The Techni-Pati-Salam model

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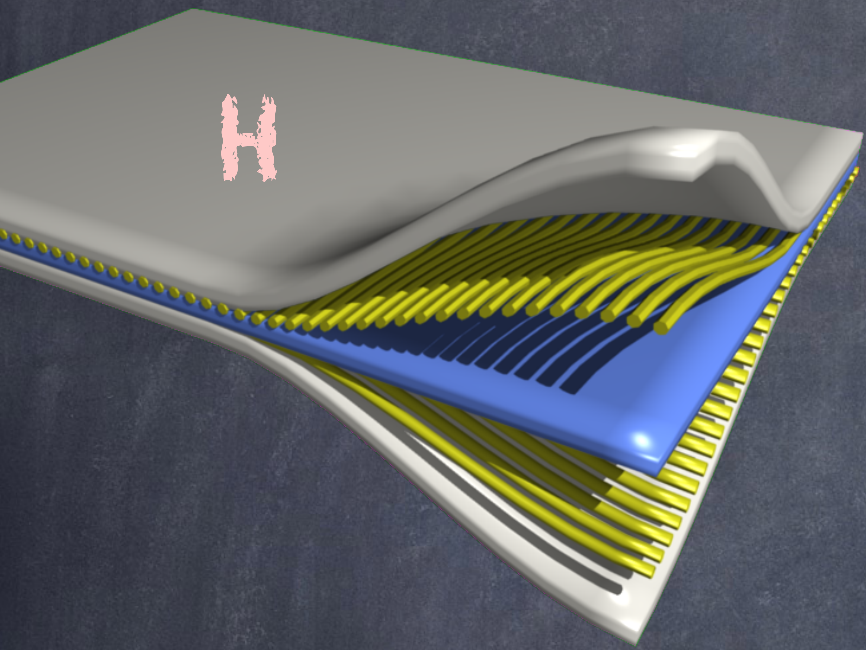
G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302

Lattice 2021
July 30

Why Higgs compositeness?



- A scalar field may be made of more fundamental fields
- We have seen this in Nature: low-energy QCD!
- Symmetries can be broken dynamically without generating hierarchies of scales!
- How to give mass to SM fermions? That is THE question! (And big challenge)

Sequestering QCD in Partial compositeness

G.Ferretti, D.Karateev
1312.5330, 1604.06467

$\mathcal{G}_{\rm TC}$: rep R — Q ; rep R′ — χ

$T' = QQ\chi$ or $Q\chi\chi$

SM : EW ; colour + hypercharge

global : $\langle QQ \rangle \neq 0$ → pNGB Higgs, DM?

a) $\langle \chi\chi \rangle \neq 0$

coloured pNGBs
di-boson

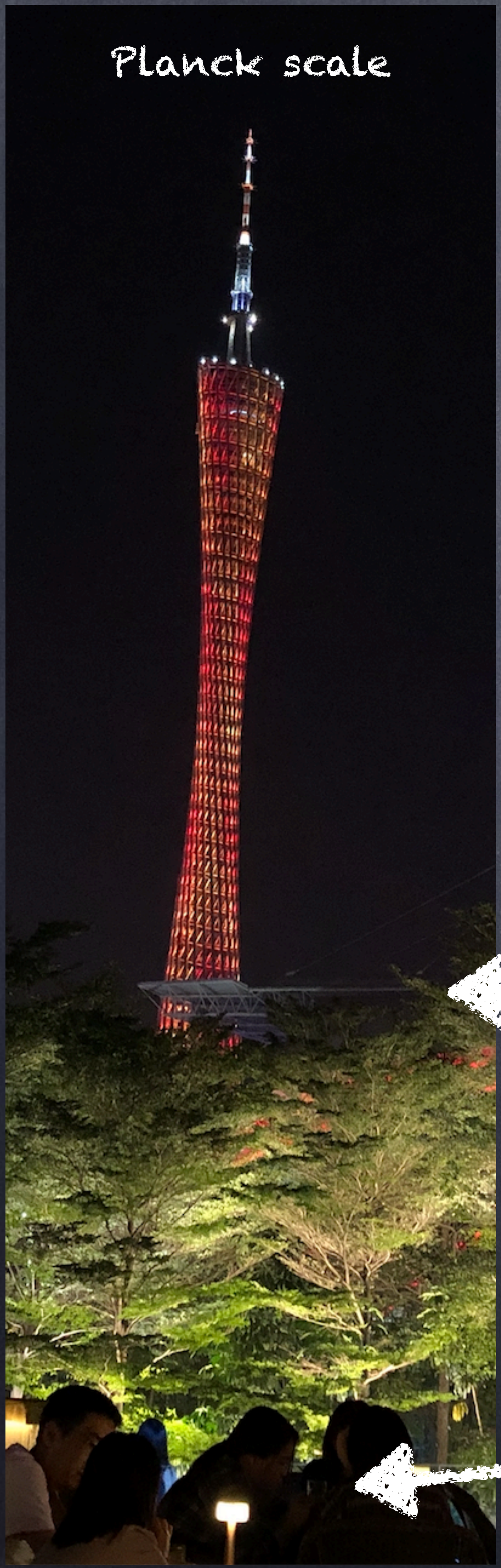
b) $\langle \chi\chi \rangle = 0$

light top partners
from t Hooft anomaly
conditions?

