Yukawas at infinite distance

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EXCELENCIA SEVERO OCHOA

AnLy Meeting in honor of Anamaria Font, Annecy, April 2024

My most frequent collaborator!!

Citation Summary

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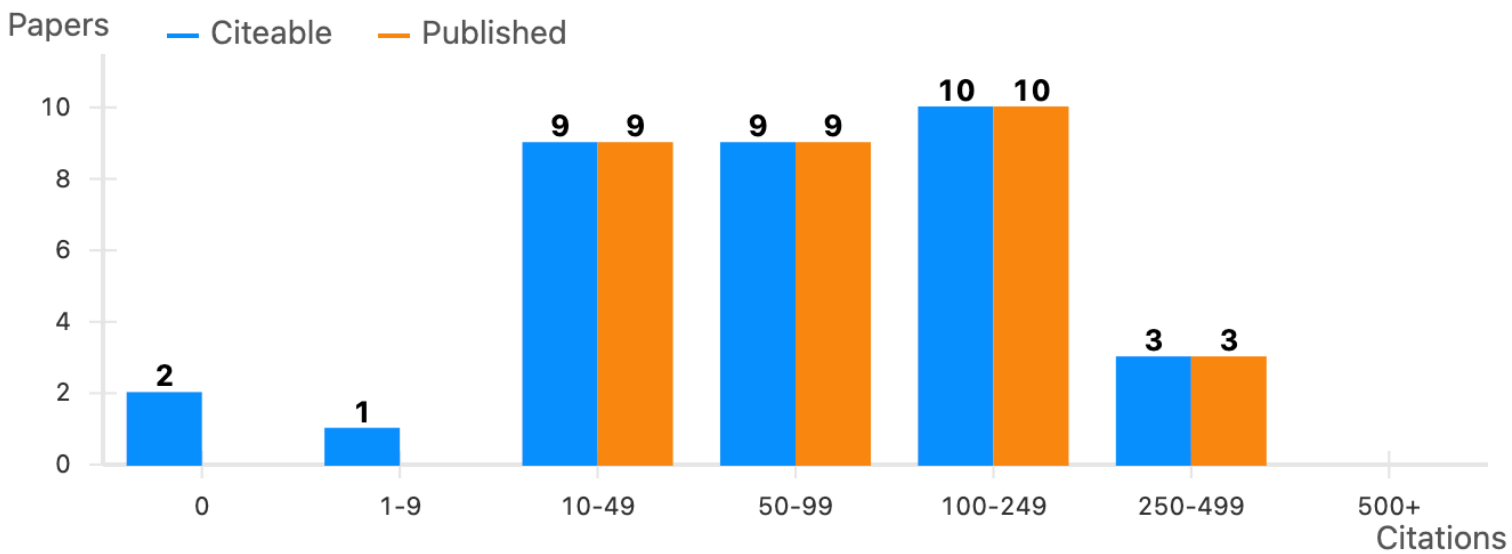
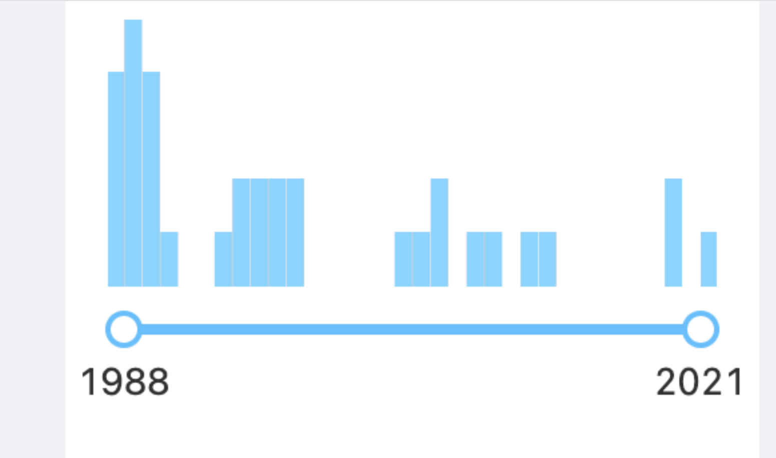
	Citeable ⓘ	Published ⓘ
Papers	**34**	**31**
Citations	**3,582**	**3,580**
h-index ⓘ	**29**	**29**
Citations/paper (avg)	**105.4**	**115.5**





A gravitino distance conjecture #1

Alberto Castellano (Madrid, IFT), Anamaría Font (Caracas, U. Central and Potsdam, Max Planck Inst.), Alvaro Herraez (IPhT, Saclay), Luis E. Ibáñez (Madrid, IFT) (Apr 20, 2021)

Published in: *JHEP* 08 (2021) 092 • e-Print: 2104.10181 [hep-th]

Working with Anamaria is a pleasure, but also a guarantee of quality!!

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Physics Letters B
Volume 245, Issues 3–4, 16 August 1990, Pages 4

Supersymmetry breaking fr
duality invariant gaugino
condensation

A. Font [a], L.E. Ibáñez [b], D. Lüst [b], F. Quevedo [c]

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Nuclear Physics B
Volume 361, Issue 1, 26 August 1991, Pages 194-232

Target-space duality, supersymmetry breaking and the stability of classical string vacua

M. Cvetič, A. Font, L.E. Ibáñez, D. Lüst, F. Quevedo

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Nuclear Physics B
Volume 345, Issues 2–3, 3 December 1990, Pages 389-430

Higher-level Kac-Moody string models and their phenomenolog implications

Anamaría Font, Luis E. Ibáñez, Fernando Quevedo

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Nuclear Physics B
Volume 536, Issues 1–2, 21 December 1998, Pages 29-68

$D = 4$, $N = 1$, type IIB orientifolds

G. Aldazabal [a], A. Font [b c], L.E. Ibáñez [d], G. Violero [d]

Physics Letters B
Volume 217, Issue 3, 26 January 1989, Pages 272-276

$Z_N \times Z_M$ orbifolds and discrete torsion

A. Font, L.E. Ibáñez, F. Quevedo

JHEP
Published by Institute of Physics Publishing for S
Received: August 1,
Accepted: August 24,
Published: September 6,

Fluxes, moduli fixing and MSSM-like vacua in a simple IIA orientifold

Pablo G. Cámara, Anamaria Font* and Luis E. Ibáñez
Departamento de Física Teórica C-XI and Instituto de Física Teórica C-XVI

JHEP
Published for SISSA by Springer
Received: June 10, 2019
Accepted: July 26, 2019
Published: August 8, 2019

The Swampland Distance Conjecture and towers of tensionless branes

Anamaría Font,[a] Alvaro Herráez[b] and Luis E. Ibáñez[b]

Strong–weak coupling duality
and non-perturbative effects in string theory

A. Font [a], L.E. Ibáñez [b], D. Lüst [b] and F. Quevedo [c]

[a] *Departamento de Fisica, Universita Central de Venezuela, Aptdo 20513, Caracas 1020-A, Venezuela*
[b] *CERN, CH-1211 Geneva 23, Switzerland*
[c] *Theoretical Division LANL, Los Alamos, NM 87545, USA*

Received 13 July 1990

We conjecture the existence of a new discrete symmetry of the modular type relating weak and strong coupling in string theory. The existence of this symmetry would strongly constrain the non-perturbative behaviour in string partition functions and introduces the notion of a maximal (minimal) coupling constant. An effective lagrangian analysis suggests that the dilaton vacuum expectation value is dynamically fixed to be of order one In supersymmetric heterotic strings, supersymmetry (as well as this modular symmetry itself) is generically spontaneously broken

S-DUALITY

ICTP Prize
1998

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Nuclear Physics B
Volume 416, Issue 2, 28 March 1994, Pages 481-538

Mirror symmetry for two-parameter models (I) ☆

Philip Candelas [a b], Xenia de la Ossa [c], Anamaría Font [d], Sheldon Katz [e], David R. Morrison [f g]

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Nuclear Physics B
Volume 429, Issue 3, 7 November 1994, Pages 626-674

Mirror symmetry for two-parameter models — II ☆

Philip Candelas [a b c], Anamaría Font [d], sheldon Katz [e], David R. Morrison [f g]

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Nuclear Physics B
Volume 511, Issues 1–2, 2 February 1998, Pages 295-3

Duality between the webs of heterotic and type II vacua

Philip Candelas, Anamaría Font ✉

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Nuclear Physics B
Volume 558, Issues 1–2, 4 October 1999, Pages 159-177

