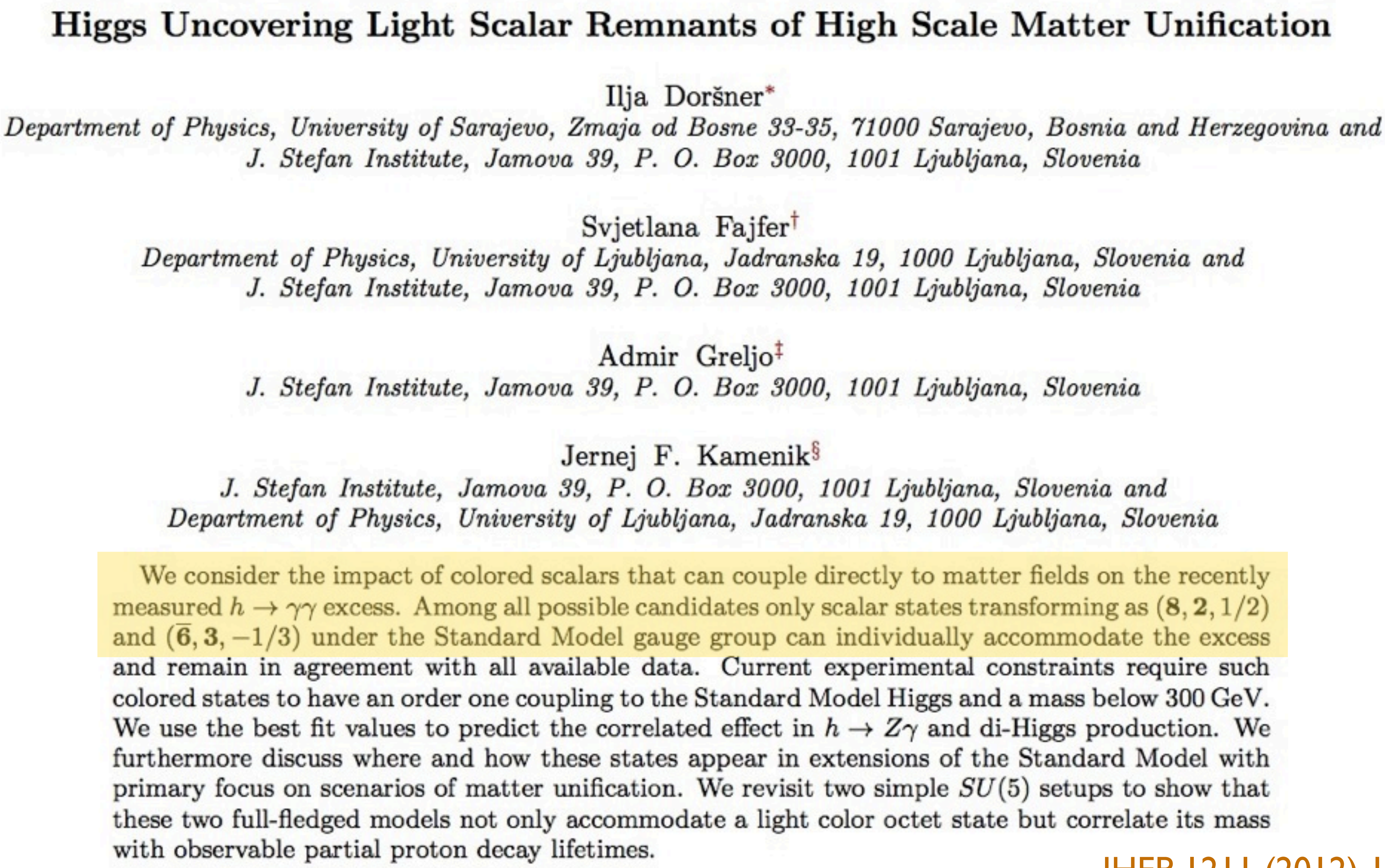

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Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$ **@ one loop** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