	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{\rm HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{\rm HC} \geq 12$	$\frac{5(N_{\rm HC}+1)}{3}$	1/3	/	
$Sp(2N_{\rm HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{\rm HC} \geq 4$	$\frac{5(N_{\rm HC}-1)}{3}$	1/3	$2N_{\rm HC} = 4$	M5
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\rm HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{\rm HC} = 4$	$\frac{5}{3}$	1/3	$N_{\rm HC} = 4$	M6
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{\rm HC} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{\rm HC} = 10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\rm HC} \leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	2/3	$2N_{\rm HC} = 4$	M8
$SO(N_{\rm HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\rm HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{\rm HC} = 11$	M9
	Complex	Real	SU(4)^2/SU(4) × SU(6)/SO(6)				
$SO(N_{\rm HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{\rm HC} = 10$	$\frac{8}{3}$	2/3	$N_{\rm HC} = 10$	M10
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{\rm HC} = 4$	$\frac{2}{3}$	2/3	$N_{\rm HC} = 4$	M11
	Complex	Complex	SU(4)^2/SU(4) × SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$N_{\rm HC} \geq 5$	$\frac{4}{3(N_{\rm HC}-2)}$	2/3	$N_{\rm HC} = 5$	M12
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \overline{\mathbf{S}}_2)$	$N_{\rm HC} \geq 5$	$\frac{4}{3(N_{\rm HC}+2)}$	2/3	/	
$SU(N_{\rm HC})$	$4 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{\rm HC} = 5$	4	2/3	/	

Partially Unified Partial Compositeness (PUPC)

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302



Condensation scale

Usual low energy description of composite Higgs models

Standard Model

One of Ferretti models

Partially Unified Partial Compositeness (PUPC)

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302

Conformal window
(large scaling dimensions)

One of Ferretti models + additional fermions

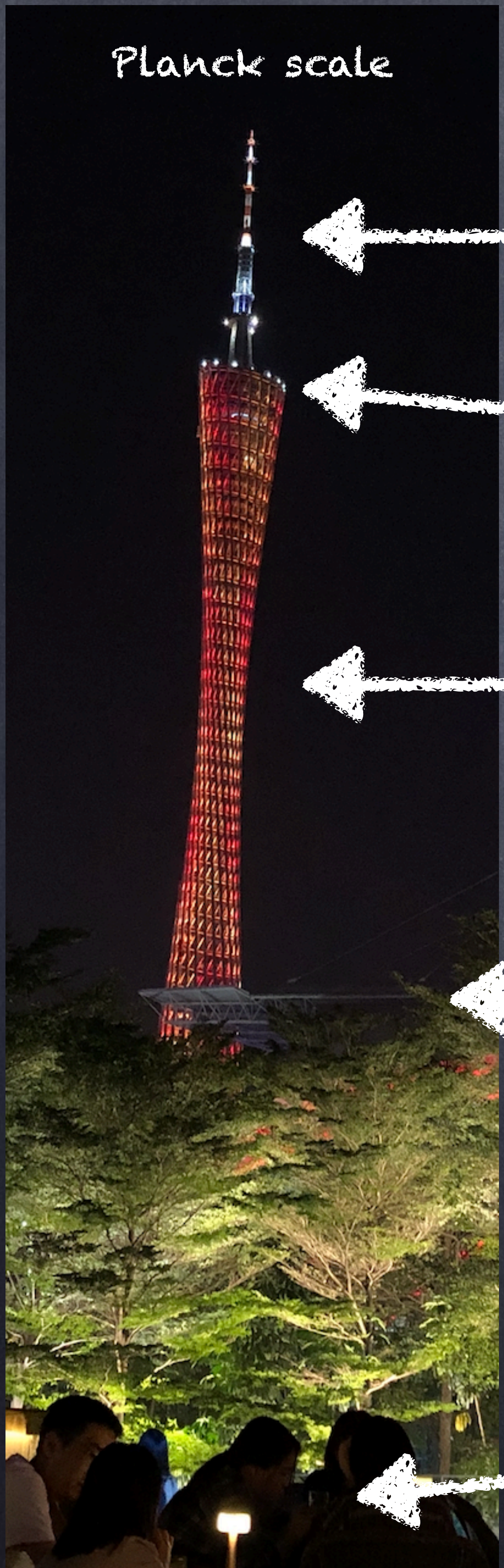
Condensation scale

Usual low energy description of composite Higgs models

One of Ferretti models

Standard Model

Partially Unified Partial Compositeness (PUPC)



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1911.05454, 2006.12302

HC and SM gauge groups partially unified

Symmetry breaking by scalars — 4-fermion Ops generated!

Conformal window (large scaling dimensions) — One of Ferretti models + additional fermions

Condensation scale

Usual low energy description of composite Higgs models

Standard Model

(Condensation scale to Standard Model): One of Ferretti models

Extended Technicolor

- Mediator is a gauge boson from an extended gauge symmetry

$$\begin{pmatrix} Q_L \\ q_L \\ \vdots \end{pmatrix}$$

$SO(N)_{TC}$

- Hard to embed spinorial irrep for TF or mediator

$SU(N)_{TC}$

- TF spectrum typically chiral (as the SM)

$Sp(N)_{TC}$

✓

Techni-Pati-Salam

$$SU(8)_{TPS} \times SU(2)_L \times SU(2)_R$$

- $SU(8)_{TPS} \times SU(2)_R \rightarrow SU(7) \times U(1)$
  splits leptons from quarks
- $SU(7) \rightarrow SU(4)_{TC} \times SU(3)_c \times U(1)$
  splits techni-fermions from quarks
- $SU(4)_{TC} \rightarrow Sp(4)_{TC}$

