Instituto de Física Teórica presents:

Yukawas & Neutrinos @ Infinite Distance

by Fernando Marchesano

based on 2403.07979 & 2406.14609

w/Luis E. Ibáñez & Gonzalo F. Casas

What is this talk about?

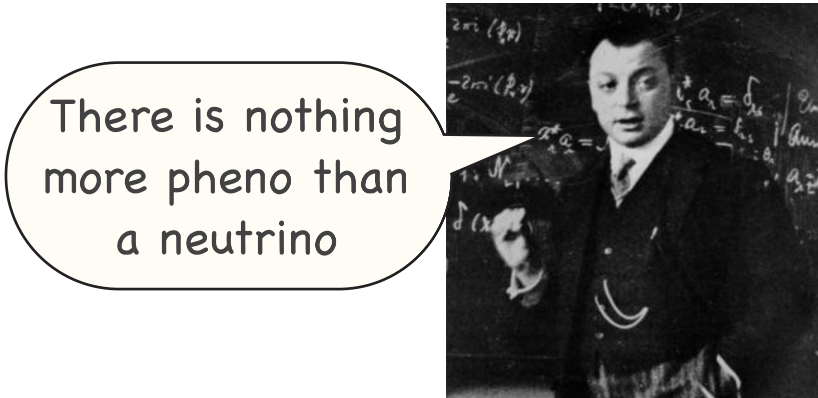
Strings & Pheno

Strings

- Yukawas in 4d N=1 chiral CY orientifold vacua
- The limit $Y \to 0$: What goes wrong?
- Kinetic terms of chiral fields
- Light gonion & KK towers
- Massive U(1)'s and monopoles

Pheno

- Dirac vs. Majorana neutrinos
- How to get small Dirac masses. As a consequence:
  - ✦ All scales fixed
  - ✦ Low M_s and 2 large dimensions
  - ✦ Λ_{cc} and large dimensions

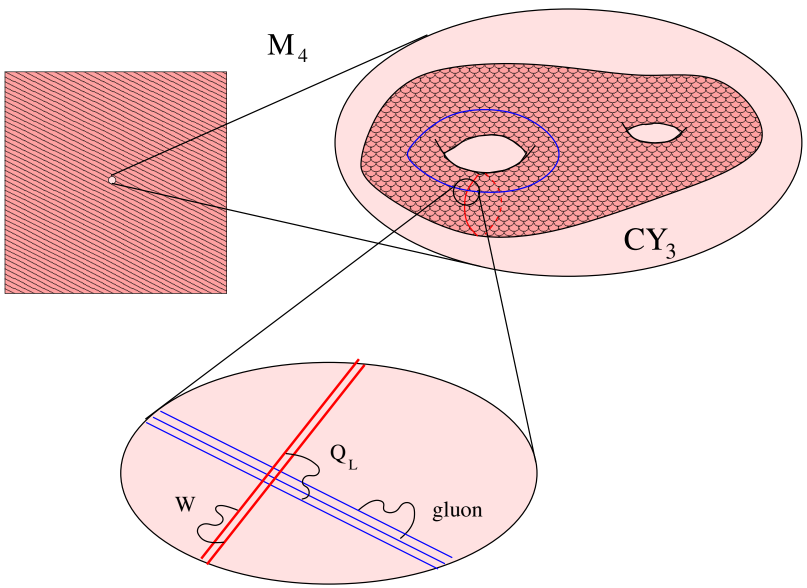


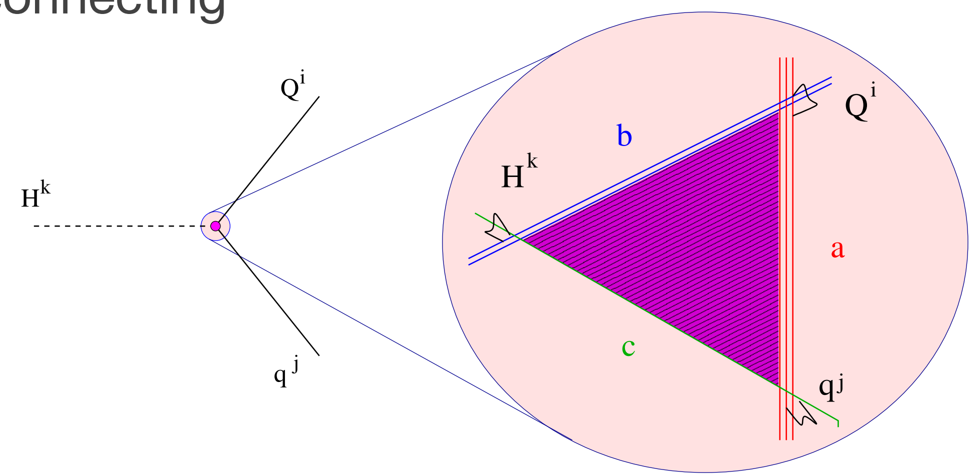
Yukawas in type IIA orientifolds

Blumenhagen et al. '00
Aldazábal et al. '00

4d $\mathcal{N} = 1$ chiral EFTs based on intersecting D6-branes

Yukawas arise from worldsheet instantons connecting three intersections hosting chiral matter