Tachyon-free orientifolds of type 0B strings in various dimensions

Ralph Blumenhagen [a] ✉, Anamaría Font [b c] ✉, Dieter Lüst [a] ✉

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Etc…

2023

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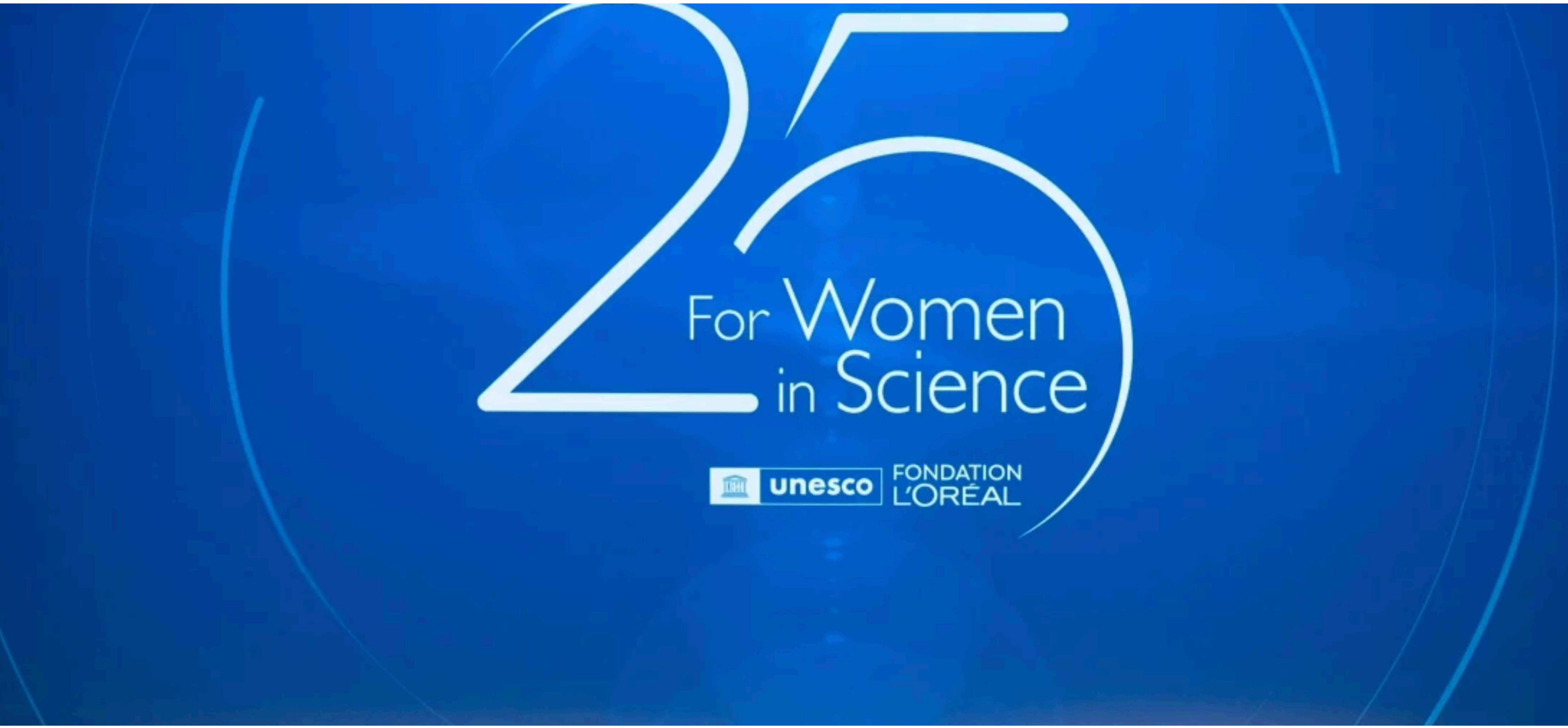
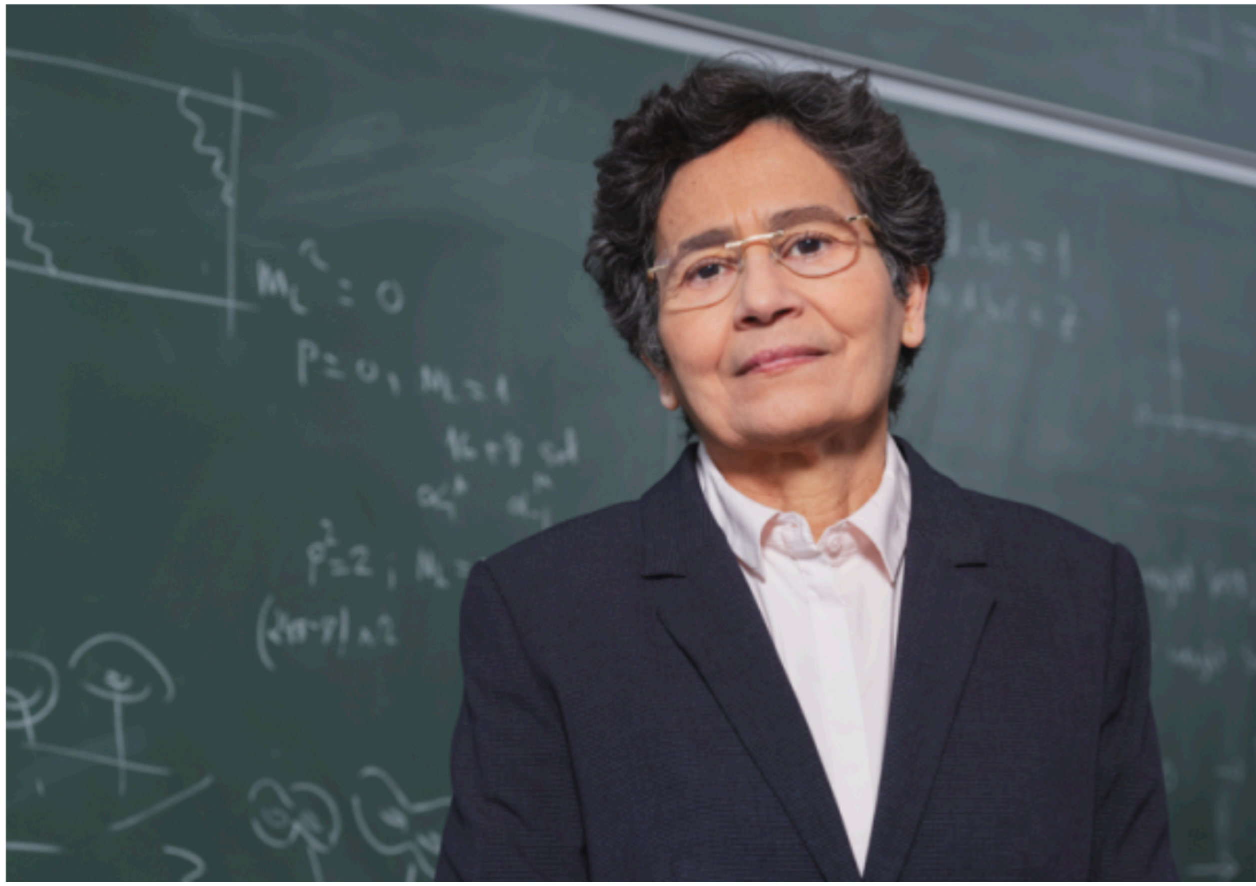


LAUREATE FOR LATIN AMERICA AND THE CARIBBEAN

PROFESSOR ANAMARÍA FONT

Professor of Physics, Central University of Venezuela.

Prof. Anamaría Font is recognized for her work in theoretical particle physics, with a particular focus on developing the theory of superstrings. This describes, in a unified and consistent way, the elementary particles of nature. Her research has enabled further understanding of the theory's consequences for the structure of matter and quantum gravity, which are also relevant to the description of black holes and the first moments after the big bang.