Techni-Pati-Salam

Field	Spin	$SU(8)_{PS}$	$SU(2)_L$	$SU(2)_R$	#	Q_G
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	3	1
Υ	1/2	$\bar{\mathbf{8}}$	$\mathbf{1}$	$\mathbf{2}$	3	-1
Ξ	1/2	$\mathbf{70}(=\mathbf{A}_4)$	$\mathbf{1}$	$\mathbf{1}$	1	0
N	1/2	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	3	0
Φ	0	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{2}$	1	1
Θ	0	$\mathbf{28}(=\mathbf{A}_2)$	$\mathbf{1}$	$\mathbf{1}$	2	2
Δ_R	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{1}$	$\mathbf{2}$	1	1
Δ_L	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{2}$	$\mathbf{1}$	1	1
Ψ	0	$\mathbf{63}(=\mathbf{Adj})$	$\mathbf{1}$	$\mathbf{1}$	2	0

Quarks, leptons and techni-fermions

PC fermions

$\Phi \rightarrow$ Breaks SU(8) x $SU(2)_R$ to SU(7) x U(1)

$\Psi \rightarrow$ Breaks SU(7) to SU(4) x SU(3) x U(1)

$\Theta \rightarrow$ Breaks SU(4) to Sp(4), U(1) x U(1) to $U(1)_Y$

Techni-Pati-Salam

Fermion sector:

1st Family	2nd Family	3rd Family
N^1	N^2	N^3
$\Omega^1 = \left(\begin{pmatrix} L_u^1 \\ u_L^1 \\ \nu_L^1 \end{pmatrix} \begin{pmatrix} L_d^1 \\ d_L^1 \\ e_L^1 \end{pmatrix} \right)$	$\Omega^2 = \left(\begin{pmatrix} L_u^2 \\ u_L^2 \\ \nu_L^2 \end{pmatrix} \begin{pmatrix} L_d^2 \\ d_L^2 \\ e_L^2 \end{pmatrix} \right)$	$\Omega^3 = \left(\begin{pmatrix} L_u^3 \\ u_L^3 \\ \nu_L^3 \end{pmatrix} \begin{pmatrix} L_d^3 \\ d_L^3 \\ e_L^3 \end{pmatrix} \right)$
$\Upsilon^1 = \left(\begin{pmatrix} U_d^1 \\ d_R^{1c} \\ e_R^{1c} \end{pmatrix} \begin{pmatrix} D_u^1 \\ u_R^{1c} \\ \nu_R^{1c} \end{pmatrix} \right)$	$\Upsilon^2 = \left(\begin{pmatrix} U_d^2 \\ d_R^{2c} \\ e_R^{2c} \end{pmatrix} \begin{pmatrix} D_u^2 \\ u_R^{2c} \\ \nu_R^{2c} \end{pmatrix} \right)$	$\Upsilon^3 = \left(\begin{pmatrix} U_d^3 \\ d_R^{3c} \\ e_R^{3c} \end{pmatrix} \begin{pmatrix} D_u^3 \\ u_R^{3c} \\ \nu_R^{3c} \end{pmatrix} \right)$
	$\Xi = \left(\begin{bmatrix} U_u \\ \chi \\ B \end{bmatrix} \begin{bmatrix} D_d \\ \tilde{\chi} \\ \tilde{B} \end{bmatrix} \right)$	

$$B = [\rho](\mathbf{1},\mathbf{1})_0 + [\eta](\mathbf{4},\bar{\mathbf{3}})_{-1/6} + [\omega](\mathbf{1},\mathbf{3})_{-1/3}, \quad \tilde{B} = [\tilde{\rho}](\mathbf{1},\mathbf{1})_0 + [\tilde{\eta}](\mathbf{4},\mathbf{3})_{1/6} + [\tilde{\omega}](\mathbf{1},\bar{\mathbf{3}})_{1/3}$$

Techni-Pati-Salam

Fermion sector: Sp(4) irreps

1st Family	2nd Family	3rd Family
N^1	N^2	N^3
$\Omega^1 = \left(\begin{pmatrix} L_u^1 \\ u_L^1 \\ \nu_L^1 \end{pmatrix} \begin{pmatrix} L_d^1 \\ d_L^1 \\ e_L^1 \end{pmatrix} \right)$	$\Omega^2 = \left(\begin{pmatrix} L_u^2 \\ u_L^2 \\ \nu_L^2 \end{pmatrix} \begin{pmatrix} L_d^2 \\ d_L^2 \\ e_L^2 \end{pmatrix} \right)$	$\Omega^3 = \left(\begin{pmatrix} L_u^3 \\ u_L^3 \\ \nu_L^3 \end{pmatrix} \begin{pmatrix} L_d^3 \\ d_L^3 \\ e_L^3 \end{pmatrix} \right)$
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	$\Xi = \left(\begin{bmatrix} U_u \\ \chi \\ B \end{bmatrix} \begin{bmatrix} D_d \\ \tilde{\chi} \\ \tilde{B} \end{bmatrix} \right)$	

$B = [\rho](\mathbf{1},\mathbf{1})_0 + [\eta](\mathbf{4},\bar{\mathbf{3}})_{-1/6} + [\omega](\mathbf{1},\mathbf{3})_{-1/3}, \quad \tilde{B} = [\tilde{\rho}](\mathbf{1},\mathbf{1})_0 + [\tilde{\eta}](\mathbf{4},\mathbf{3})_{1/6} + [\tilde{\omega}](\mathbf{1},\bar{\mathbf{3}})_{1/3}$