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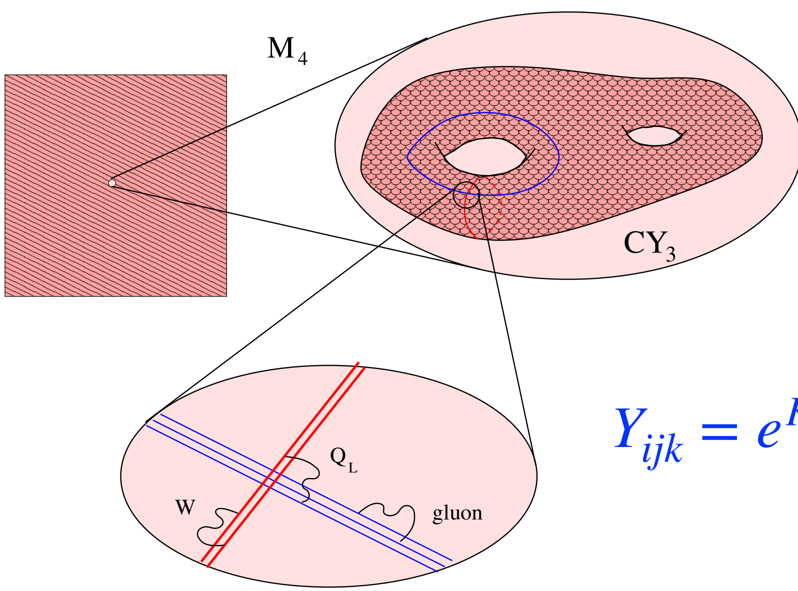
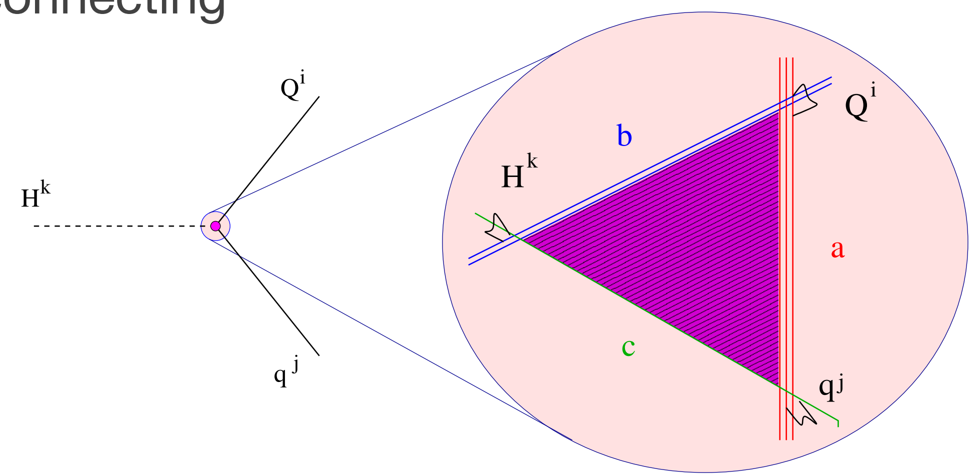




$$Y_{ijk} = e^{K/2} \left[K_{i\bar{i}} K_{j\bar{j}} K_{k\bar{k}} \right]^{-1/2} \left(W_{ijk}^{\text{tree}} + W_{ijk}^{\text{np}} \right)$$

Kähler moduli T

complex structure moduli (~ $e^{-2\pi U}$)

Cremades, Ibanez, F.M '03-04, Conlon, Maharana, Quevedo'08, Abel & Goodsell'06, Blumenhagen et al.'07, Ibáñez & Richter'08

Some questions

Pheno & Swampy

Pheno

- Can we reproduce the fermion mass hierarchies of the SM + ν's in string theory?
- Initial strategy: use $Y_{ijk}^{\text{tree}} + Y_{ijk}^{\text{np}}$ + see-saw mechanism for ν's

Blumenhagen, Cvetic, Weigand'06   Ibáñez & Uranga'06

- However, in practice it is not that easy: *Ibáñez, Schellekens, Uranga'07*
- So what if we tried to obtain the hierarchies directly from Y_{ijk}^{tree}?
- Neutrinos should be Dirac, and we are close to the limit $Y \to 0$

Swampy

- What happens when $Y \to 0$?
- Do Yukawas behave like gauge couplings in quantum gravity?

Palti'20   Cribiori & Farakos'23

- Does $Y \to 0$ happen at infinite distance only? If yes, why? What goes wrong with the EFT?
- Do towers of light particles arise when $Y \to 0$? Is there a WGC-like bound $m \leq Y M_{\text{P}}$?