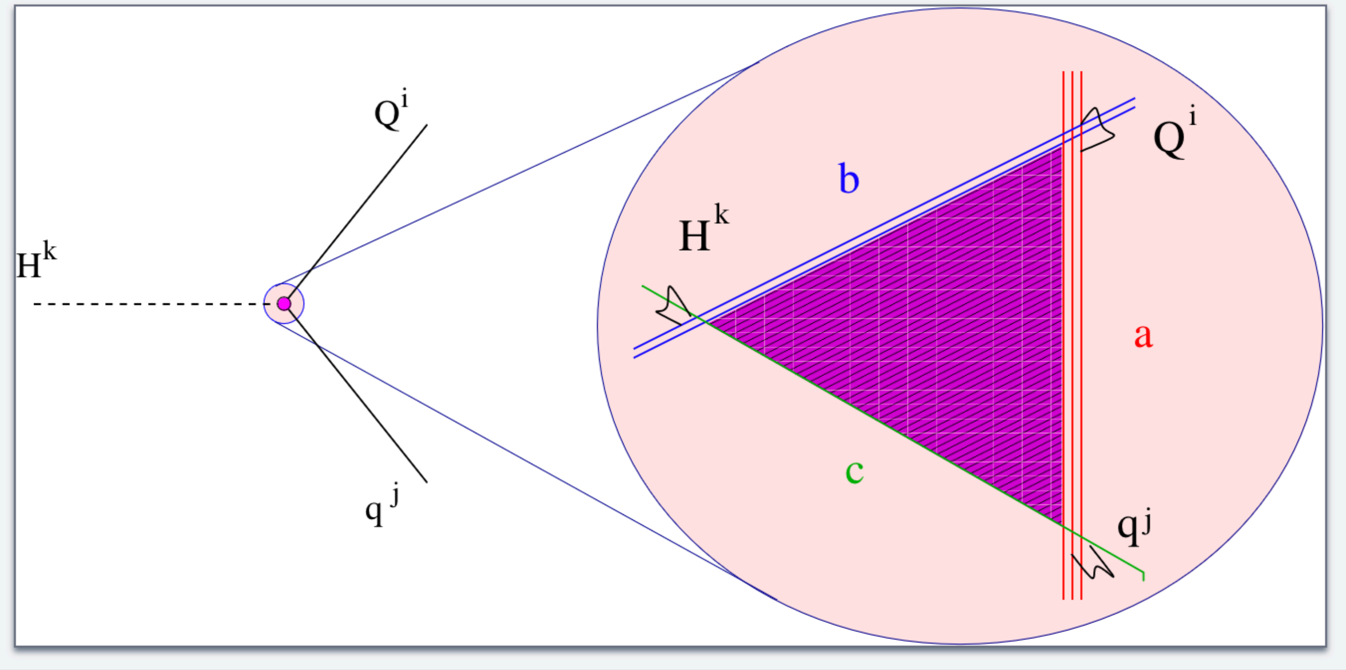


Paris, 15-th June 2023

Congratulations Anamaria !!

Yukawas at infinite distance


Yukawas at infinite distance



Work in collaboration with:

G.F. Casas and F. Marchesano
arXiv: 2403.09775 and
2404.XXXX to appear

I have written several papers on Yukawas with Anamaria:

Non-perturbative effects and Yukawa hierarchies in F-theory SU(5) Unification #1

Anamaria Font (Caracas, U. Central), Luis E. Ibanez (Madrid, IFT and Madrid, Autonoma U.), Fernando Marchesano (Madrid, IFT), Diego Regalado (Madrid, IFT and Madrid, Autonoma U.) (Nov, 2012)

Published in: *JHEP* 03 (2013) 140, *JHEP* 07 (2013) 036 (erratum) • e-Print: 1211.6529 [hep-th]

pdf DOI cite claim reference search 59 citations

Matter wave functions and Yukawa couplings in F-theory Grand Unification #2

A. Font (Caracas, U. Central), L.E. Ibanez (Madrid, Autonoma U. and Madrid, IFT) (Jul, 2009)

Published in: *JHEP* 09 (2009) 036 • e-Print: 0907.4895 [hep-th]

pdf DOI cite claim reference search 71 citations

Yukawa Structure from U(1) Fluxes in F-theory Grand Unification #3

A. Font (Caracas, U. Central), L.E. Ibanez (Madrid, Autonoma U.) (Nov, 2008)

Published in: *JHEP* 02 (2009) 016 • e-Print: 0811.2157 [hep-th]

pdf DOI cite claim reference search 105 citations

Yukawa Couplings in Degenerate Orbifolds: Towards a Realistic SU(3) x SU(2) x U(1) Superstring #4

A. Font (Annecy, LAPP), Luis E. Ibanez (Madrid, Autonoma U.), Hans Peter Nilles (CERN), F. Quevedo (CERN) (May, 1988)

Published in: *Phys.Lett.B* 210 (1988) 101, *Phys.Lett.B* 213 (1988) 564 (erratum)

DOI cite claim reference search 191 citations

Some classical Swampland lore

Vafa 2005, Palti (2019), van Beest et al. (2021), Graña, Herraez (2021)

- U(1) WGC: a particle exists with $\boxed{m \;\leq qgM_p}$

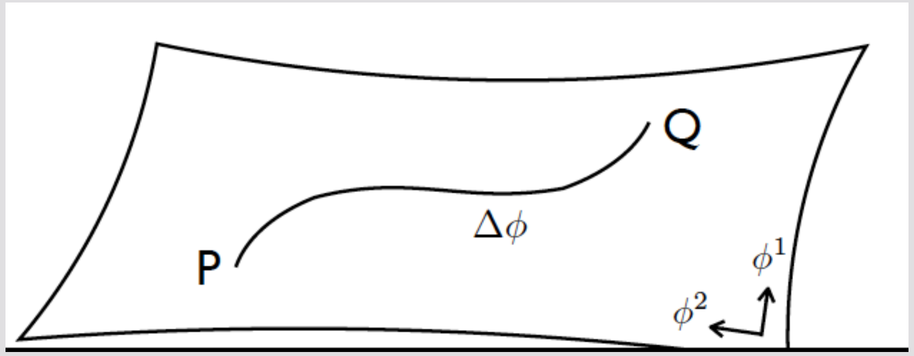
- Consistency under dimensional reduction in a circle: (sub)Lattice/Tower WGC

$$m_n \;=\; nqM_p$$

- The limit $g \;\longrightarrow\; 0 \; is \; singular$

A tower of particles should become massless

- Related: as a modulus goes to infinity a tower arises: $\Delta\phi \to \infty$



$$m(Q) \simeq m(P)e^{-\lambda\Delta\phi}$$

$$\lambda \sim 1$$

The case of 4D, N=1 and Yukawas

- Not much studied. New features like 4d CHIRALITY

- Also Yukawa couplings of charged matter fields $Y_{abc}(\Phi^a \Phi^b \Phi^c)$

- Although less SUSY, results reliable in the perturbative regime

Questions:

$$Is\ Y_{abc} \longrightarrow 0\ at\ infinite\ distance?$$

- What goes wrong if at all in that limit ? Are there towers of particles becoming massless?

- If there are towers, what is their structure?

- Are they consistent with the (sub)Lattice WGC?

Answers we find in this work

- We use Type IIA CY orientifolds with chiral matter at intersecting branes

- $$Y_{abc} \longrightarrow 0 \; IS \; at \; infinite \; distance$$

- $Y_{abc} \longrightarrow 0$

  - Large volume: $Y_{abc} \sim \left(\frac{m_{D0}}{M_p}\right)$ $decompactification \; to \; M-th$
  - Large C.S. $Y_{abc} \sim \prod_a \left(\frac{m^a_{gon}}{M_p}\right)^{1/2}$ $and \; p = 2,4,6 \; large \; dimensions$

- Gonions are charged oscillator states localised at intersections, with

$$m^2_{gon} \simeq n \, \theta \, M_s^2$$

- Gonions have all same charge (violate Lattice/Tower WGC) and not extremal

$$m_{gon} \simeq g_*^2 M_p$$

- Simplest examples for single large c.s. saxion u go to zero like

$$Y \sim \frac{1}{u^r} \qquad\qquad Y \sim g_*^{2r}$$

$r = 1/4, 1/2, 3/4, 1$

Explains what goes wrong…

- Application to small Dirac neutrino masses : a dark photon, two large dimensions….but challenging

4d, N=1 Type IIA CY Orientifolds as a laboratory

- CY compactification of IIA with orientifold quotient $\Omega_{ws}(-1)^{F_L}\mathcal{R}$, $\mathcal{R}(J,\Omega)=(-J,\overline{\Omega})$
- There are O(6) planes and D6-branes wrapping 3-cycles Π_α *and mirrors* Π_{α^*}

$$[\Pi_\alpha] = P_{\alpha\,J}[\Sigma_+^J] + Q_\alpha^K[\Sigma_K^-]$$

$$[\Sigma_K^-]\cdot[\Sigma_+^J] = 2\delta_K^J$$

- Closed string moduli:

