A Path from Strings to Particles and the Cosmos

Saúl Ramos-Sánchez

Mexican Workshop on Particles & Fields

October 21, 2025

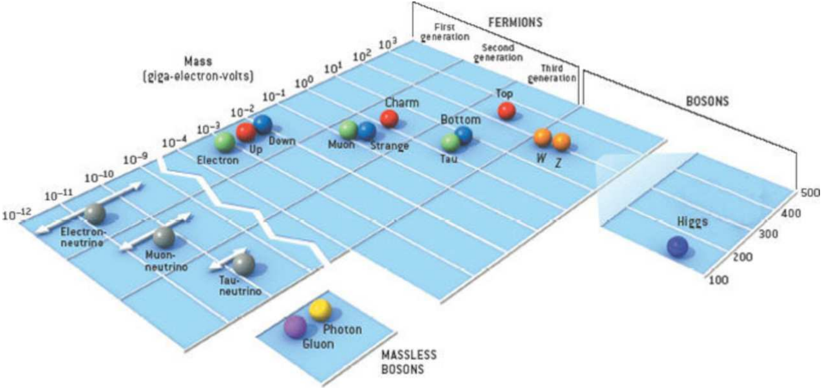
In collaboration with

H. Gordillo-Ruiz, M. Hernández-Segura, I. Portillo-Castillo, I. Zavala: 2509.22781

A. Baur, M.-C. Chen, V. Knapp-Pérez: 2409.02178

A. Baur, H.P. Nilles, A. Trautner, P. Vaudrevange: 2112.06940 & 2207.10677

What we understand: the standard model (SM)



$$\mathcal{G}_{SM} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \iff \text{QCD} + \text{QED}$$

3 generations/flavors of quarks and leptons & Higgs

Need fixing 19–28 parameters

Some open questions

- We want/can explain
  - why three flavors
  - mass hierarchies of fermions
  - mix *textures* of quarks and leptons
  - neutrino nature and mass origin
  - dark matter nature and origin
  - clues on SUSY or its absence
  - ...

Mix textures of quarks (CKM) and leptons (PMNS)

$$\begin{pmatrix} 0.9737 & 0.2243 & 0.0038 \\ 0.2210 & 0.9750 & 0.0411 \\ 0.0086 & 0.0415 & 1.010 \end{pmatrix}_{CKM} , \qquad \begin{pmatrix} 0.829 & 0.539 & 0.147 \\ 0.493 & 0.584 & 0.645 \\ 0.262 & 0.607 & 0.75 \end{pmatrix}_{PMNS}$$

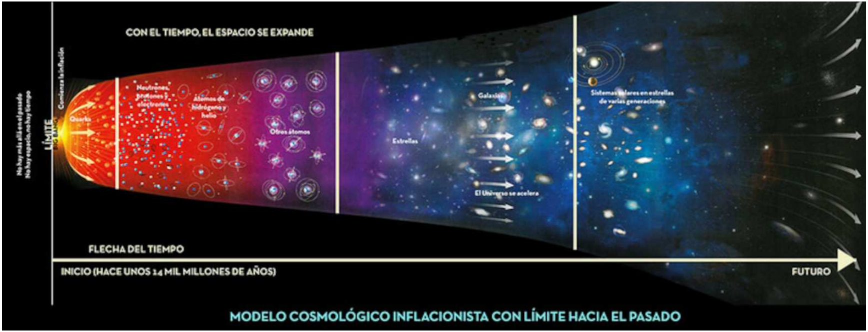
$m_{u,c,t} \sim 2.16, 1273, 172570$ MeV

$m_{d,s,b} \sim 4.70, 93.5, 4183$ MeV

$\Delta m^2_{21} = 7.49 \cdot 10^{-5}, \Delta m^2_{31(23)} \approx 2.51 \cdot 10^{-3}$ eV^2