Yukawas @ infinite
distance

How do we implement $Y \to 0$?

$$Y_{ijk} = e^{K/2}\left[K_{i\bar{i}}K_{j\bar{j}}K_{k\bar{k}}\right]^{-1/2}\left(W^{\text{tree}}_{ijk} + W^{\text{np}}_{ijk}\right)$$

In principle one can move in field space to set $W^{\text{tree}}_{ijk} = 0$ for some entries

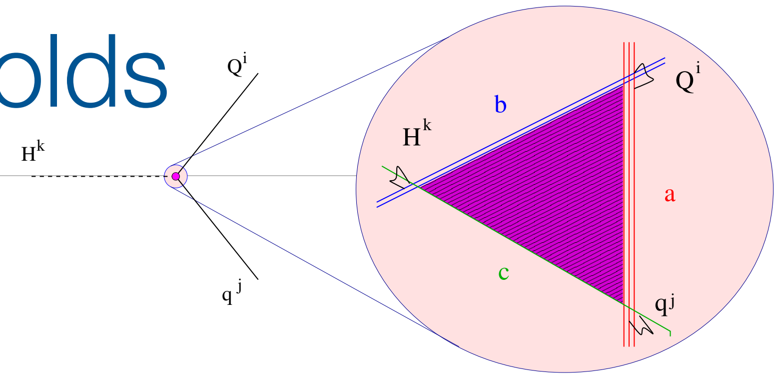
However:

- There is no guarantee that $W^{\text{np}}_{ijk} = 0$
- A continuous limit $W^{\text{np}}_{ijk} \to 0$ is typically at infinite distance
- The rank of W^{tree}_{ijk} is oftentimes topological

Cecotti et al. '09

Our strategy will be to take $K_{i\bar{i}} \to \infty$

Yukawas in type IIA orientifolds

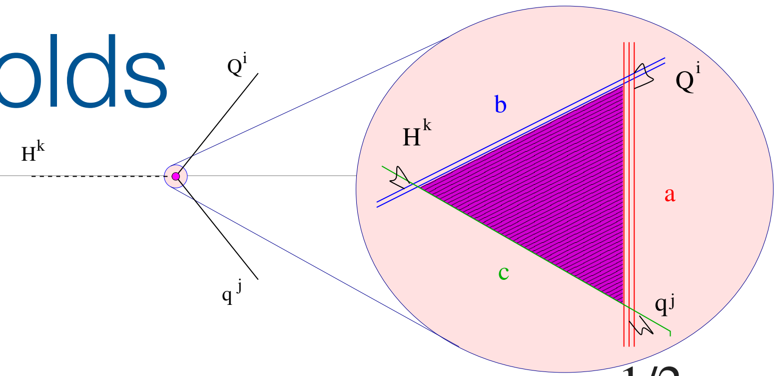


Toroidal setup: *Cremades, Ibanez, F.M '03-04*

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

- $e^{\phi_4/2}$ → 4d dilaton
- $\prod_{r=1}^{3}$ → cpx. dim
- $\left(\text{Im}\, T^r\right)^{1/4}$ → Kähler moduli
- $\left[\Theta^{(r)}\right]^{1/4}$ → intersection angles (cpx. str. moduli U^r)
- $e^{H^{(r)}}$ → D6-brane moduli ν^r
- $W_{ijk}^{(r)}$ → Holomorphic piece (T, ν)

Yukawas in type IIA orientifolds



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4d dilaton

cpx. dim

Kähler moduli

intersection angles (cpx. str. moduli U^r)

D6-brane moduli ν^r

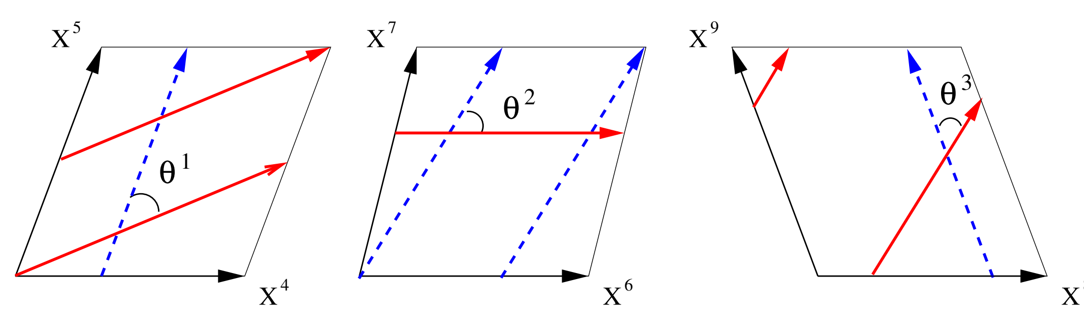
Holomorphic piece (T, ν)

$$K_{i\bar{i}} = F(T)\, e^{\phi_4} \prod_{r=1}^{3} \left[\frac{\Gamma(|\chi_i^r|)}{\Gamma(1-|\chi_i^r|)}\right]^{1/2}$$

Cvetic & Papadimitriou '03
Lüst et al. '04, Font & Ibáñez '04
Bertolini et al. '05, Akerblom et al. '07
Billò et al. '07, Di Vecchia et al. '08
Cámara, Condeescu, Dudas '09