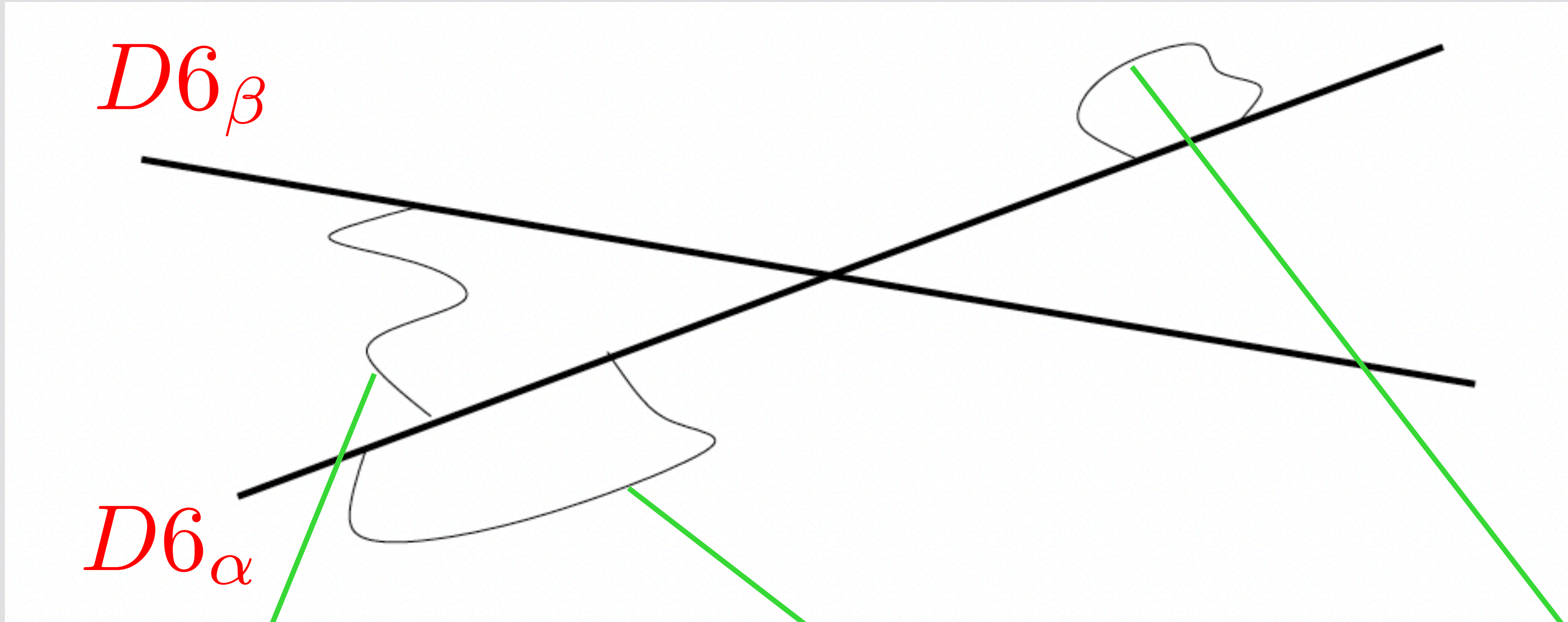
$$Kahler:\ T^a = b^a + it^a\ , where\ J_c \equiv B + iJ = (b^a + it^a)\omega_a$$

$$C.S:\ U^K = \zeta^K + iu^K\ , where\ \Omega_c \equiv C_3 + ie^{-\phi}Re\Omega = (\zeta^K + iu^K)\alpha_K$$

- Closed string moduli: (up to w.s. and D2 instantons)

$$K_K \equiv -\log\left(\mathrm{Vol}_{X_6}\right) = -\log\left(\frac{i}{48}\mathcal{K}_{abc}(T^a-\bar{T}^a)(T^b-\bar{T}^b)(T^c-\bar{T}^c)\right)$$

$$K_Q \equiv -2\log\mathcal{H} = -2\log\left(\frac{i}{8\ell_s^6}\int_{X_6} e^{-2\phi}\Omega\wedge\bar{\Omega}\right) = 4\phi_4$$



$(also\ SO, Sp)$

$U(N_\beta)$

$U(N_\alpha)$

$I_{\alpha\beta} \times (N_\alpha, \overline{N}_\beta)$

$2\pi i f_{\alpha\alpha} \; = \; P_{\alpha K} U^K$

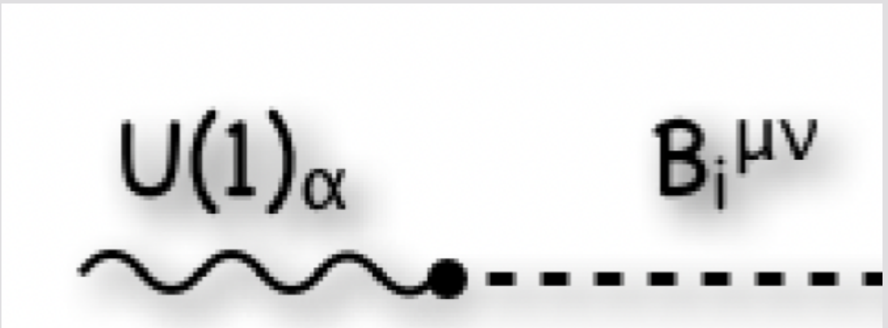
$$chiral\ bi - fundamentals\ at\ intersections$$

Berkooz,Douglas and Leigh, (1996)

Reviews: Blumenhagen et al(2006), Marchesano (2007),Ibañez,Uranga (2012),Marchesano, Schellekns, Weigand (2024)

U(1)'s

- Some U(1)'s become massive getting Stuckelberg mass mixing with 2-forms:



$$G_{KL}\, Q_\alpha^K (d\zeta^K \;\; A^\alpha)$$

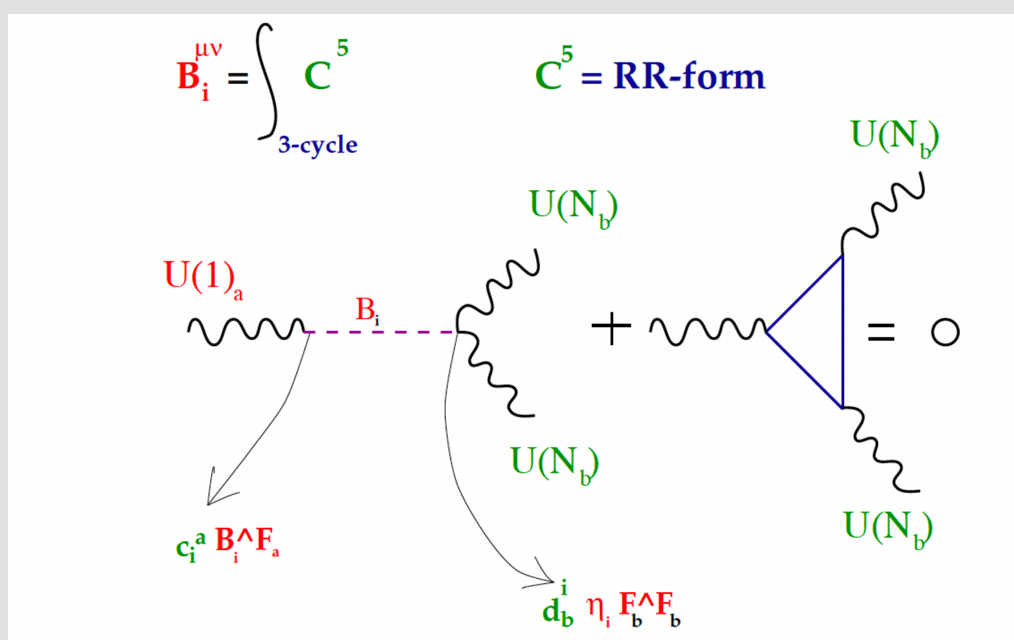
$d\zeta^K$: dual to $B^K_{\mu\nu}$

- Stuckelberg masses:

$$M^2_{\alpha\beta} = 4 G_{KL} Q^K_\alpha Q^L_\beta g_\alpha g_\beta \, M^2_{\mathrm{P}}$$

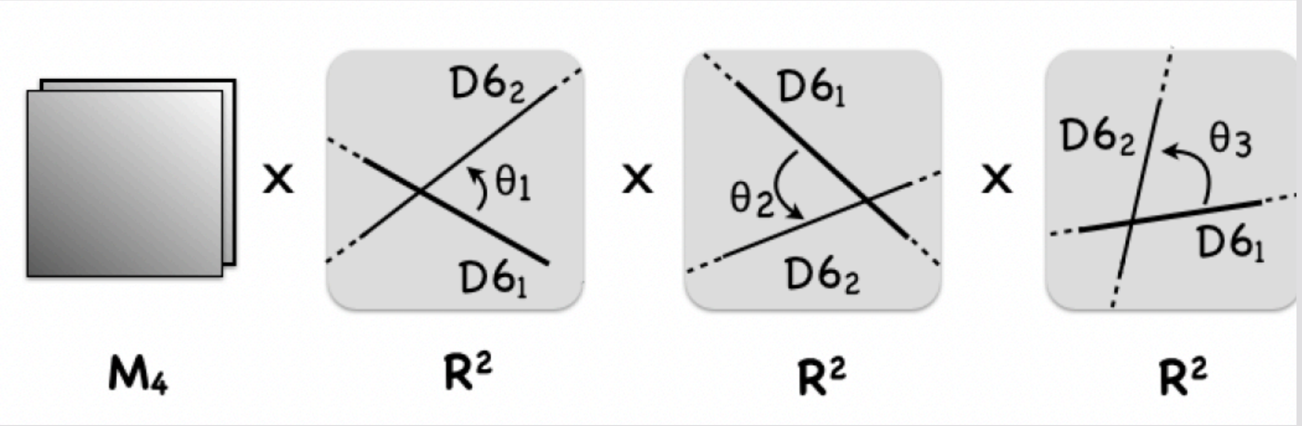
$$(may\ have\ massless\ eigenvalues, e.g.\ hypercharge\ in\ SM)$$