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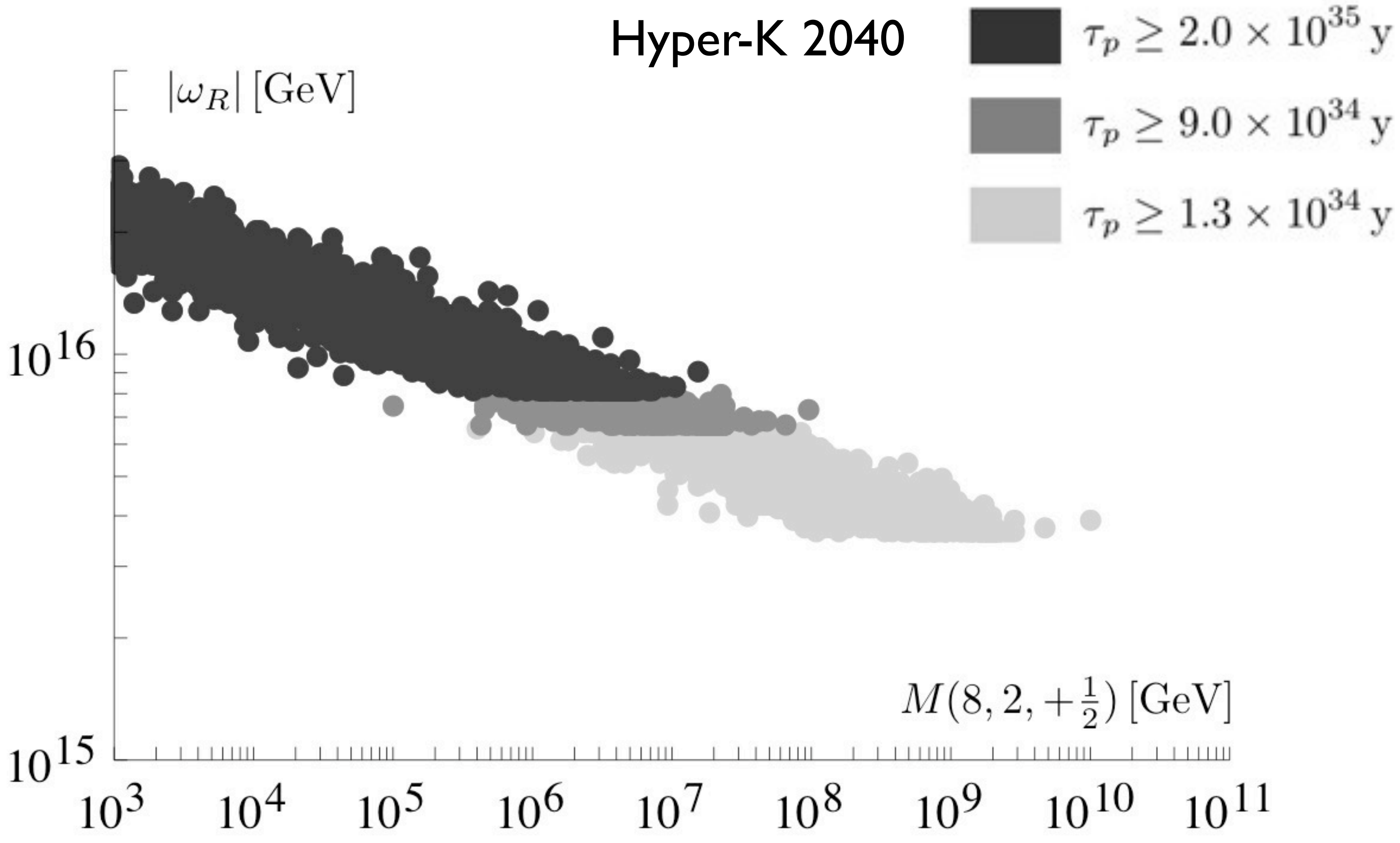
Hyper-K 2040

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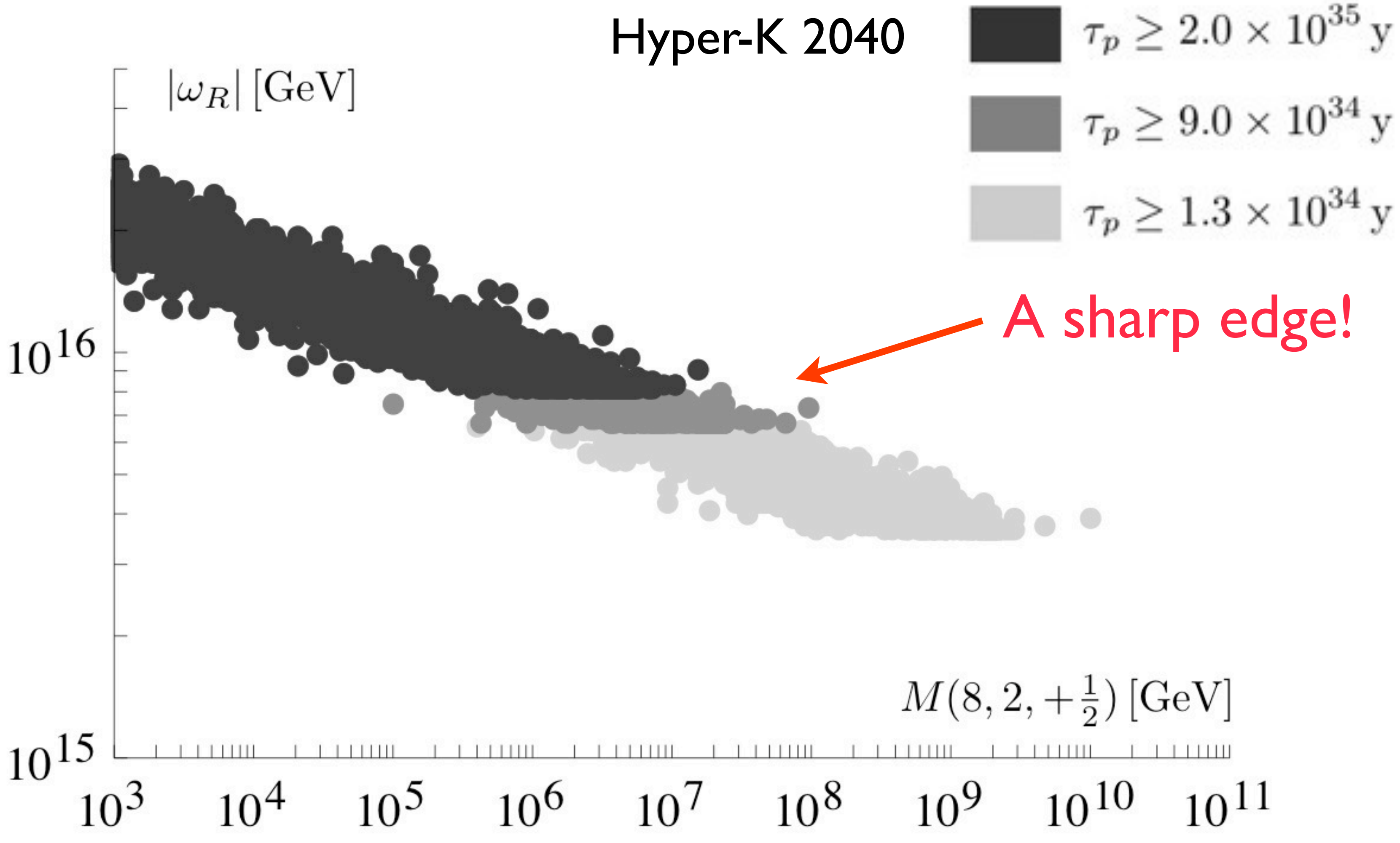