$\mathcal{N} = 2$ sectors: only two angles $\theta_{ab}^1, \theta_{ab}^2$

Open string twist: $|\chi_i^r| = |\theta_{ab}^r|$ or $1 - |\theta_{ab}^r|$



Kähler metrics and gonions

$$K_{i\bar{i}} = F(T)\, e^{\phi_4} \prod_{r=1}^{3} \left[\frac{\Gamma(|\chi_i^r|)}{\Gamma(1-|\chi_i^r|)} \right]^{1/2} \xrightarrow[\Gamma(x) \simeq \frac{1}{x} + \dots]{|\theta^3| \simeq |\theta^1| + |\theta^2|} \simeq \left[\frac{e^{2\phi_4} |\theta^3|}{|\theta^1||\theta^2|} \right]^{1/2}$$

Kinetic terms blow up for small intersection angles. Precisely in this limit a tower of light open string oscillations appears → *gonions*

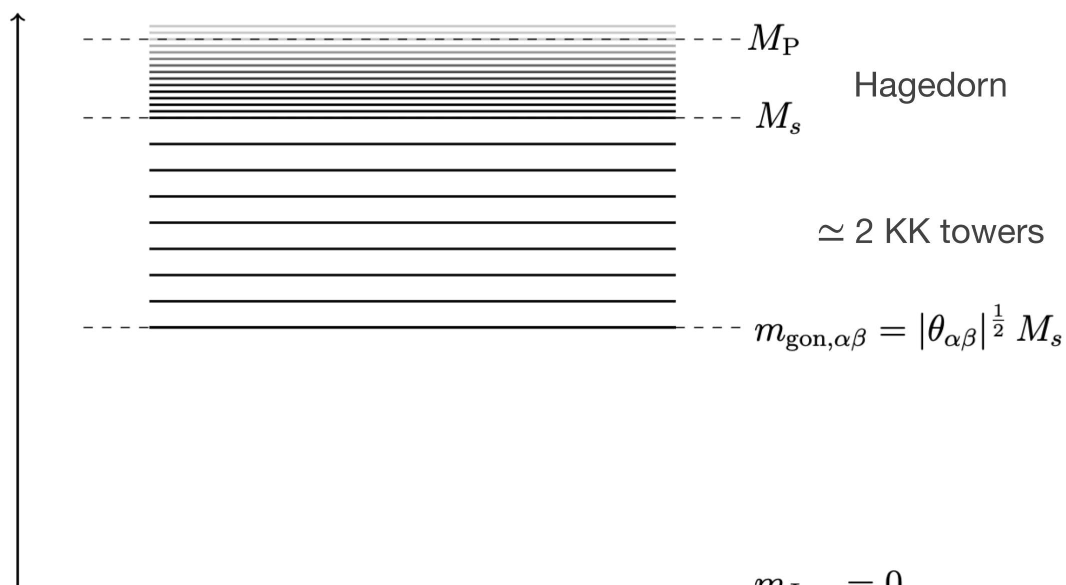
Berkooz, Douglas, Leigh '96
Aldazábal et al. '00

$$K_{i\bar{i}} \simeq e^{2\phi_4} \left(\frac{M_P}{m^i_{\rm gon}} \right)^{1/2}$$

Lightest gonion tower

Can be derived from the *Emergence Proposal*

See Gonzalo F. Casas' talk!



Yukawas and gonions

Due to locality, all this is valid in a CY as well:

$$|Y_{ijk}|^2 \simeq B\, e^{-2\phi_4} \frac{m^i_{\rm gon}}{M_{\rm P}} \frac{m^j_{\rm gon}}{M_{\rm P}} \frac{m^k_{\rm gon}}{M_{\rm P}}$$

$$|Y| \to 0 \implies \frac{m^i_{\rm gon}}{M_{\rm P}} \to 0$$ for some i

$e^{-\phi_4} \gg 1$ control regime

Large complex structure limits:

$$e^{\phi_4} \to 0 \implies \frac{m_{\rm gon}}{M_{\rm P}} = e^{\phi_4} \frac{m_{\rm gon}}{M_s} < e^{\phi_4} \to 0$$

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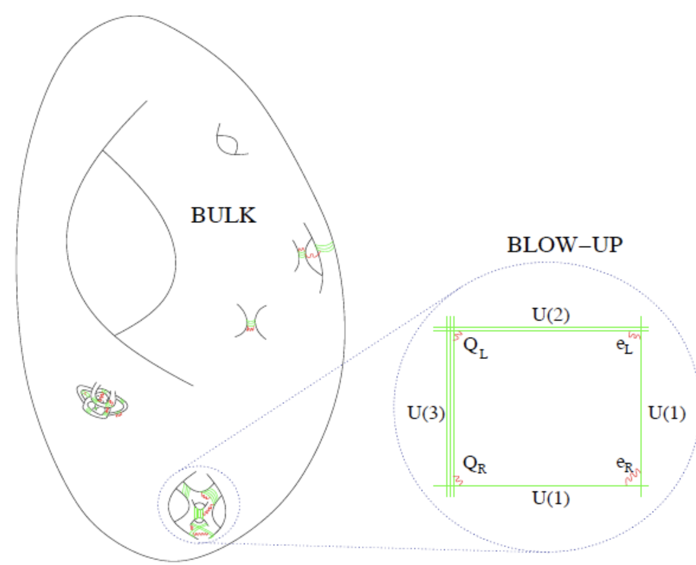
Special case: $\mathcal{N} = 2$ sector involved