- Green-Schwarz cancel some U(1) pure and mixed anomalies



Gonions: flavour towers at intersections

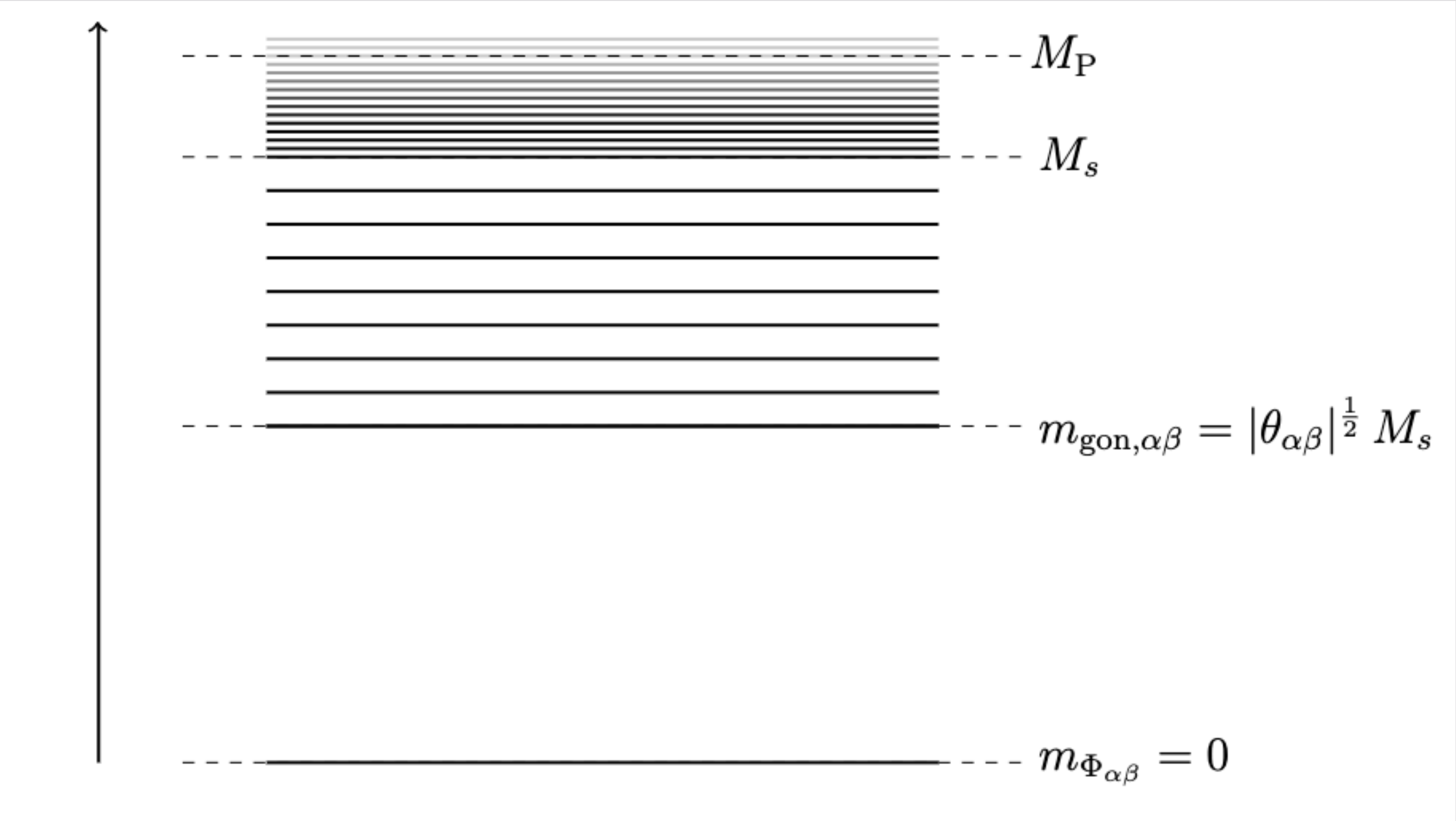
- At an intersection local geometry specified by 3 angles

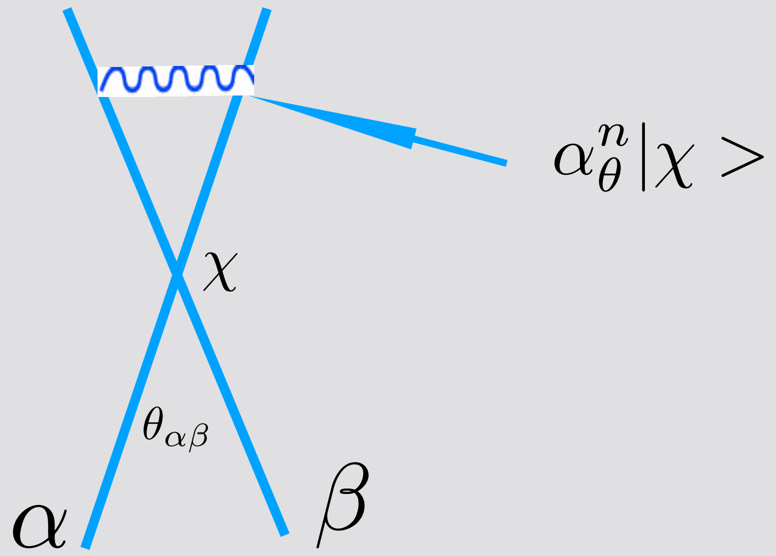


- SUSY preserved at intersection: $\theta_1 + \theta_2 + \theta_3 \ \in 2\mathbf{Z}$

Aldazabal et al (2001)

- In addition to massless chiral bifundamental, a tower of bi-fundamentals: 'Gonions'



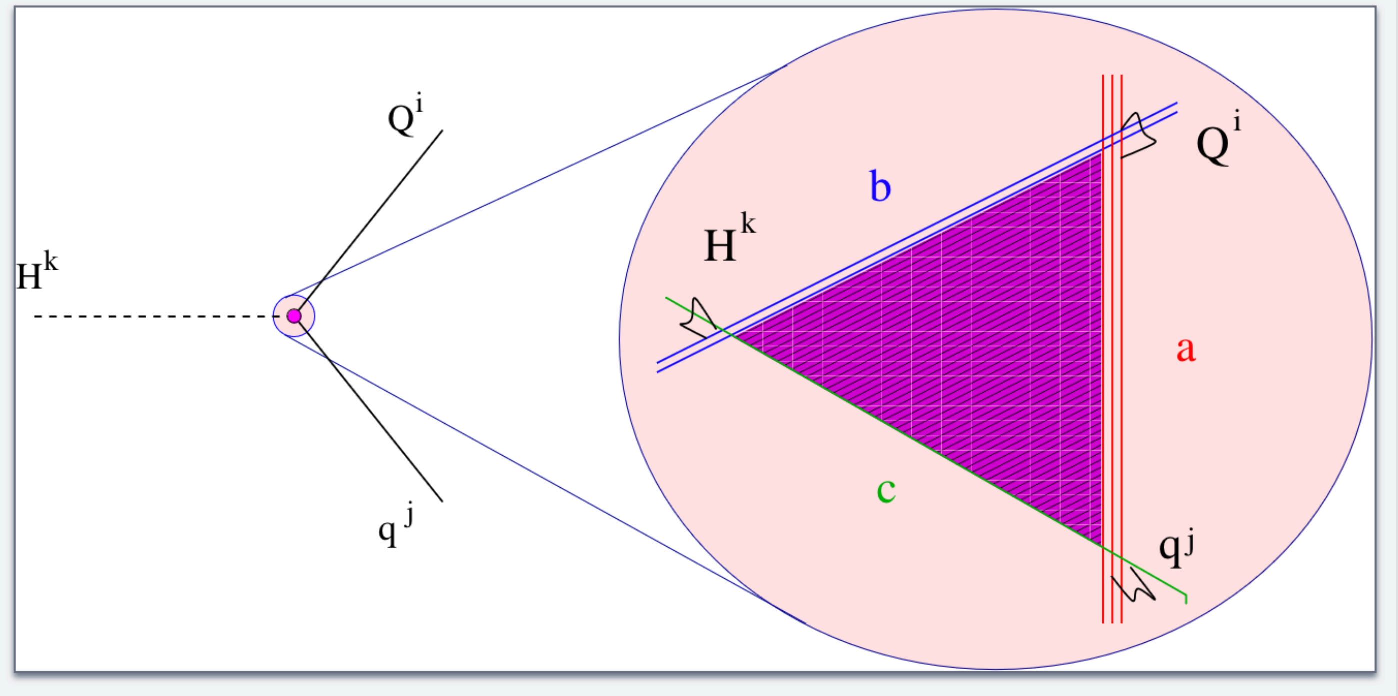


$$m^2_{n;\alpha\beta} \simeq n \ |\theta_{\alpha\beta}| \ M_s^2$$

'p =2 tower'