Hyper-K 2040

A sharp edge!

The octet should be light!!!

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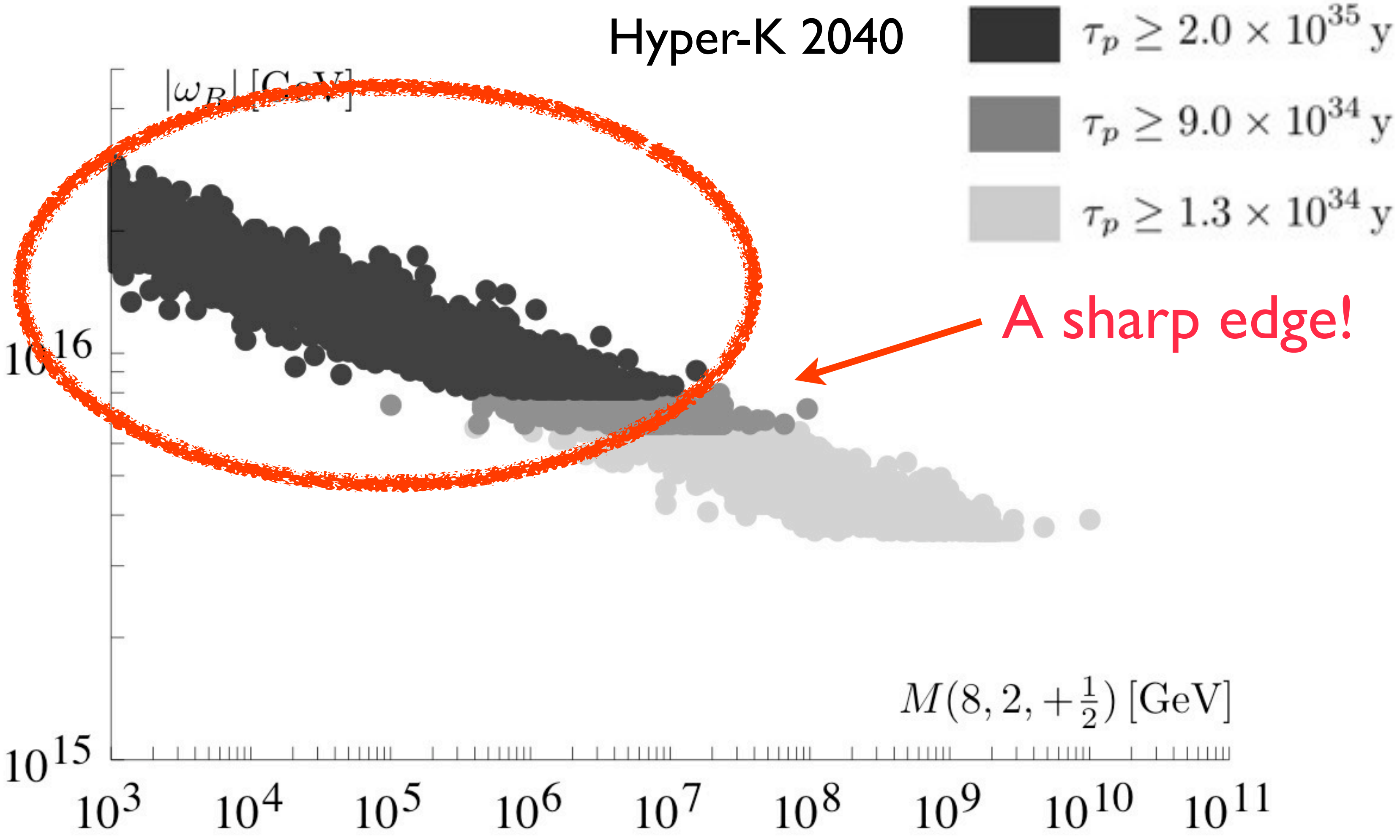