$$K_{i\bar{i}} \simeq e^{2\phi_4} h_{i\bar{i}} \implies |Y_{ijk}|^2 \simeq h_{i\bar{i}}^{-1} \frac{m^j_{\rm gon}}{M_s} \frac{m^k_{\rm gon}}{M_s}$$

e.g. mirror of local IIB models

Conlon, Cremades, Quevedo '06



Gonions and monopoles

$$K_{i\bar{i}} \simeq \left[\frac{e^{2\phi_4}|\theta^3|}{|\theta^1||\theta^2|}\right]^{1/2} \simeq e^{2\phi_4}\left(\frac{M_P}{m^i_{\rm gon}}\right)^{1/2}$$

Ideally, one would like to express the Kähler metrics in terms of complex structure moduli vevs, instead of intersection angles

Extremely challenging beyond toroidal geometries

Idea: relate intersection angles with FI-terms, in turn related to the tensions of 4d EFT strings that couple to massive U(1)'s, and end on their monopoles

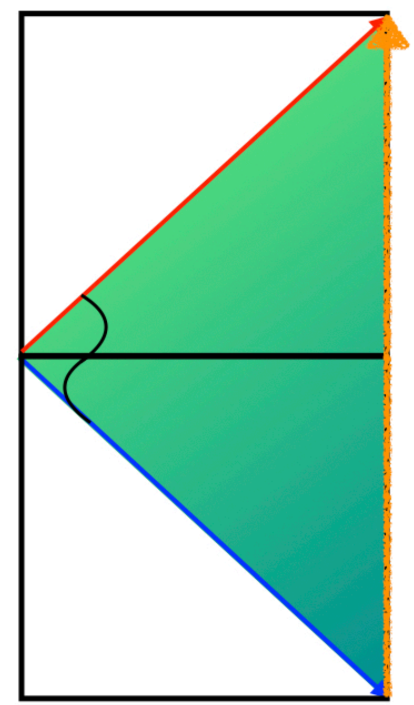
$$\left(\theta^1 + \theta^2 + \theta^3\right) M_s^2 = g^2 \xi = Q^K T_{\rm D4,K}$$

Estimate:

$$m^2_{\rm gon,min} \sim \min_K \{g^2 Q^K T_{\rm D4,K}\}$$

4d EFT string
T only vanishes at infinite distance boundaries

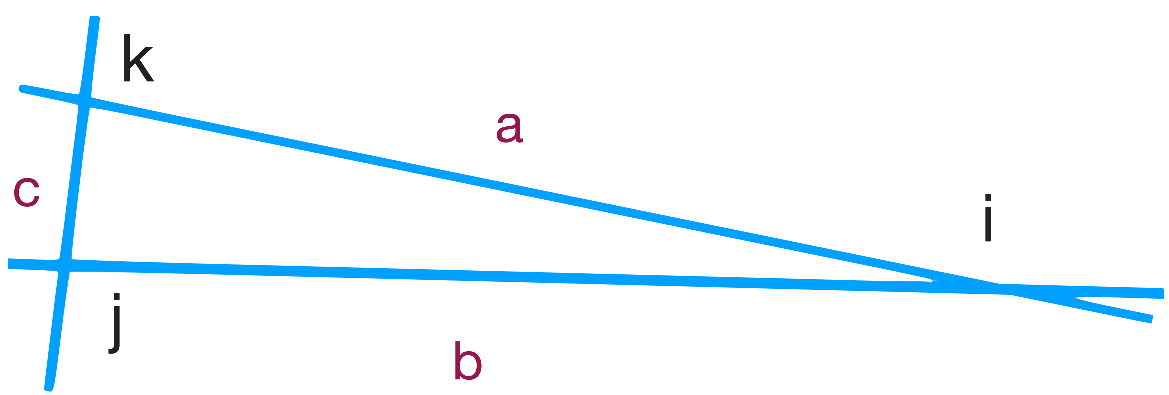
Lanza et al. '21



The limit $Y \to 0$

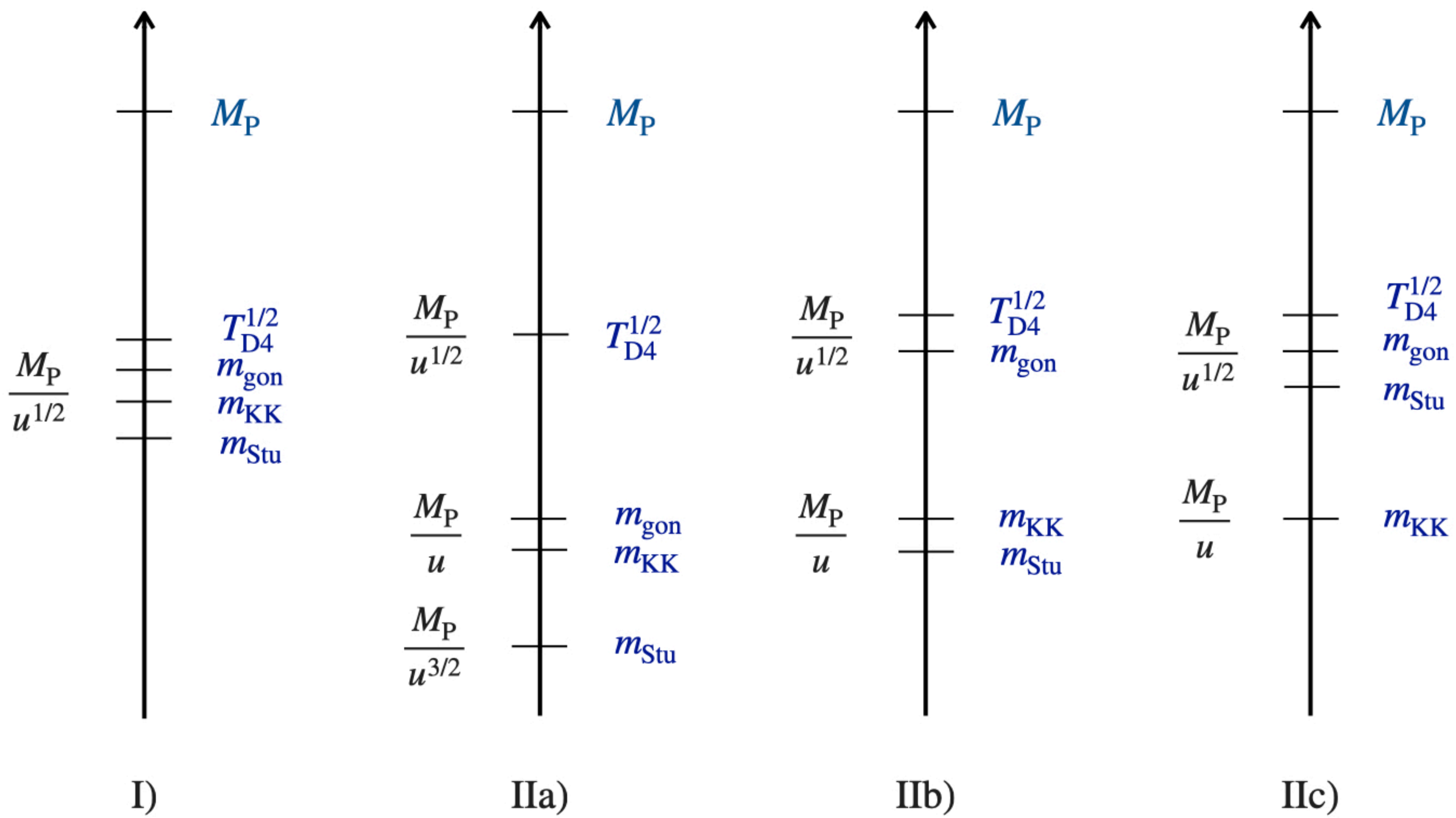
Using this estimate, one obtains the following picture:

- $Y \to 0$ implies $g \to 0$, for some gauge coupling
- There is always a tower of CY KK modes below the gonion tower
- If they scale similarly, the KK towers are equally or more dense than the gonion towers → dimensions open up in pairs
- Typical asymptotic behaviour of the Yukawas: $Y \sim \frac{1}{u^r}$ $\quad r = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1$
- Species scale: M_s or $T_{\rm D4}$