All same charge

Yukawas in toroidal and CY orientifolds



Aldazabal et al(2001), Cremades et al(2003), Cvetic et al (2003), Lust et al (2004))

$E.g.\ \ T^2 \times T^2 \times T^2\ orientifolds\ (or\ Abelian\ orbifolds)$

$$Y_{ijk} = e^{\phi_4/2} \prod_{r=1}^{3} (\mathrm{Im}\, T^r)^{-1/2} \left[\Theta^{(r)}\right]^{1/4} W_{ijk}^{(r)}$$

$(ignoring\ open\ string\ moduli)$

$$\Theta^{(r)} = 2\pi \frac{\Gamma(1-|\chi_{ab}^r|)}{\Gamma(|\chi_{ab}^r|)} \frac{\Gamma(1-|\chi_{bc}^r|)}{\Gamma(|\chi_{bc}^r|)} \frac{\Gamma(1-|\chi_{ca}^r|)}{\Gamma(|\chi_{ca}^r|)}$$

$|\chi_{\alpha\beta}^r| = |\theta_{\alpha\beta}^r|$ or $1 - |\theta_{\alpha\beta}^r|$;

- Essentially depends only on local geometry

- Depends only on local geometry: Expect structure valid for general CY:

$$Y_{ijk} = \frac{e^{\phi_4/2}}{Vol_X^{1/2}} \Theta_{ijk}^{1/4} \, W_{ijk}$$

- N=1 supergravity: canonically normalized Yukawas given by

$$Y_{ijk} = e^{K/2} \left(K_{i\bar{i}} K_{j\bar{j}} K_{k\bar{k}} \right)^{-1/2} W_{ijk}$$

  - Gives information about Kahler metric of chiral matter fields:

$$K_{i\bar{i}} K_{j\bar{j}} K_{k\bar{k}} = e^{3\phi_4} \Theta_{ijk}^{-1/2}$$

Kinetic terms of chiral fields

- Thus for the toroidal case, recalling

$$\Theta^{(r)} = 2\pi \frac{\Gamma(1-|\chi^r_{ab}|)}{\Gamma(|\chi^r_{ab}|)} \frac{\Gamma(1-|\chi^r_{bc}|)}{\Gamma(|\chi^r_{bc}|)} \frac{\Gamma(1-|\chi^r_{ca}|)}{\Gamma(|\chi^r_{ca}|)}$$

$$K_{i\bar{i}} = e^{\phi_4}(2\pi)^{-1/2} \prod_{r=1}^{3} \left(\frac{\Gamma(|\chi^r_i|)}{\Gamma(1-|\chi^r_i|)} \right)^{1/2}$$

$$|\chi^r_{\alpha\beta}| = |\theta^r_{\alpha\beta}| \text{ or } 1 - |\theta^r_{\alpha\beta}|$$

$$\mathcal{H} = e^{-2\phi_4}$$

- For small angles, recalling $\theta^r \simeq (m^r_{gon}/M_s)^2$

$$K_{i\bar{i}} \simeq \frac{e^{\phi_4}}{(\theta^{min}_{\alpha\beta})^{1/2}} \simeq e^{2\phi_4} \frac{M_p}{m^{min}_{gon,\alpha\beta}}$$

- Will give rise to a singular behaviour as $m^{min}_{gon,\alpha\beta} \to 0$

The $Y \longrightarrow 0$ limit and infinite distance

$$Y_{ijk} = \frac{W_{ijk}}{Vol_X^{1/2}} \quad e^{\phi_4/2}\Theta_{ijk}^{1/4}$$

- Infinite distance and Kahler moduli (fixed c.s.)

$$Y_{ijk} \simeq A\,\frac{W_{ijk}}{Vol_X^{1/2}} \longrightarrow 0 \quad \Rightarrow \quad Vol_X \longrightarrow \infty$$

$(W_{ijk} \to 0 \ typically \ requires \ non-generic \ fine-tuning)$

- These limits are at infinite distance: SDC a tower of particles should become massles: the D0's

$$m_{D0}^2 \simeq \frac{M_p^2}{Vol_X} \longrightarrow \qquad |Y| \simeq \frac{m_{D0}}{M_p}$$

- So this limit is the M-theory limit

A tower of particles should become massless

Small Yukawas and gonion masses

- Infinite distance and complex structure (fixed Kahler moduli)

$$Y_{ijk} \simeq B \; e^{\phi_4/2} \Theta_{ijk}^{1/4}$$

- With e.g. at least one small angle per complex plane and SUSY (No N=2 planes)

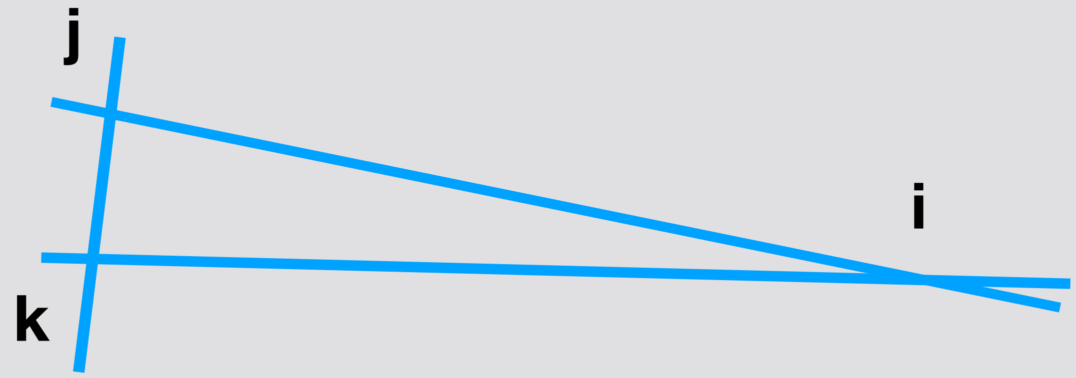
$$Y_{ijk} \sim e^{K_Q/2} \left(K_{i\bar{i}} K_{j\bar{j}} K_{k\bar{k}}\right)^{-1/2}$$

$$Y_{ijk} \sim e^{-\phi_4} \left(\frac{m_{gon,i}}{M_p}\right)^{1/2} \left(\frac{m_{gon,j}}{M_p}\right)^{1/2} \left(\frac{m_{gon,k}}{M_p}\right)^{1/2}$$

$$Y_{ijk} \to 0$$ → • At least one tower of light charged gonions !

See also Castellano, Herraez, Ibañez (2023)

- Simple example with a dominant small angle:



$$Y_{ijk} \simeq e^{-\phi_4} \left(\frac{m_{gon,i}}{M_p}\right)^{1/2} \left(\frac{M_s}{M_p}\right)^{1/2} \left(\frac{M_s}{M_p}\right)^{1/2}$$

$$\boxed{Y_{ijk} \simeq \left(\frac{m_{gon,i}}{M_p}\right)^{1/2}}$$

- Small Yukawas imply a tower of light particles with same charge as the massless field

- In EFT gonion masses come from FI-term of U(1) gauge group felt at the intersection

$$m_{gon}^2 \simeq g_*^2 \xi_{FI}^* \simeq g_*^2 \frac{Q_*^u}{u} M_p^2 \simeq \frac{Q_*^u}{u^2} M_p^2$$

$\theta \sim 1/u$ $\quad -log(U + U^* - Q_*^u V_*)$ $\quad Ref_* \simeq \frac{1}{g_*^2} \simeq u$

g_* is the gauge coupling of the U(1) (sub)group under which the leading gonions transform

General asymptotic behaviour of Yukawas

- We have considered the infinite c.s. limit in several settings/examples:

  - ‘STU’ Type IIA orientifold models models, dual to magnetized Type I and SO(32) models with U(1) bundles — *Blumenhagen, Honecker, Weigand (2005)*
  - ‘EFT String Limits of refs. — *Lanza, Marchesano, Martucci, Valenzuela (2021)*
  - Specific toroidal Type IIA orientifolds (e.g. Pati-Salam-like) — *Cremades, Ibañez, Marchesano (2002)*

- A lot of casuistics…….For limits parametrized by a single growing c.s. field u :

$$Y_* \sim \frac{1}{u^r}$$

$$r = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1$$

(Recall Y~ $e^{\phi_4/2}\Theta_{ijk}^{1/4}$)