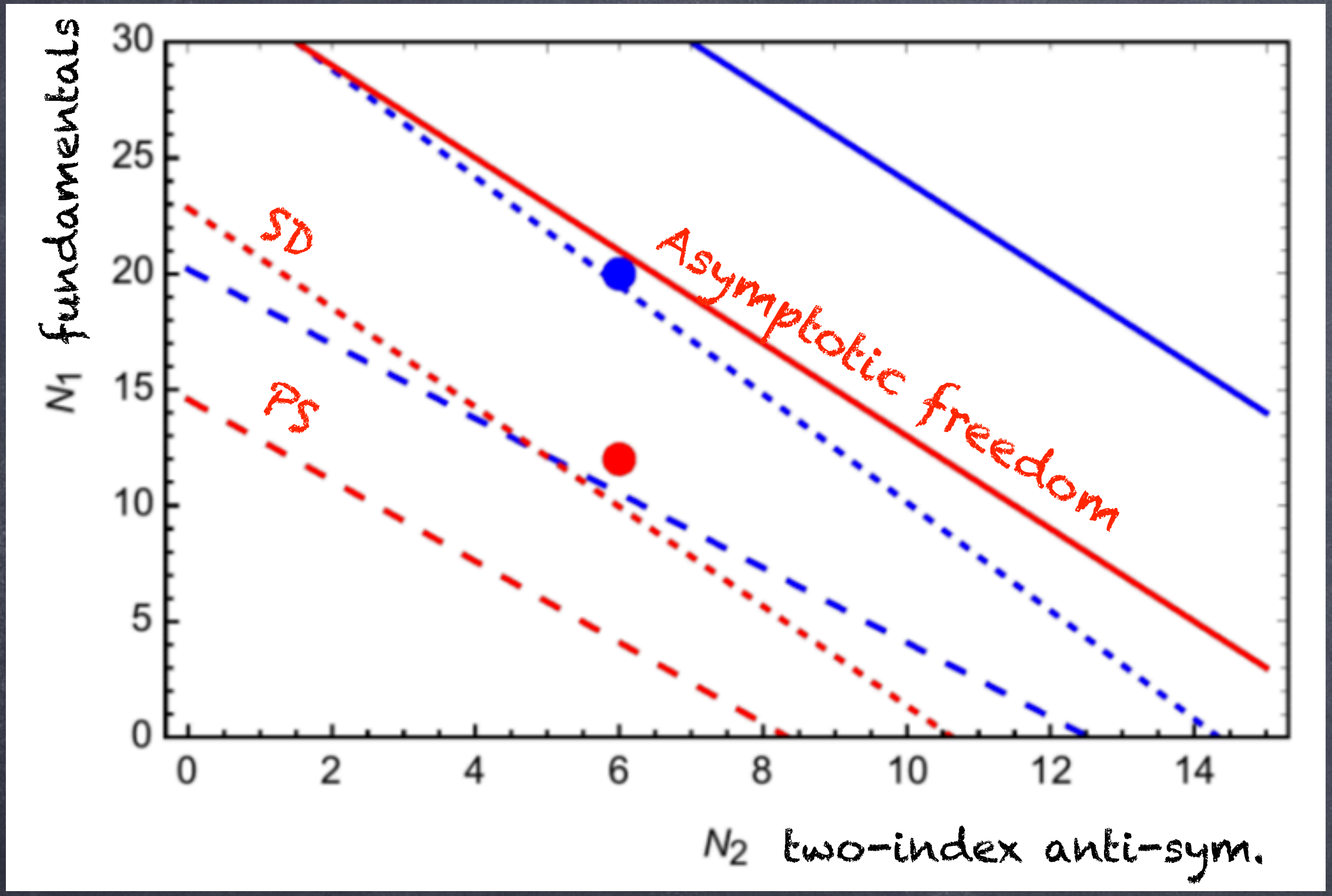
Heavy

Top PC

Lepton PC

Higgs components

Inside or outside the conformal window: That is the question!



Red: Sp(4)
6F + 3A

SD = Schwinger-Dyson
PS = Pica-Sannino

If SU(4) to Sp(4) broken at high scale, the theory with 12 light fundamental flavours is near the SD boundary.