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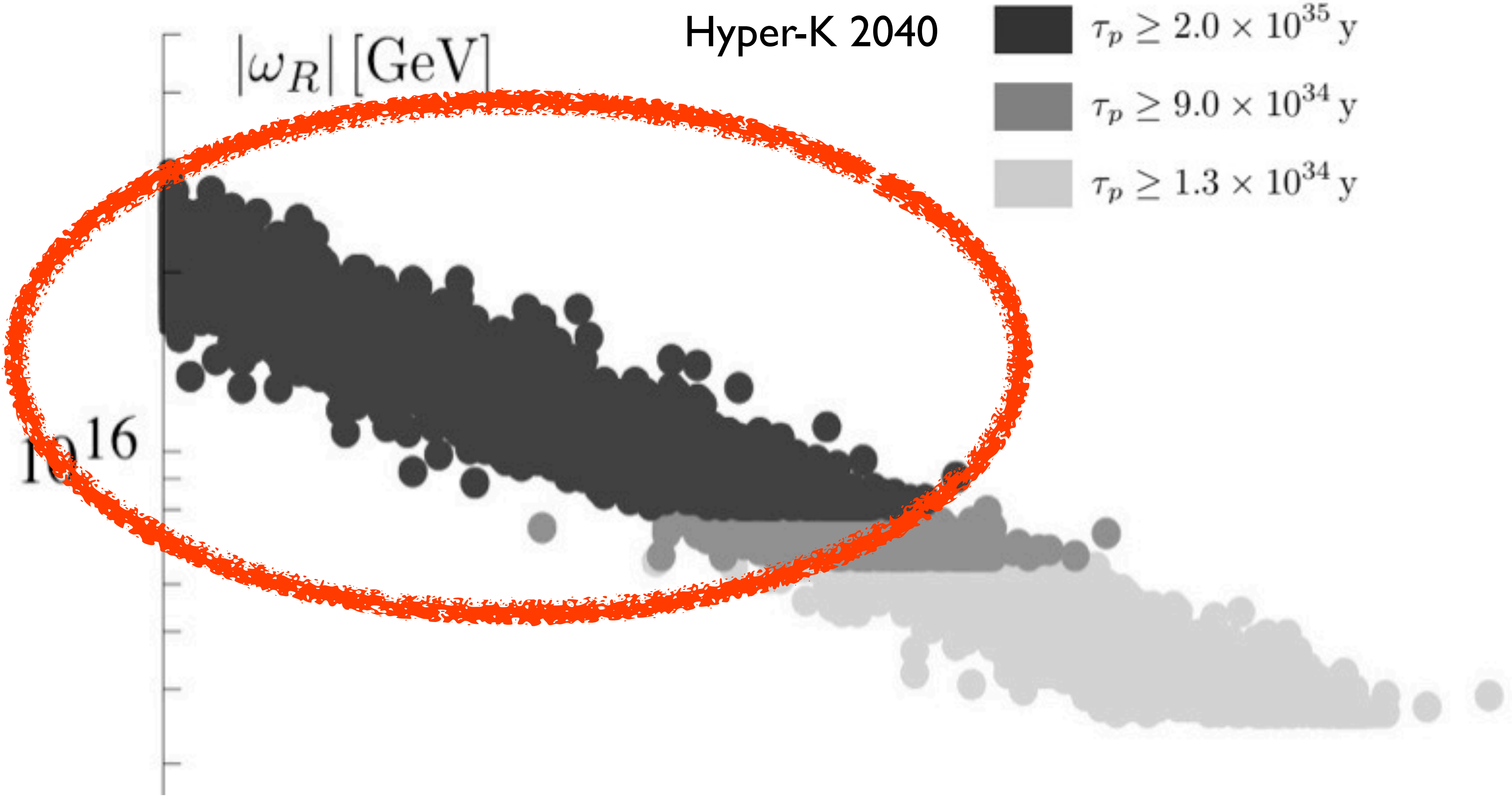
Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8,2,+\frac{1}{2})$ @ LO