- Consistent with Type IIB results in : *Conlon, Cremades, Quevedo hep-th/0609180 (2006)*

- Thus in general one will have

$$Y_* \sim g_*^{2r}$$

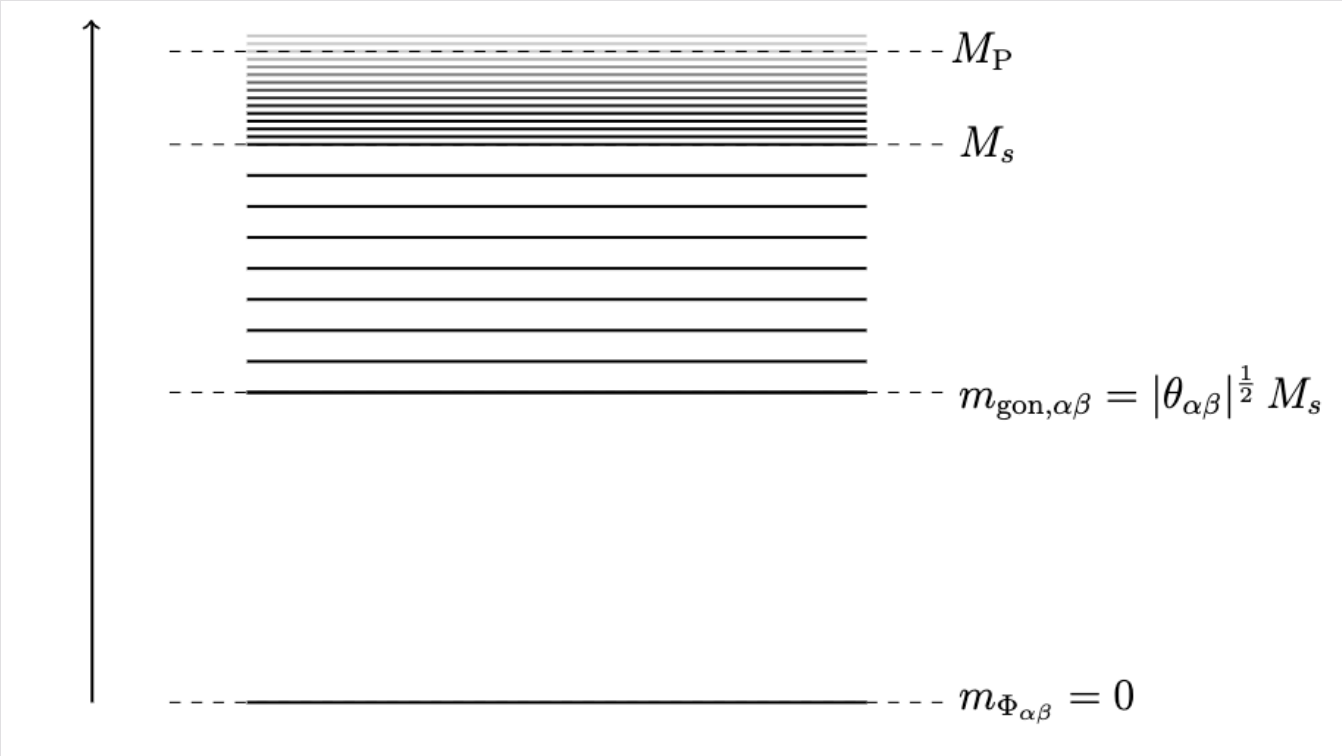
g_* again, is the gauge coupling of the (sub)group under which the leading gonions transform

- Thus in a vanishing Yukawa coupling limit :

$$Y_* \to 0 \quad \longrightarrow \quad g_* \to 0$$

- This explains why this limit is singular: the gauge group would survive as a global symmetry, which is forbidden in QG

More about the gonion towers



$$m^2_{n;\alpha\beta} \simeq n\ |\theta_{\alpha\beta}|\ M_s^2$$

'p =2 tower'

All same charge: not BPS

- Thus e.g. in the simple class of models with a single leading gonion tower (along with two large dimensions) one has

$$m_{\text{gon}} \sim g_* M_s \sim g_*^2 M_P\ , \qquad Y_* \sim g_*\ , \qquad g_* \sim e^{\phi_4}\ .$$

$The\ WGC\ condition\ m \ \leq\ \sqrt{2} g M_p\ verified\ with\ room\ to\ spare$

- The (sub)Lattice/Tower WGC not realised here (all gonions have same charge)

Neutrinos at infinite distance?

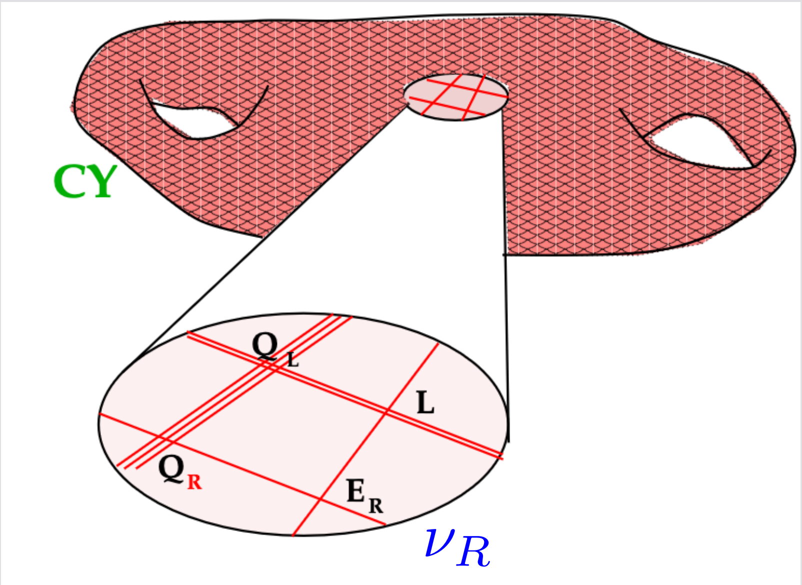
$If\ neutrinos\ are\ Dirac\ tiny\ Yukawas\ \sim\ 10^{-13}\ needed....$

ν_R

$\nu_R\ \nu_R$

Dirac neutrinos at infinite distance

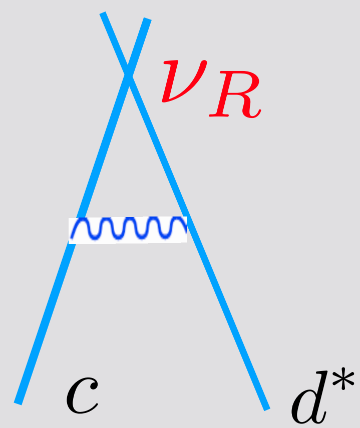
G. Casas, L. Ibañez, F. Marchesano
hep-th/2404.XXXX



The SM at intersecting D6-branes:

$$U(3)_a \times Sp(2)_b \times U(1)_c \times U(1)_d$$

only hypercharge massless after $B \wedge F$ *couplings*



ν_R'*s only charged under*

$$Q_\nu \equiv (Q_c + Q_d) \ = \ 2I_R - L$$

With a single large c.s. field M :

$$Y_\nu \simeq \left(\frac{m^\nu_{gon}}{M_p}\right)^{1/2} \simeq g_\nu \simeq \ 6.9 \times 10^{-13} \ (exp.)$$

- Then all scales fixed since they are determined by g_ν in rather universal way :

String Scale	KK small dim	SM KK replicas	$\nu_R, \tilde{\nu}_R$ tower	large dim	Dark vector boson
M_s	$M_{KK}, M_{KK/W}(D6)$	m^{SM}_{gon}	m^ν_{gon}	m_{KK}	M_V
$g_\nu M_p$	$\lesssim g_\nu M_p$	$\lesssim g_\nu M_p$	$g_\nu^2 M_p$	$g_\nu^2 M_p$	$g_\nu \lvert \bar{H} \rvert - g_\nu M_s$
700 TeV	$\lesssim 700 TeV$	10 – 100 TeV	500 eV	500 eV	5×10^{-2} - 500 eV

- However: only SUSY, examples with just Hypercharge massless known are the CFT orientifold examples of Schellekens et al (2004) which are non-geometric

- Implementation in a geometric setting challenging

Conclusions

- Using Type IIA CY N=1 orientifolds as a laboratory:

$$Y_{abc} \longrightarrow 0 \; IS \; at \; infinite \; distance$$

- $Y_{abc} \longrightarrow 0$
  - Large volume: Decompactification to M-th
  - Large C.S: at least one tower of charged 'gonions' $and \; p = 2,4,6 \; large \; dimensions$

$$Y_{abc} \sim \prod_a \left(\frac{m^a_{gon}}{M_p} \right)^{1/2}$$

- Gonions have all same charge (violate Lattice/Tower WGC) and not extremal,e.g. for a single tower of gonions

$$m_{gon} \simeq g_*^2 M_p \qquad\qquad M_s \simeq g_* M_p$$

- Simplest examples for single large c.s. saxion u go to zero like

$$Y \sim \frac{1}{u^r} \qquad r = 1/4, 1/2, 3/4, 1$$

- Also the gauge coupling of (sub)group felt at the intersection

$$Y \sim g_*^{2r}$$

Explains what goes wrong when $Y \to 0$

- Application to small Dirac neutrino masses: rather unique setting with

$$Y_\nu \simeq \left(\frac{m_{gon}^\nu}{M_p}\right)^{1/2} \simeq g_\nu \simeq 6.9 \times 10^{-13} \ (exp.)$$

e.g. light gauge boson coupling to $(2I_R - L)$ with a mass $\sim 5 \times 10^{-2}$ eV

- Implementation in a geometric string setting challenging

Thank you !!