$m_{e,\mu,\tau} \sim 0.511, 105.66, 1776.93$ MeV

normal ordering



Cosmology = relativity + cosmological prin + inflation ☺

68% dark energy (DE) + 27% dark matter (DM) + 5% SM

Dark energy seems dynamic - not cosmological constant

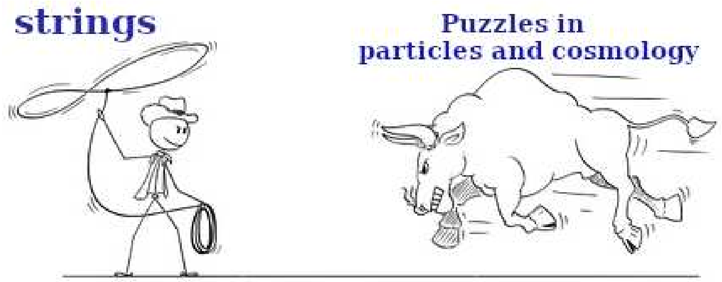
DES (2401.02929), DESI (2503.14738)

Workshop Tools

Workshop Tools

String theory for pragmatists and agnostics

Theoretical *workshop* with consistent tools consistentes to solve physics problems of particles and cosmo



The tools of string theory

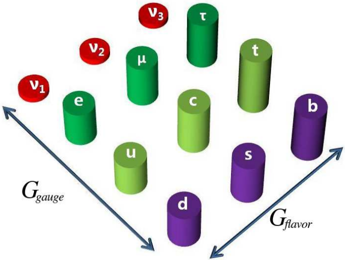
Theoretical *workshop* with consistent tools consistentes to solve physics problems of particles and cosmo

The tools:

- SUSY
- 6 extra dimensions $\rightarrow$ compactify on toroidal orbifolds
- $\Rightarrow$ symmetries and particles of SM
- $\Rightarrow$ moduli: fields describing sizes and shapes
- $\Rightarrow$ modular symmetries $\mathrm{SL}(2,\mathbb{Z})$ and its quotients
- $\Rightarrow$ discrete symmetries of flavor
- $\Rightarrow$ scalars and axions
- $\Rightarrow$ extra R and $\mathcal{CP}$ symmetries

Traditional + modular symm = *eclectic* symmetry

<u>Traditional</u>: discrete non-Abelian flavor symmetries G_{trad}



Field multiplets transform as $\phi \to \underbrace{\rho_\phi(g)}_{\text{rep of } g}\,\phi, g \in G_{trad} = D_8, \Delta(54), \ldots$

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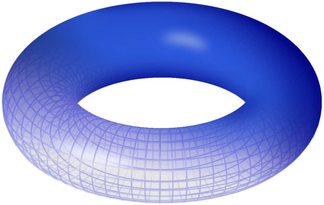
Modular: Yukawa coupl. are modular forms $Y = Y(T)$

$$Y(T) \to Y(\gamma T) = (cT+d)^{n_Y}\rho_Y(\gamma)Y(T), \gamma \in \Gamma = \mathrm{SL}(2,\mathbb{Z}), \rho_Y \in \Gamma_N, \Gamma'_N$$



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Similar field transformations: $\phi \to \underbrace{(cT+d)^{n_\phi}}_{\text{automorphy}}\rho_\phi(\gamma)\phi$

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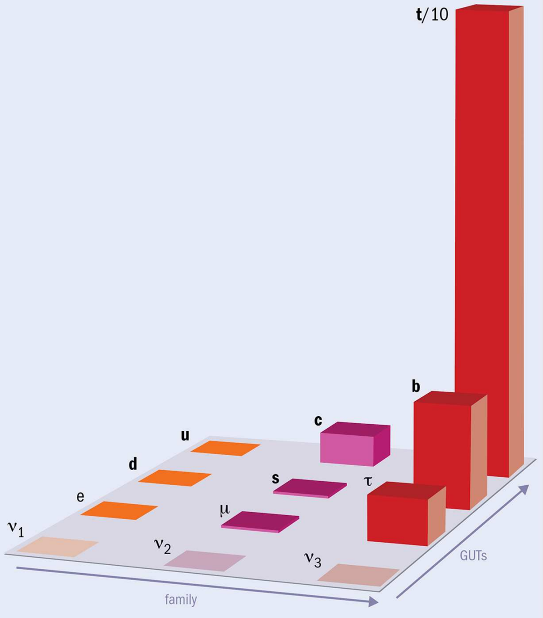
Eclectic scheme: traditional + modular in string theory ☺