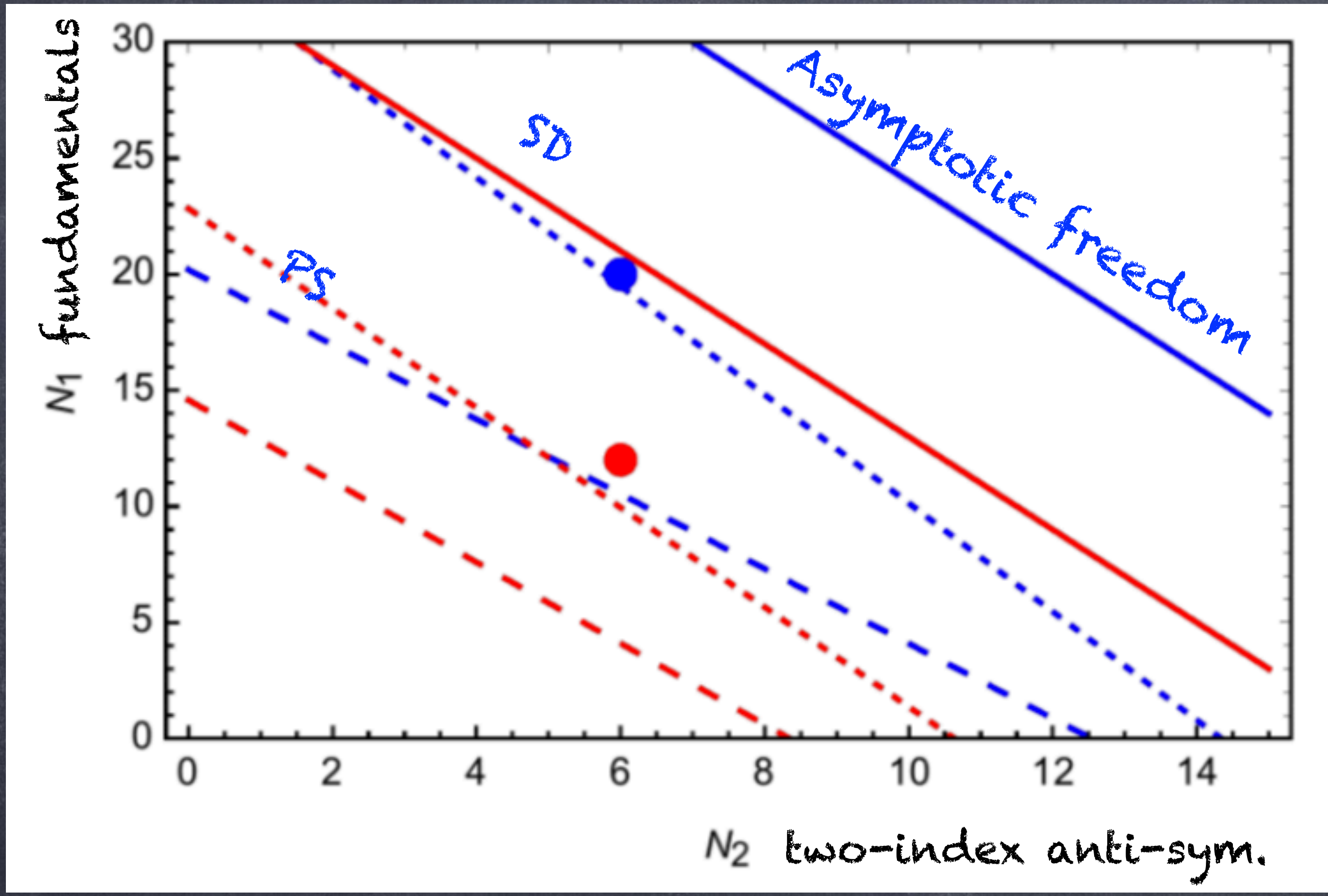
Techni-Pati-Salam

Fermion sector: SU(4) irreps

1st Family	2nd Family	3rd Family
N^1	N^2	N^3
$\Omega^1 = \left(\begin{pmatrix} L_u^1 \\ u_L^1 \\ \nu_L^1 \end{pmatrix} \begin{pmatrix} L_d^1 \\ d_L^1 \\ e_L^1 \end{pmatrix} \right)$	$\Omega^2 = \left(\begin{pmatrix} L_u^2 \\ u_L^2 \\ \nu_L^2 \end{pmatrix} \begin{pmatrix} L_d^2 \\ d_L^2 \\ e_L^2 \end{pmatrix} \right)$	$\Omega^3 = \left(\begin{pmatrix} L_u^3 \\ u_L^3 \\ \nu_L^3 \end{pmatrix} \begin{pmatrix} L_d^3 \\ d_L^3 \\ e_L^3 \end{pmatrix} \right)$
$\Upsilon^1 = \left(\begin{pmatrix} U_d^1 \\ d_R^{1c} \\ e_R^{1c} \end{pmatrix} \begin{pmatrix} D_u^1 \\ u_R^{1c} \\ \nu_R^{1c} \end{pmatrix} \right)$	$\Upsilon^2 = \left(\begin{pmatrix} U_d^2 \\ d_R^{2c} \\ e_R^{2c} \end{pmatrix} \begin{pmatrix} D_u^2 \\ u_R^{2c} \\ \nu_R^{2c} \end{pmatrix} \right)$	$\Upsilon^3 = \left(\begin{pmatrix} U_d^3 \\ d_R^{3c} \\ e_R^{3c} \end{pmatrix} \begin{pmatrix} D_u^3 \\ u_R^{3c} \\ \nu_R^{3c} \end{pmatrix} \right)$
Light	$\Xi = \left(\begin{bmatrix} U_u \\ \chi \\ B \end{bmatrix} \begin{bmatrix} D_d \\ \tilde{\chi} \\ B \end{bmatrix} \right)$	Massless! (chiral)

$$B=[\rho](\mathbf{1},\mathbf{1})_0+[\eta](\mathbf{4},\bar{\mathbf{3}})_{-1/6}+[\omega](\mathbf{1},\mathbf{3})_{-1/3},\quad \tilde{B}=[\tilde{\rho}](\mathbf{1},\mathbf{1})_0+[\tilde{\eta}](\mathbf{4},\mathbf{3})_{1/6}+[\tilde{\omega}](\mathbf{1},\bar{\mathbf{3}})_{1/3}$$

Inside or outside the conformal window: That is the question!