Congratulations Anamaria for your fantastic work!!

Your friendship is a privilege!!

Thank you !!

Back-up

Consistency with WGC under dimensional reduction

- It has been argued it is required that the WGC comes with a full tower of states with all charges (Lattice/Tower WGC)

- Gonions are a counterexample *This is because ofthe double supression* $m_{gon} \simeq g_*^2 M_p$

  - After compactifying the theory on a circle, the 'convex hull' contains the extremal region if we remain in perturbation theory

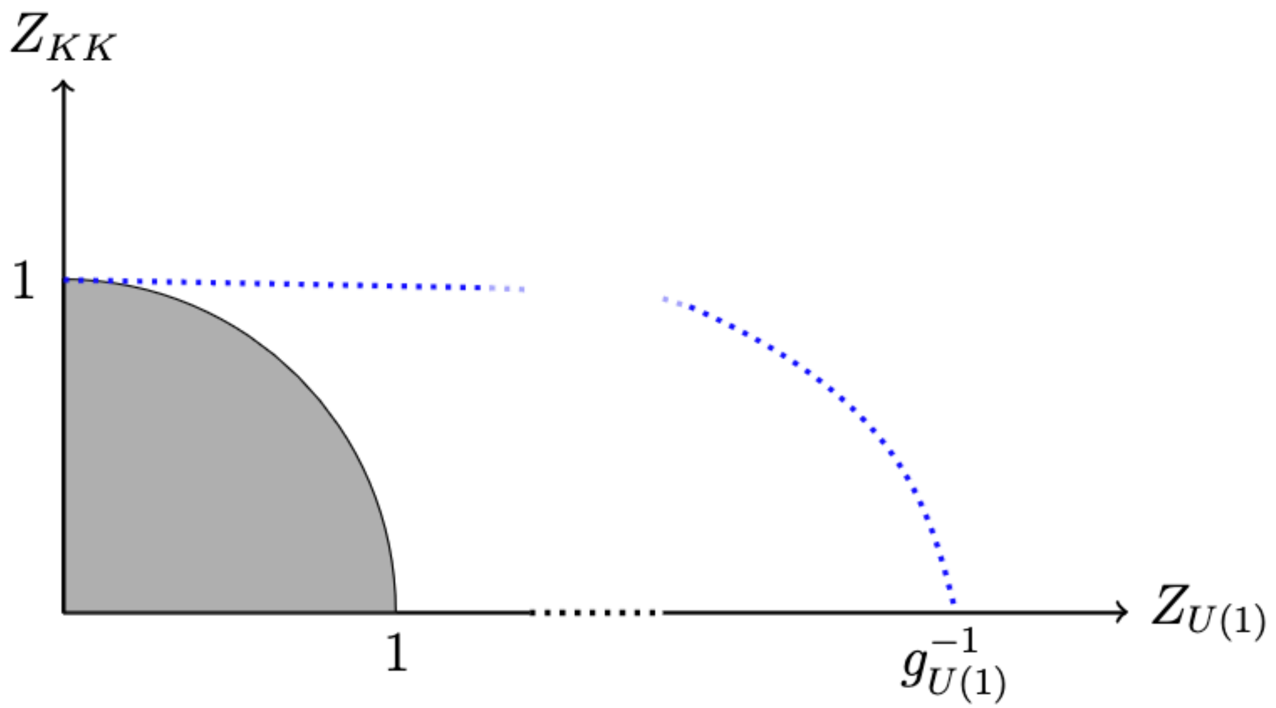
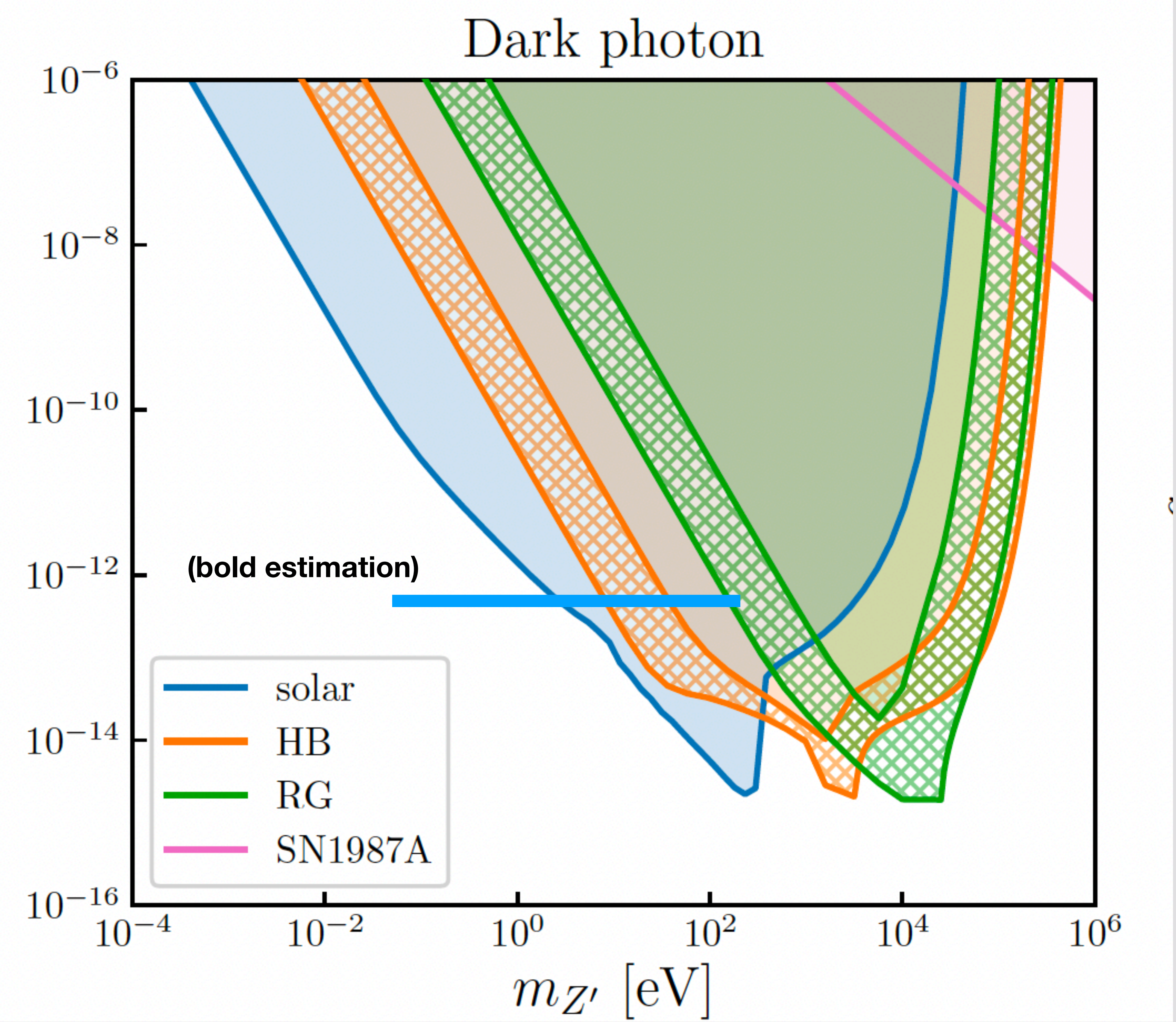


Figure 9: Blue line corresponds to the convex hull of the charge-to-mass ratio $\vec{Z} = \vec{Q}/m_{\text{gon}}^{\text{KK}}$, where $m_{\text{gon}}^{\text{KK}}$ are the gonion Kaluza-Klein replicas. If the radius of the circle compactification satisfies $R \gtrsim M_{\text{P}}^{-1}$, the convex hull always contains the extremal region (grey area, see [108, eq.(83)]). Here we stay in a perturbative regime $g_{U(1)} \ll 1$.


Dark photon
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
(bold estimation)
solar
HB
RG
SN1987A
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
m_{Z'} [eV]