Physics *beyond* the SM



First stringy model

with realistic eclectic pheno

Baur, Nilles, SRS, Trautner, Vaudrevange: 2112.06940, 2207.10677

Explicit stringy model

- $\mathbb{T}^2/\mathbb{Z}_3$ sector with $\Delta(54) \cup T'$

  & properties of fermions fixed by theory (not *ad hoc*):

  Baur, Nilles, SRS, Trautner, Vaudrevange (2112.06940, 2207.10677)

	quarks and leptons						Higgs fields	
label	q	$\bar{u}$	$\bar{d}$	ℓ	$\bar{e}$	$\bar{\nu}$	H_u	H_d
$SU(3)_c$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	$1/6$	$-2/3$	$1/3$	$-1/2$	1	0	$1/2$	$-1/2$
$\Delta(54)$	$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{1}$	$\mathbf{1}$
T'	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
n	$-2/3$	$-2/3$	$-2/3$	$-2/3$	$-2/3$	$-2/3$	0	0

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- flavons break the eclectic flavor symmetry

flavons							
φ_e	φ_u	φ_ν	ϕ^0	ϕ^0_M	ϕ^0_e	ϕ^0_u	ϕ^0_d
$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
0	0	0	0	0	0	0	0
$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{3}_2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{2}' \oplus \mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
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0	0	0	0	0	0	0	0
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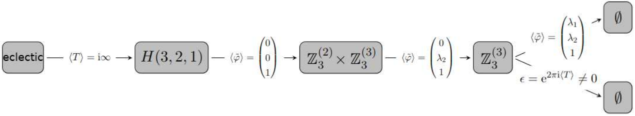
$\mathbf{2}'\oplus\mathbf{1}$	$\mathbf{2}'\oplus\mathbf{1}$	$\mathbf{2}'\oplus\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$-2/3$	$-2/3$	$-2/3$	0	0	0	0	0



Explicit stringy model

After

- computing the corresponding action: $\mathcal{W}, K$
- fixing by hand the VEV of the moudlus ($\langle T \rangle \sim 3\mathrm{i}$ "close" to $\mathrm{i}\infty$), &
- computing the effective couplings among the particles (with 20 params)

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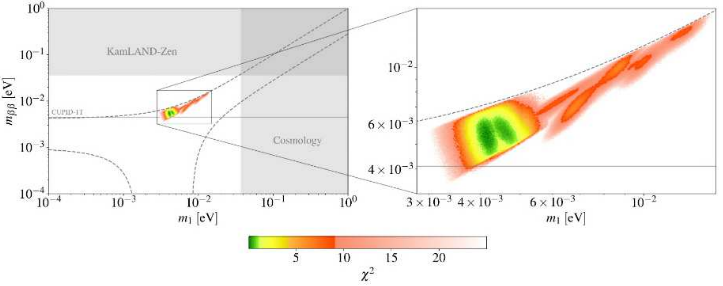
Outcome:



Explicit stringy model

Outcome:

	parameter	best-fit value
superpotential	$\mathrm{Im}\,\langle T\rangle$	3.195
	$\mathrm{Re}\,\langle T\rangle$	0.02279
	$\langle\tilde{\varphi}_{\mathrm{u},1}\rangle$	$2.0332\cdot10^{-4}$
	$\langle\vartheta_{\mathrm{u},1}\rangle$	1.6481
	$\langle\tilde{\varphi}_{\mathrm{u},2}\rangle$	$6.3011\cdot10^{-2}$
	$\langle\vartheta_{\mathrm{u},2}\rangle$	-1.5983
	$\langle\tilde{\varphi}_{\mathrm{e},1}\rangle$	$-4.069\cdot10^{-5}$
	$\langle\tilde{\varphi}_{\mathrm{e},2}\rangle$	$5.833\cdot10^{-2}$
	$\langle\tilde{\varphi}_{\nu,1}\rangle$	$1.224\cdot10^{-3}$
	$\langle\tilde{\varphi}_{\nu,2}\rangle$	-0.9857
	Λ_ν [eV]	0.05629
Kähler potential	α_1^{u}	-0.94917
	α_2^{u}	0.0016906
	α_3^{u}	0.31472
	α_1^{d}	0.95067
	α_2^{d}	0.0077533
	α_3^{d}	0.30283
	α_1^{q}	-0.96952
	α_2^{q}	-0.20501
	α_3^{q}	0.041643

(a)

	observable	model best fit	exp. best fit	exp. 1σ interval
quark sector	$m_{\mathrm{u}}/m_{\mathrm{c}}$	0.00193	0.00193	$0.00133\to0.00253$
	$m_{\mathrm{c}}/m_{\mathrm{t}}$	0.00280	0.00282	$0.00270\to0.00294$
	$m_{\mathrm{d}}/m_{\mathrm{s}}$	0.0505	0.0505	$0.0443\to0.0567$
	$m_{\mathrm{s}}/m_{\mathrm{b}}$	0.0182	0.0182	$0.0172\to0.0192$
	ϑ_{12} [deg]	13.03	13.03	$12.98\to13.07$
	ϑ_{13} [deg]	0.200	0.200	$0.193\to0.207$
	ϑ_{23} [deg]	2.30	2.30	$2.26\to2.34$
	$\delta^{\mathrm{q}}_{\mathcal{CP}}$ [deg]	69.2	69.2	$66.1\to72.3$
lepton sector	m_{e}/m_μ	0.00473	0.00474	$0.00470\to0.00478$
	m_μ/m_τ	0.0586	0.0586	$0.0581\to0.0590$
	$\sin^2\theta_{12}$	0.303	0.304	$0.292\to0.316$
	$\sin^2\theta_{13}$	0.0225	0.0225	$0.0218\to0.0231$
	$\sin^2\theta_{23}$	0.449	0.450	$0.434\to0.469$
	$\delta^{\ell}_{\mathcal{CP}}/\pi$	1.28	1.28	$1.14\to1.48$
	η_1/π	0.029	-	-
	η_2/π	0.994	-	-
	$J_{\mathcal{CP}}$	-0.026	-0.026	$-0.033\to-0.016$
	$J^{\max}_{\mathcal{CP}}$	0.0335	0.0336	$0.0329\to0.0341$
	$\Delta m^2_{21}/10^{-5}$ [eV^2]	7.39	7.42	$7.22\to7.63$
	$\Delta m^2_{31}/10^{-3}$ [eV^2]	2.521	2.510	$2.483\to2.537$
	m_1 [eV]	0.0042	<0.037	-
	m_2 [eV]	0.0095	-	-
	m_3 [eV]	0.0504	-	-
	$\sum_i m_i$ [eV]	0.0641	<0.120	-
	$m_{\beta\beta}$ [eV]	0.0055	<0.036	-
	m_β [eV]	0.0099	<0.8	-
	χ^2	0.11		

Baur, Nilles, SRS, Trautner, Vaudrevange (2207.10677)

Quintessence from strings

Quintessence

with flavor and strings

Gordillo-Ruiz, Hernández-Segura, Portillo-Castillo, SRS, Zavala: 2509.22781

See talk by Hansel Gordillo-Ruiz TODAY!