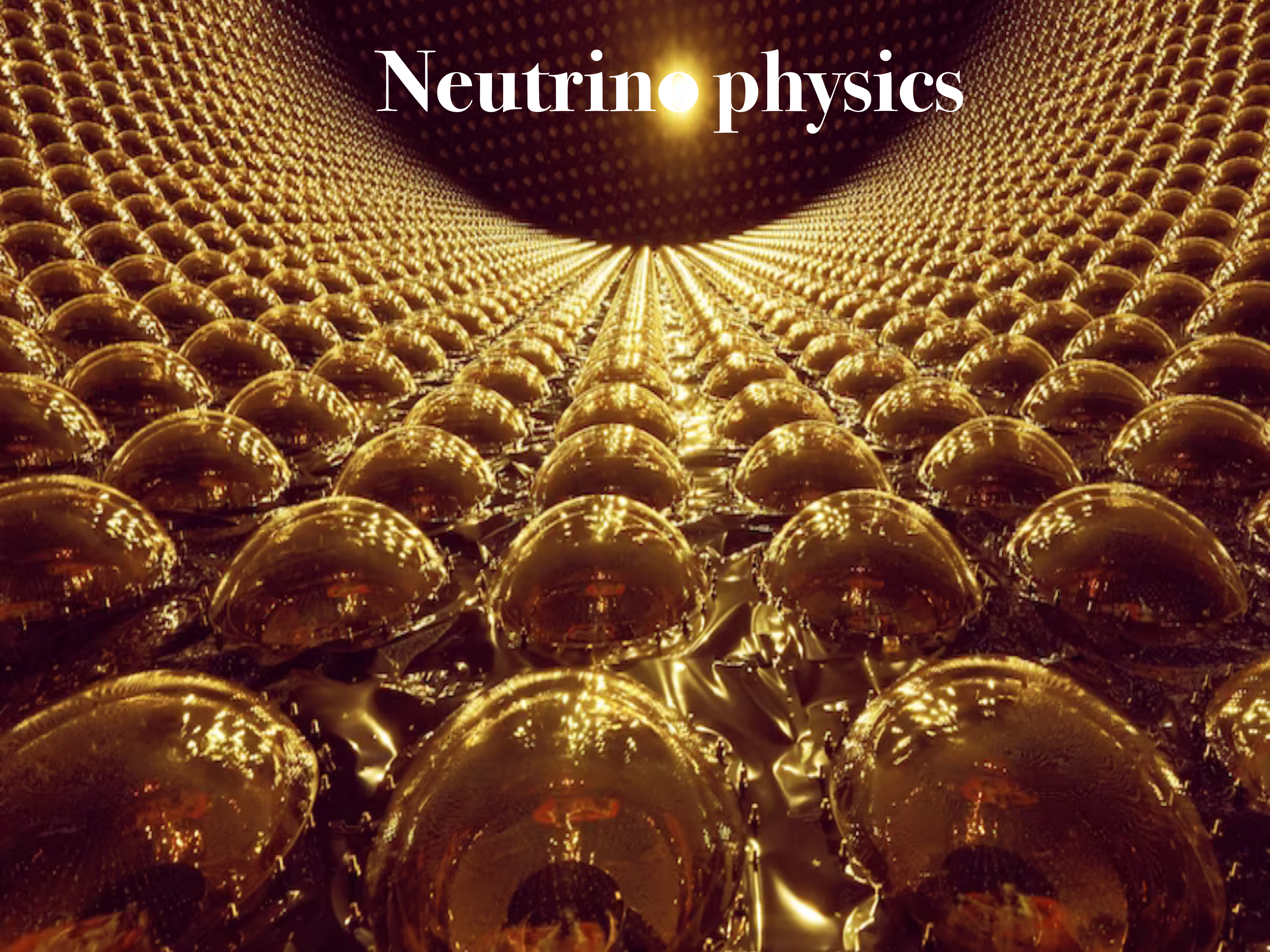


The limit $Y \to 0$

Wide casuistic, but there are some prototypical scenarios:



Neutrino physics

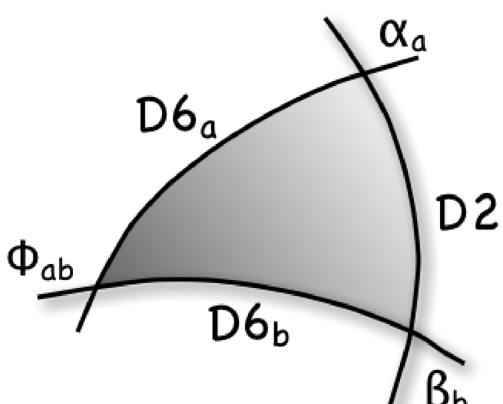


Neutrino Nature

Majorana or Dirac

- Involve O(1) D-brane instantons
- Large M_s, instanton cycle small
- Specific intersection angles with SM branes. In practice not easy

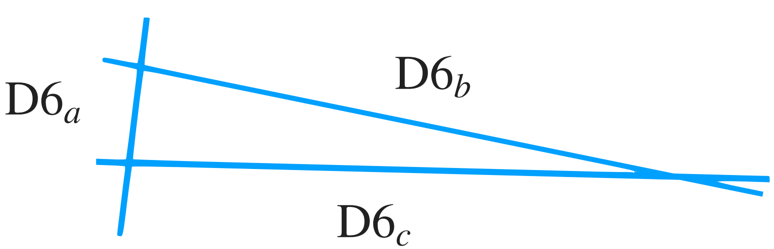
Blumenhagen, Cvetic, Weigand'06
Ibáñez & Uranga'06



$$\nu_R\nu_R\, M_s e^{-2\pi T}$$

- Small Dirac masses arise at small angles: boundaries of field space
- Small 4d dilaton → M_s small
- Swampland criteria prefer Dirac over Majorana. Bound $m_\nu^{\rm min} \lesssim \Lambda_{\rm cc}^{1/4}$