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



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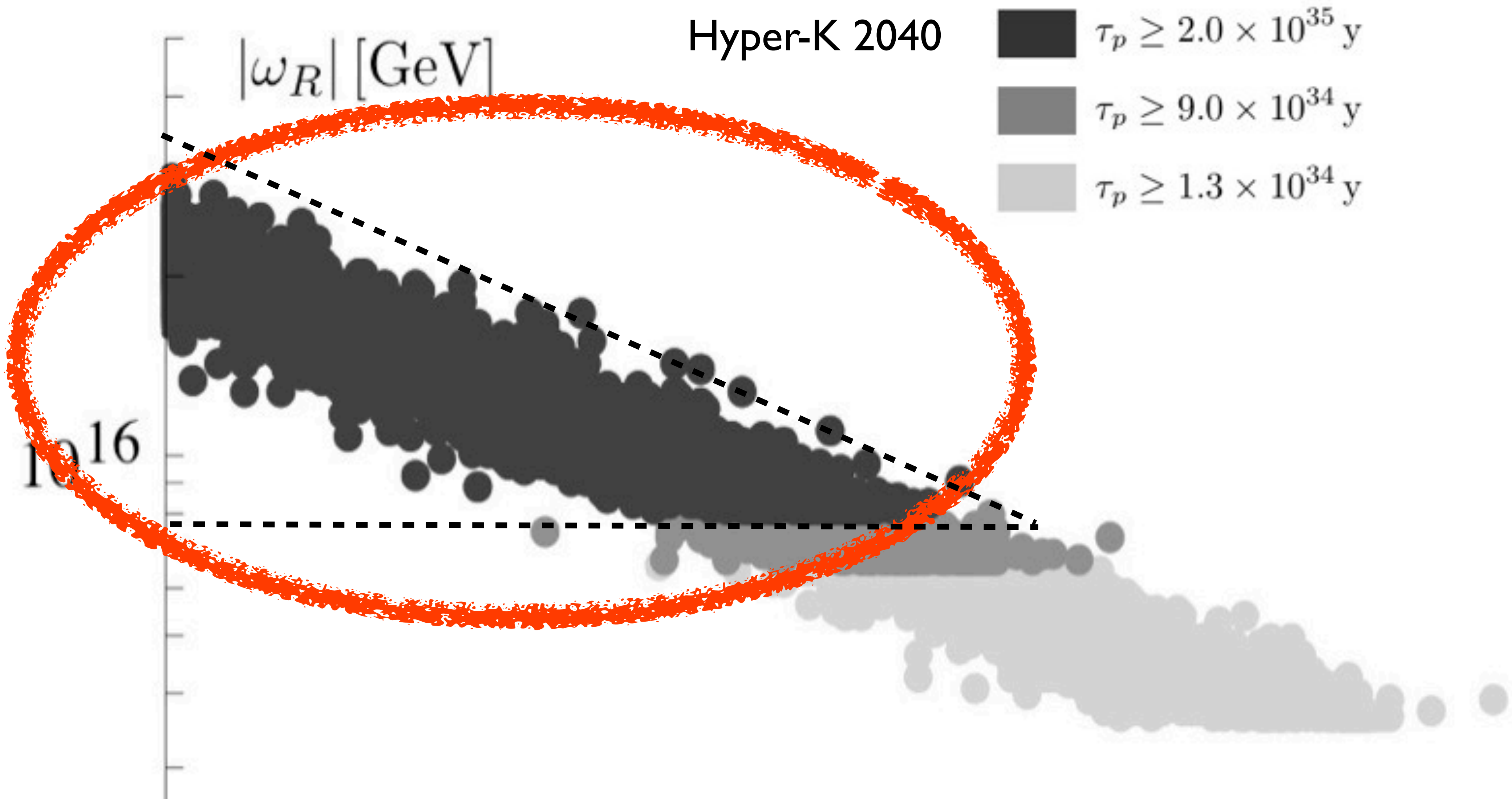
Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)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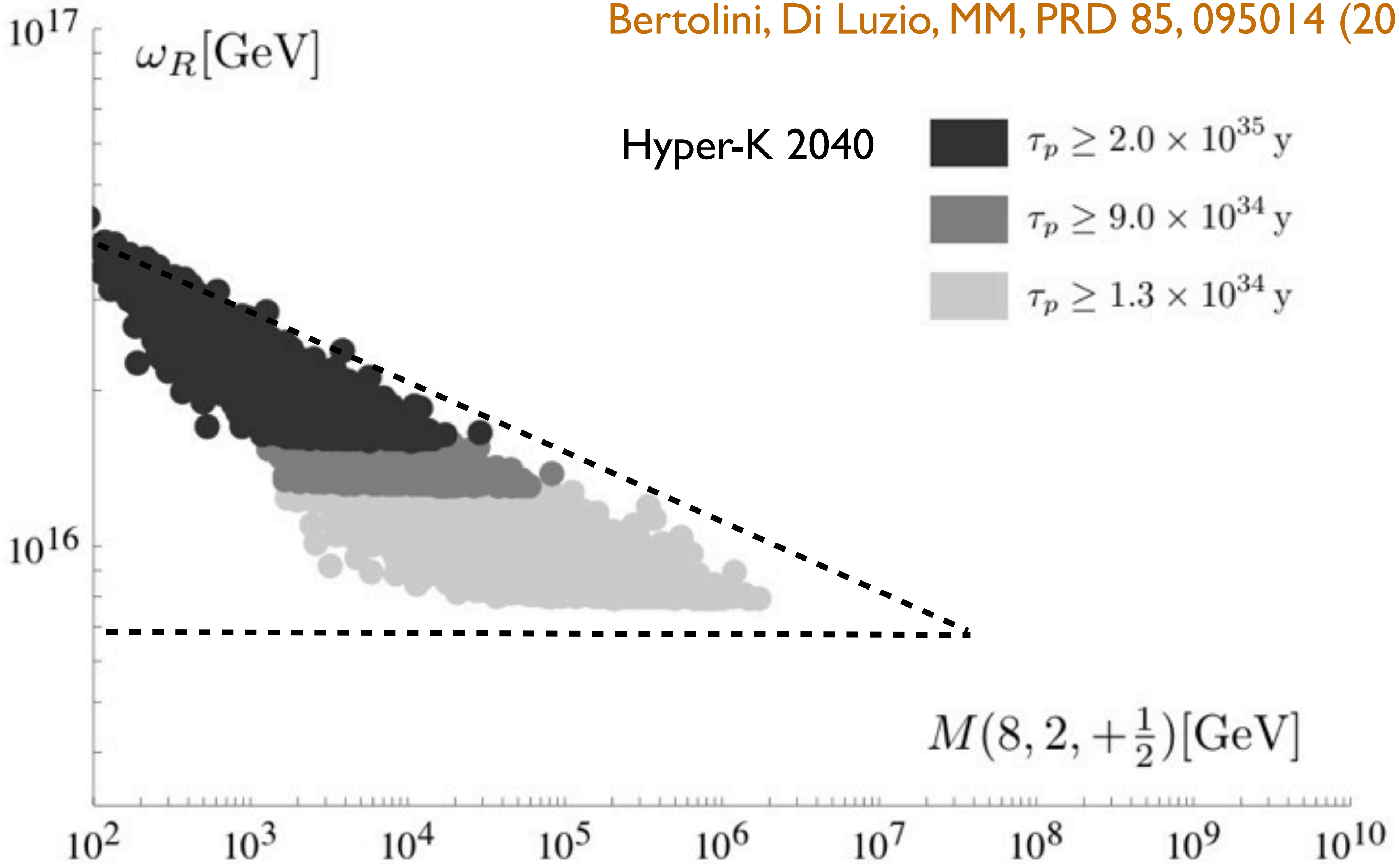