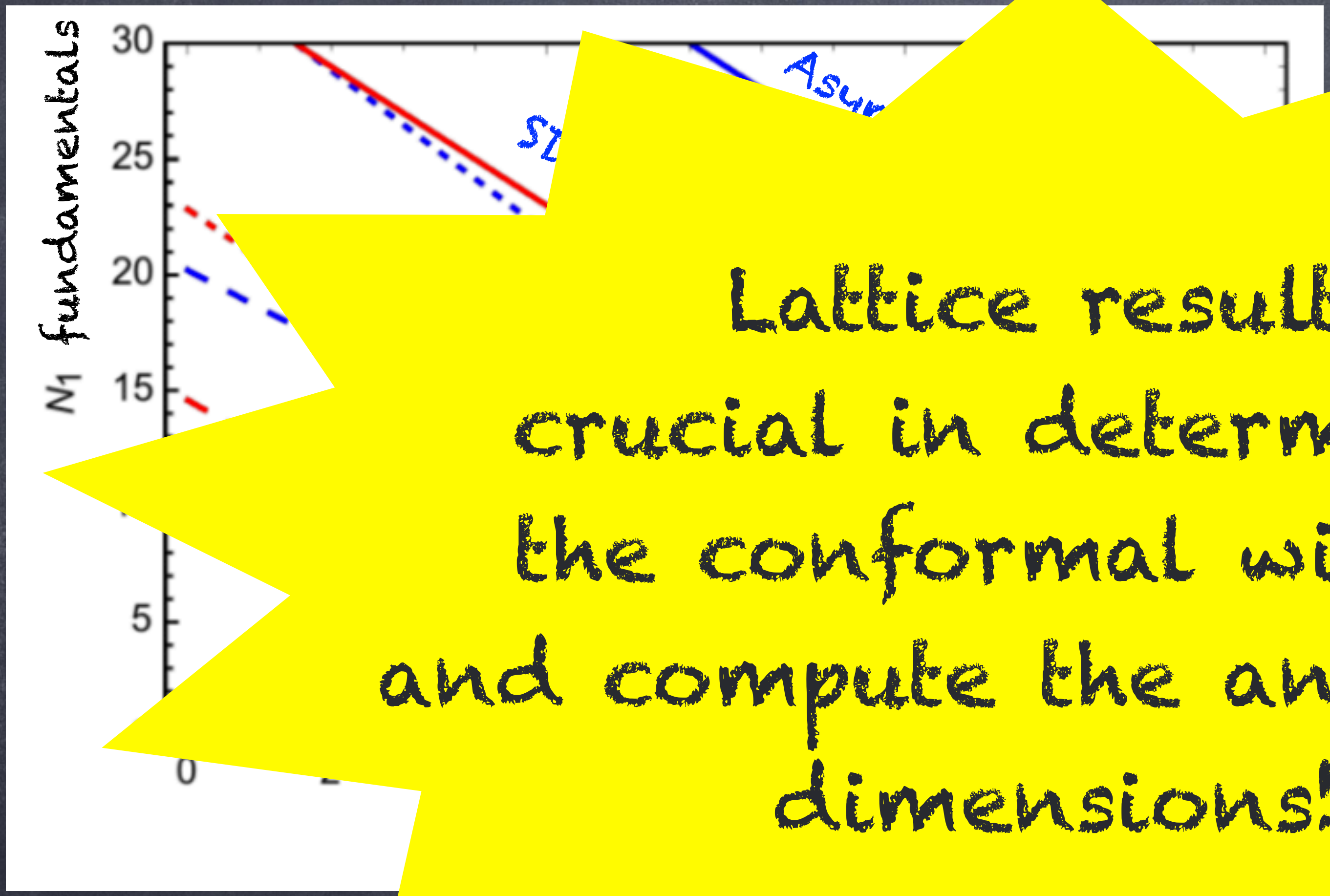


Blue: SU(4)
10F + 3A

SD = Schwinger-Dyson
PS = Pica-Sannino

If SU(4) to Sp(4) broken at low scale, the theory with 20 light fundamental flavours is near the SD boundary.

Inside or outside the conformal window: That is the question!



Blue: SU(4)

...nger-Dyson
...nnino

Lattice results crucial in determining the conformal window and compute the anomalous dimensions!

If SU(4) to Sp... broke... at low scale, the theory with 20 light fundamental flavours is near the SD boundary.

The Lagrangian

Field	Spin	$SU(8)_{\mathrm{PS}}$	$SU(2)_L$	$SU(2)_R$	#	Q_G
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	3	1
Υ	1/2	$\bar{\mathbf{8}}$	$\mathbf{1}$	$\mathbf{2}$	3	-1
Ξ	1/2	$\mathbf{70}(=\mathbf{A}_4)$	$\mathbf{1}$	$\mathbf{1}$	1	0
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Φ	0	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{2}$	1	1
Θ	0	$\mathbf{28}(=\mathbf{A}_2)$	$\mathbf{1}$	$\mathbf{1}$	2	2
Δ_R	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{1}$	$\mathbf{2}$	1	1
Δ_L	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{2}$	$\mathbf{1}$	1	1
Ψ	0	$\mathbf{63}(=\mathbf{Adj})$	$\mathbf{1}$	$\mathbf{1}$	2	0

$$\mathcal{L}_Y = -\frac{1}{2}\mu_N^a N^a N^a - \frac{1}{2}\mu_\Xi \Xi\Xi - \frac{1}{2}\lambda_\Psi \Xi\Psi\Xi - \left(\lambda_\Phi^{ab}\Upsilon^a \Phi N^b + \lambda_{\Theta L}^a \Omega^a \Theta^* \Omega^a + \lambda_{\Theta R}^a \Upsilon^a \Theta \Upsilon^a + \lambda_\Delta^a \Upsilon^a \Delta^* \Xi + \mathrm{h.c.}\right) ,$$

- TPS gauge bosons can give mass to one generation!

The Lagrangian

Field	Spin	$SU(8)_{\rm PS}$	$SU(2)_L$	$SU(2)_R$	#	Q_G
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	3	1
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$$\mathcal{L}_Y = -\frac{1}{2}\mu_N^a N^a N^a - \frac{1}{2}\mu_\Xi \Xi\Xi - \frac{1}{2}\lambda_\Psi \Xi\Psi\Xi - \left(\lambda_\Phi^{ab}\Upsilon^a\Phi N^b + \lambda_{\Theta L}^a \Omega^a\Theta^*\Omega^a + \lambda_{\Theta R}^a \Upsilon^a\Theta\Upsilon^a + \lambda_\Delta^a \Upsilon^a\Delta^*\Xi + \text{h.c.}\right),$$
$$-\left(\lambda_{\Theta L}^{kab}\Omega^a\Theta_k^*\Omega^b + \lambda_{\Theta R}^{kab}\Upsilon^a\Theta_k\Upsilon^b + \text{h.c.}\right) - \frac{1}{2}\lambda_\Psi^k \Xi\Psi_k\Xi\,.$$

- TPS gauge bosons can give mass to one generation!
- Adding a second copy of scalars give mass to second generation!