1) Quintessential model

- Two moduli: T & dilaton S
- Effective superpotential:

$$W(S,T) \sim \lambda_1 Y_1(T) + \lambda_2 Y_2(T) + \alpha_1(T)\mathrm{e}^{-\beta_1 S} + \alpha_2(T)\mathrm{e}^{-\beta_2 S}$$

$Y_1(T), Y_2(T), \alpha_1(T), \alpha_2(T)$: computable modular forms

- Kähler potential:

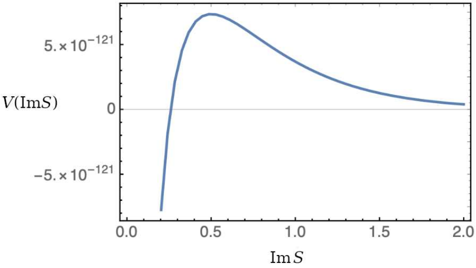
$$K(S,T) = -\log\left[S + \bar{S} - \chi\log(\mathrm{i}\bar{T} - \mathrm{i}T)\right] - \log(\mathrm{i}\bar{T} - \mathrm{i}T)$$

- $\Rightarrow$ Scalar potential:

$$V(\mathrm{Re}\,S, \mathrm{Im}\,S, \mathrm{Re}\,T, \mathrm{Im}\,T) = \mathrm{e}^K\left[K^{A\bar{B}} D_A W D_{\bar{B}}\overline{W} - 3|W|^2\right]$$

1) Quintessential model with axions

- Quintessence potential of axion $\mathrm{Im}\, S$



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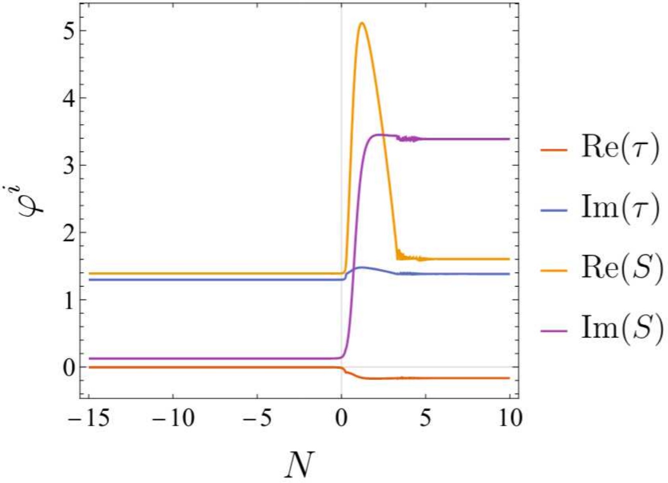
- Quintessence potential of axion $\mathrm{Im}\, S$
- $\Rightarrow$ Cosmological dynamics controlled by FLRW



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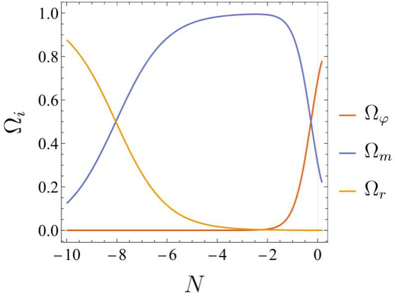
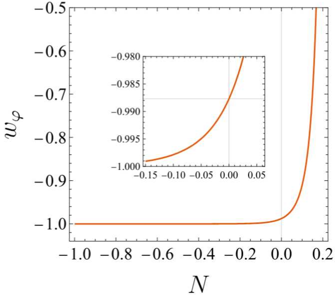
- $\Rightarrow$ correct abundances Ω_i & eq. of state w_φ ☺





$$\Omega_{\varphi,0} \sim 0.68, \Omega_{m,0} \sim 0.28, \Omega_{r,0} \sim 0, \qquad w_{\varphi,0} \sim -0.99$$