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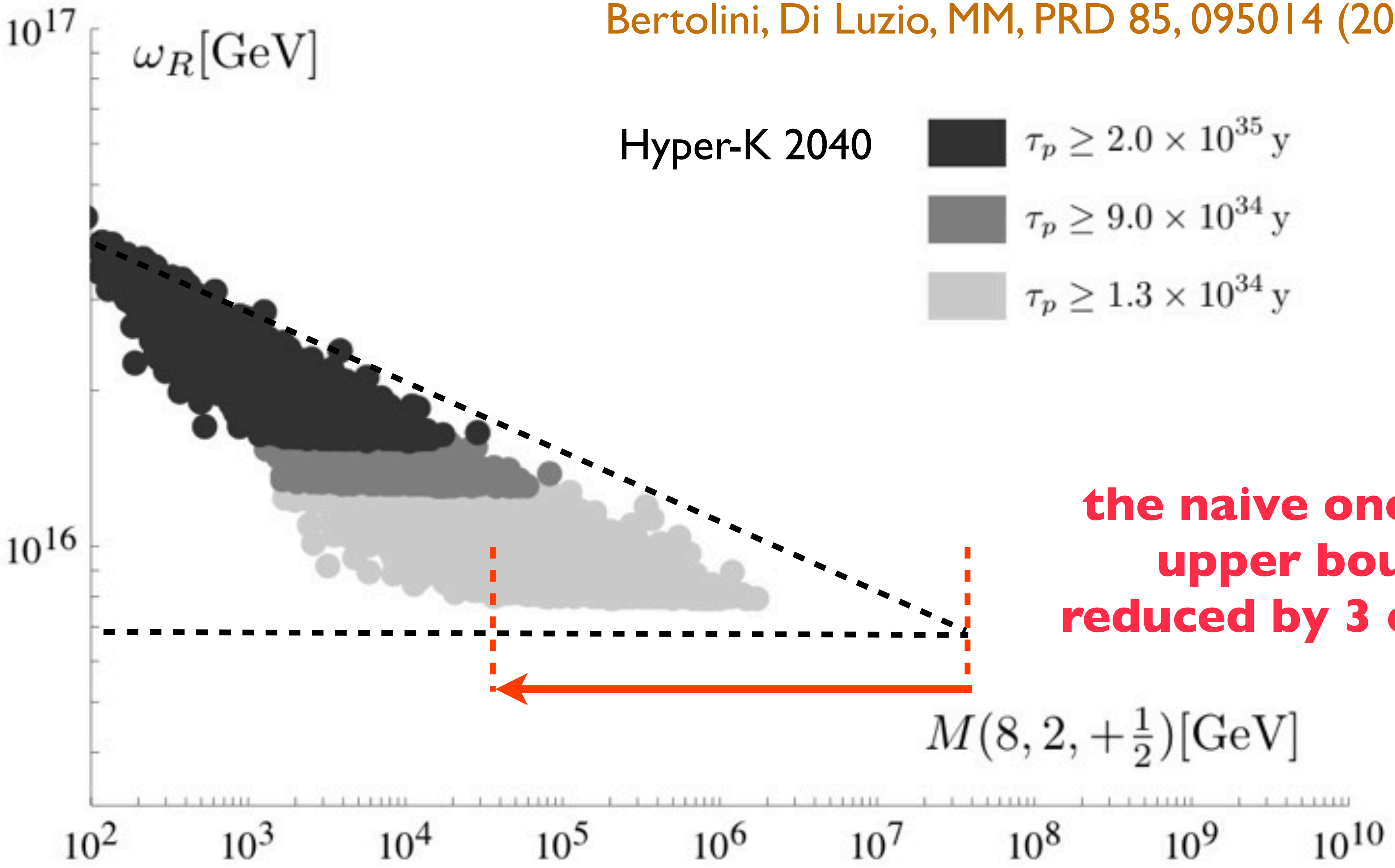

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

Hyper-K 2040

the naive one-loop upper bound reduced by 3 o.o.m. !