The Lagrangian

Field	Spin	$SU(8)_{PS}$	$SU(2)_L$	$SU(2)_R$	#	Q_G
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	3	1
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Ψ	0	$\mathbf{63}(=\mathbf{Adj})$	$\mathbf{1}$	$\mathbf{1}$	2	0

$$\mathcal{L}_Y = -\frac{1}{2}\mu_N^a N^a N^a - \frac{1}{2}\mu_\Xi \Xi\Xi - \frac{1}{2}\lambda_\Psi \Xi\Psi\Xi - (\lambda_\Phi^{ab}\Upsilon^a\Phi N^b + \lambda_{\Theta L}^a \Omega^a\Theta^*\Omega^a + \lambda_{\Theta R}^a \Upsilon^a\Theta\Upsilon^a + \lambda_\Delta^a \Upsilon^a\Delta^*\Xi + \text{h.c.}) ,$$

$$-\left(\lambda_{\Theta L}^{kab}\Omega^a\Theta_k^*\Omega^b + \lambda_{\Theta R}^{kab}\Upsilon^a\Theta_k\Upsilon^b + \text{h.c.}\right)$$

$$-\frac{1}{2}\lambda_\Psi^k \Xi\Psi_k\Xi .$$

$$-\lambda_{\Delta L}^a \Omega^a \Delta_L \Xi + \text{h.c.}$$

- TPS gauge bosons can give mass to one generation!
- Adding a second copy of scalars give mass to second generation!
- Delta's give mass to the first generation!

The Lagrangian

Field	Spin	$SU(8)_{PS}$	$SU(2)_L$	$SU(2)_R$	#	Q_G
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	3	1
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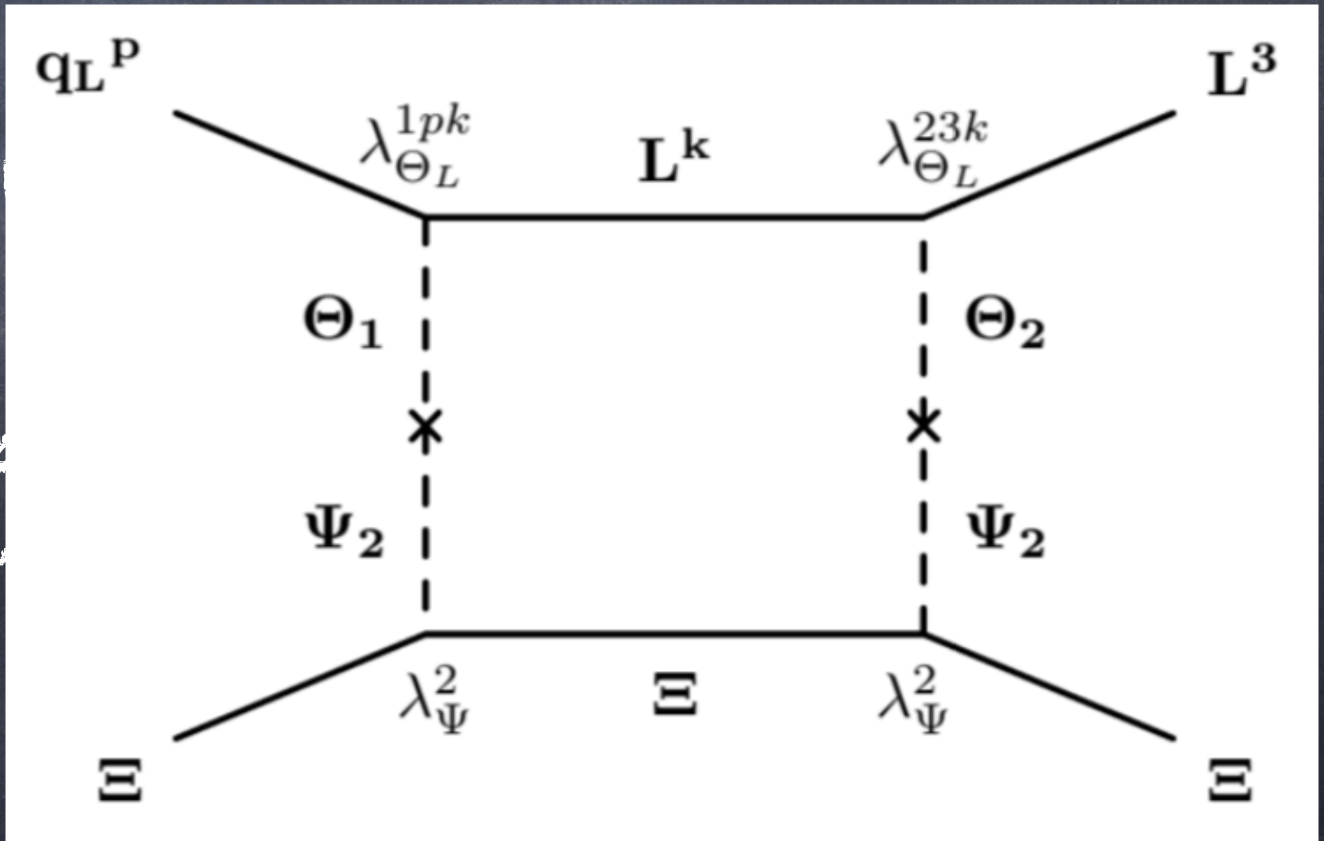
~~Δ_L~~	~~0~~	~~$\mathbf{56}(=\mathbf{A}_3)$~~	~~$\mathbf{2}$~~	~~$\mathbf{1}$~~	~~1~~	~~1~~
Ψ	0	$\mathbf{63}(=\mathbf{Adj})$	$\mathbf{1}$	$\mathbf{1}$	2	0