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- BUT
  - Unsolved hyper-mega-ultra fine tuning of $\Lambda := \langle V\rangle$ ☹
  - Too light moduli masses ☹
  - w_φ only grows vs. DES + DESI's "otros datos" ☹

Dark matter

with flavor and strings

Baur, Chen, Knapp-Pérez, SRS: 2409.02178

2) Flavored dark matter model

Inspired by our model with $\Gamma_3' \cong T'$, propose:

	L	(E_1^c, E_2^c, E_3^c)	H_d	H_u	ϕ_3	$\phi_{1'}$	ζ_3	$\zeta_{1''}$	$Y(T)$
$\mathrm{SU}(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U}(1)_Y$	$-\frac{1}{2}$	1	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0	0
$\Gamma_3 \cong A_4$	$\mathbf{3}$	$(\mathbf{1}, \mathbf{1}'', \mathbf{1}')$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}''$	$\mathbf{3}$
k_i	1	0	-1	0	0	0	0	0	2
$\mathrm{U}(1)_\mathrm{R}$	1	1	0	0	0	0	2	2	0
$\mathbb{Z}_2$	0	0	0	0	0	-1	0	-1	0

Key: modular symmetry & flavons $\phi_3, \phi_{1'}$ + driving fields $\zeta_3, \zeta_{1''}$

Baur, Chen, Knapp-Pérez, SRS: 2409.02178

2) Flavored dark matter model

Inspired by our model with $\Gamma_3' \cong T'$, propose:

	L	(E_1^c, E_2^c, E_3^c)	H_d	H_u	ϕ_3	$\phi_{1'}$	ζ_3	$\zeta_{1''}$	$Y(T)$
$\mathrm{SU}(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U}(1)_Y$	$-\frac{1}{2}$	1	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0	0
$\Gamma_3 \cong A_4$	$\mathbf{3}$	$(\mathbf{1}, \mathbf{1}'', \mathbf{1}')$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}''$	$\mathbf{3}$
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Aim at a model of

- lepton masses
- dark matter

2) Flavored dark matter model

- Effective action for leptons given by

$$\mathcal{W}_{\rm L} = \frac{1}{\Lambda} H_u L H_u L Y(T) + \frac{\alpha_1}{\Lambda_\phi} E_1^{\rm c} H_d (L\phi_3)_{\mathbf{1}} + \frac{\alpha_2}{\Lambda_\phi} E_2^{\rm c} H_d (L\phi_3)_{\mathbf{1}'} + \frac{\alpha_3}{\Lambda_\phi} E_3^{\rm c} H_d (L\phi_3)_{\mathbf{1}''}$$

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Tuned parameters: $\alpha_i, \Lambda, \Lambda_\phi, \langle\phi_3\rangle, \tan\beta$

observables	best-fit values
$m_{\rm e}/m_\mu$	0.00473 ± 0.00004
m_μ/m_τ	0.0450 ± 0.0007
y_τ	0.795 ± 0.012
$\Delta m_{21}^2/10^{-5}$ [eV^2]	$7.41^{+0.21}_{-0.20}$
$\Delta m_{32}^2/10^{-3}$ [eV^2]	$-2.487^{+0.027}_{-0.024}$
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$
$\sin^2\theta_{13}$	$0.02222^{+0.00069}_{-0.00057}$
$\sin^2\theta_{23}$	$0.568^{+0.016}_{-0.021}$
$\delta^\ell_{\mathcal{CP}}/\pi$	$1.52^{+0.13}_{-0.15}$

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DM = light combination of fermions from flavons & driving fields
$\rightarrow$ modular-flavored dark matter
correct abundance Ω_{DM} only by *freeze-in* production
Stringy flavor does give DM too! ☺

Summary

To take home...

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  Computable particle physics and cosmology

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- Dark matter: moduli and flavons controlled by flavor symmetries

To conclude...

Thanks!