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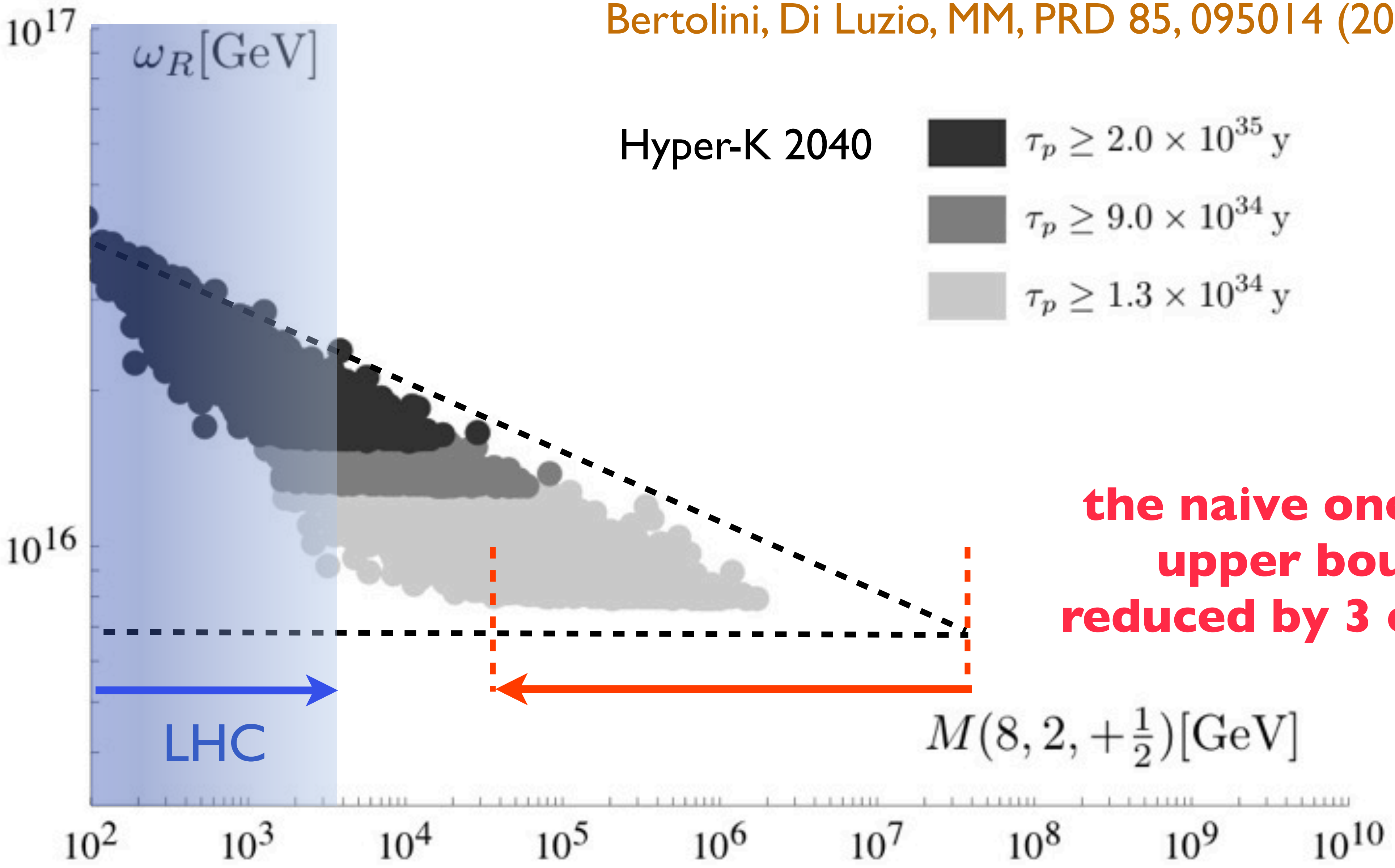

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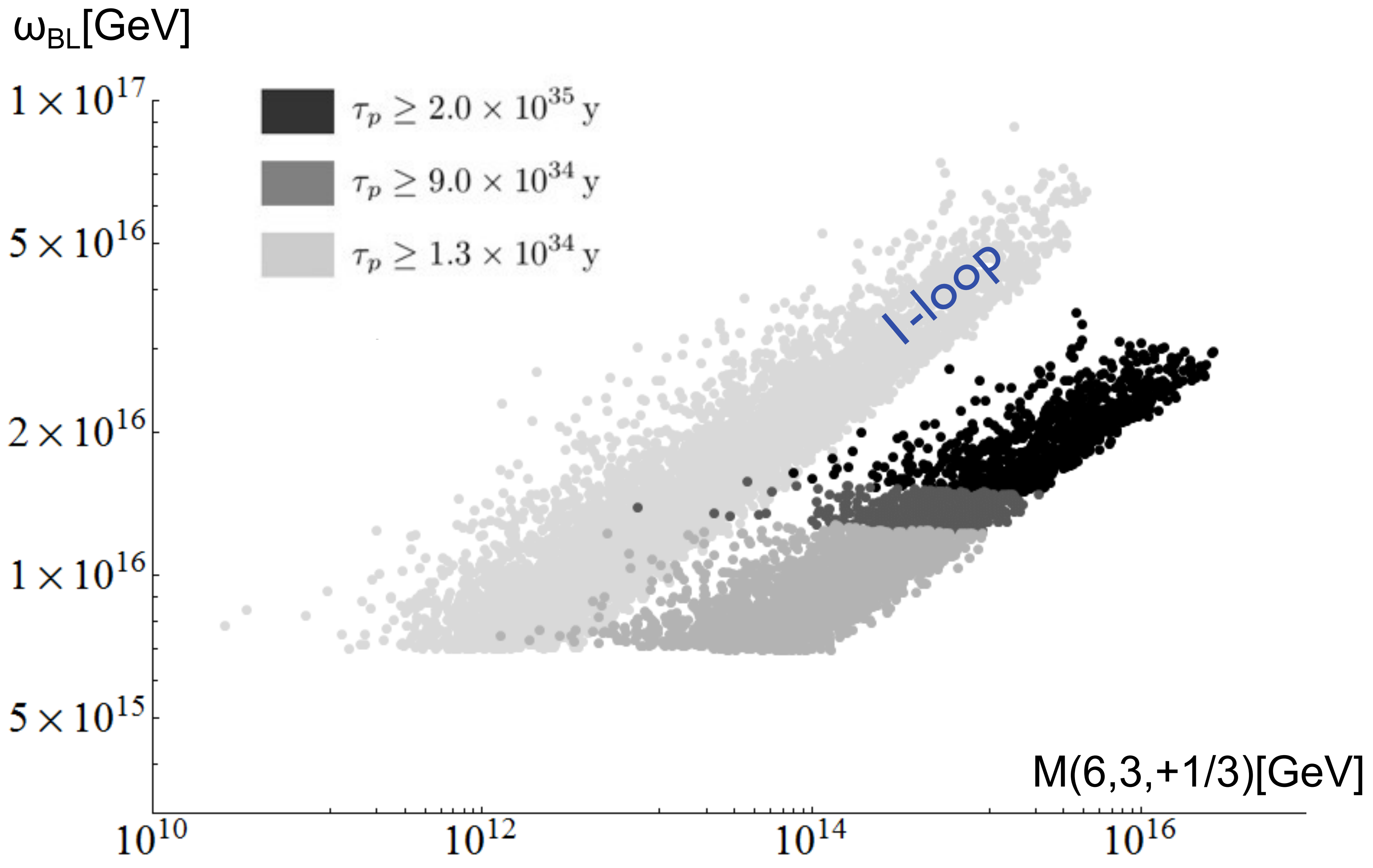
Towards a consistent & potentially realistic SO(10) scenario