$$\mathcal{L}_Y = -\frac{1}{2}\mu_N^a N^a N^a - \frac{1}{2}\mu_\Xi \Xi\Xi - \frac{1}{2}\lambda_\Psi \Xi\Psi\Xi - (\lambda_\Phi^{ab}\Upsilon^a\Phi N^b + \lambda_{\Theta L}^a \Omega^a\Theta^*\Omega^a + \lambda_{\Theta R}^a \Upsilon^a\Theta\Upsilon^a + \lambda_\Delta^a \Upsilon^a\Delta^*\Xi + \text{h.c.}) \,, - (\lambda_{\Theta L}^{kab}\Omega^a\Theta_k^*\Omega^b + \lambda_{\Theta R}^{kab}\Upsilon^a\Theta_k\Upsilon^b + \text{h.c.}) - \frac{1}{2}\lambda_\Psi^k \Xi\Psi_k\Xi \,.$$

- TPS gauge bosons ca
  generation!
- Adding a second cop
  to second generatio
- ... or loop induced!



Lattice wishlist

- Is Sp(4) with 6F + 3A conformal?
- If yes, what are the chimera baryon anomalous dimensions? [This could rule out the scenario]
- Is SU(4) with 10F + 3A conformal?
- If yes, what are the chimera baryon anomalous dimensions? [This could rule out the low SU(4) breaking scenario]
- Low energy spectrum and form-factors of Sp(4) with 2F+3A or 3F+3A.

Neutrino masses

- Can be generated by an inverse see-saw mechanism (naturally built-in)

$$\mathcal{L}_\nu = -\frac{1}{2}\begin{pmatrix}\nu_L & \nu_R^c & N & \rho & \tilde{\rho}\end{pmatrix}\begin{pmatrix}0 & \mu_\nu & 0 & 0 & 0\\ \mu_\nu & 0 & \mu_\Phi & 0 & 0\\ 0 & \mu_\Phi & \mu_N & 0 & 0\\ 0 & 0 & 0 & 0 & \mu_0\\ 0 & 0 & 0 & \mu_0 & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ \nu_R^c\\ N\\ \rho\\ \tilde{\rho}\end{pmatrix} + \text{h.c.}$$

A Dark Matter candidate from baryon number

- Baryon number is conserved by the Yukawa interactions (and scalar VEVs)

Global charges			
Fields	B	L	H
SM quarks	1/3	0	0
SM leptons	0	1	0
L^p	0	0	1/2
U_d^p, D_u^p	0	0	−1/2
U_t	−1/2	1/2	1/2
χ, ω	−1/6	1/2	0
η	1/6	1/2	−1/2
ρ	1/2	1/2	−1
N^p	0	0	0
v_{PS}^{Φ}	0	1	0
v_{EHC}^{Ψ}	0	0	0
$v_{\mathrm{CHC}}^{\Theta}$	0	0	1

Assuming asymmetric production:

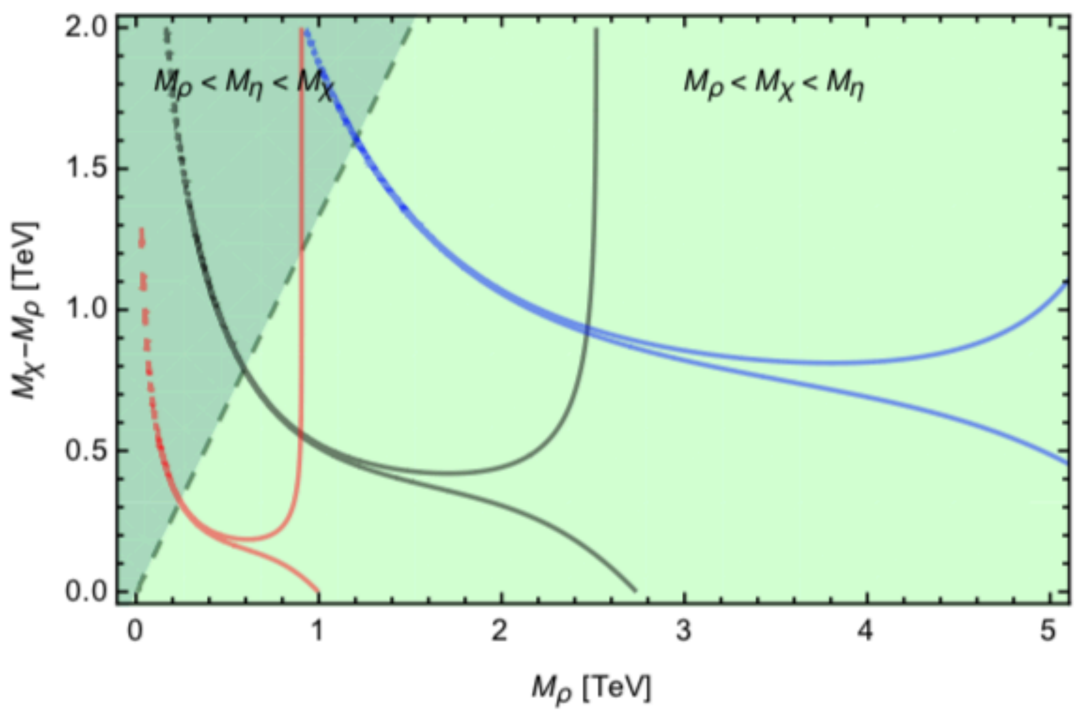


FIG. 6: Points saturating the DM relic density in the M_ρ vs. $M_\chi - M_\rho$ parameter space. The solid lines correspond to $T_* = 246$ GeV (black), $T_* = 100$ GeV (red) and $T_* = 500$ GeV (blue).