Case II: light $(6, 3, +\frac{1}{3})$@ NLO

H. Kolešová, MM, PRD 90, 115001 (2014)



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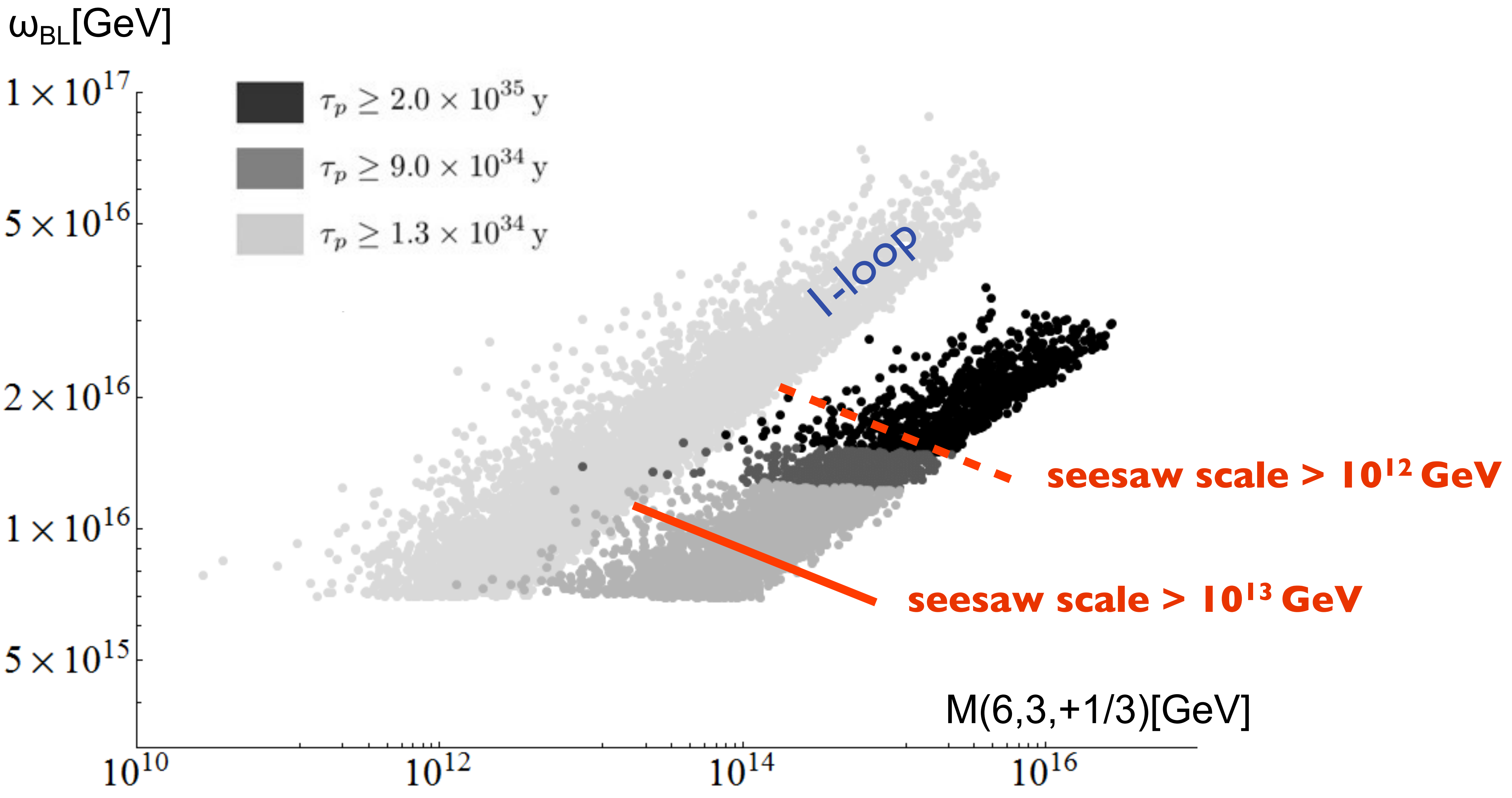

Conclusions / outlook

It's almost impossible to calculate the proton lifetime accurately enough to make the experimentalists happy...

The minimal SO(10) broken by a scalar 45 is very special

At the majority of the allowed parameter space it says that

either

one should see a scalar color octet @ LHC

or

one should see proton decay @ Hyper-K

Thanks for your kind attention!