Ibáñez, Martin-Lozano, Valenzuela'17
Hamada & Shiu'17




Neutrinos @ infinite
distance

How to get small Dirac neutrino masses

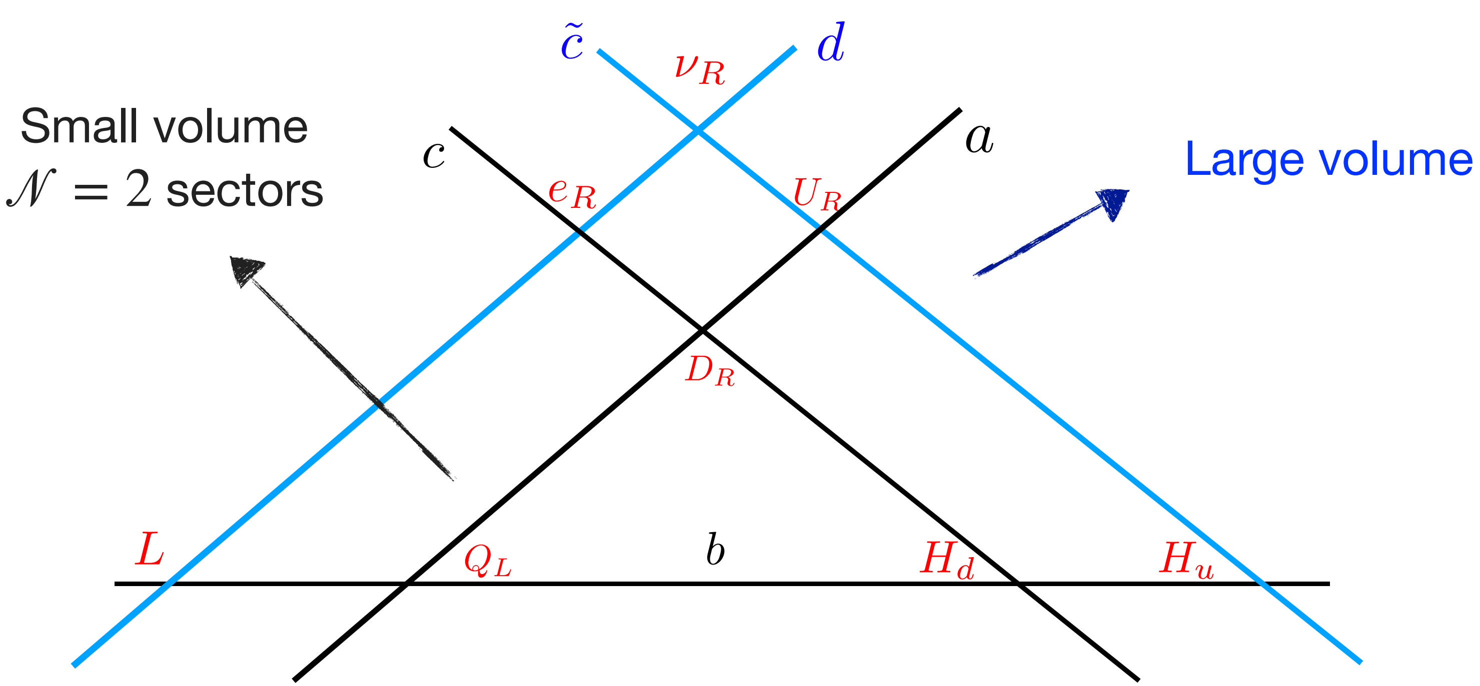
Example: five-stack D-brane model

Aldazábal et al. '00, Wijnholt & Verlinde '05
Antoniadis & Rondeau '21

$$SU(3) \times SU(2) \times U(1)_a \times U(1)_b \times U(1)_c \times U(1)_{\tilde{c}} \times U(1)_d$$

$$Q_Y = \frac{2}{3}Q_a + \frac{1}{2}Q_b + Q_c \qquad Q_\nu = Q_{\tilde{c}} - Q_d$$

$$g_a, g_b, g_c \sim \text{const}\,. \qquad g_\nu \to 0$$



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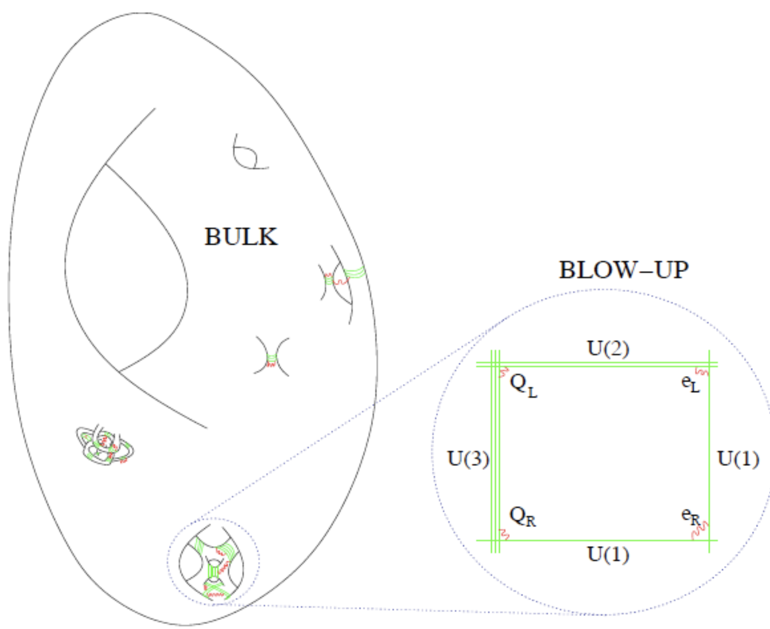
Mirror type IIB picture:



Small volume
$\mathcal{N} = 2$ sectors

How to get small Dirac neutrino masses

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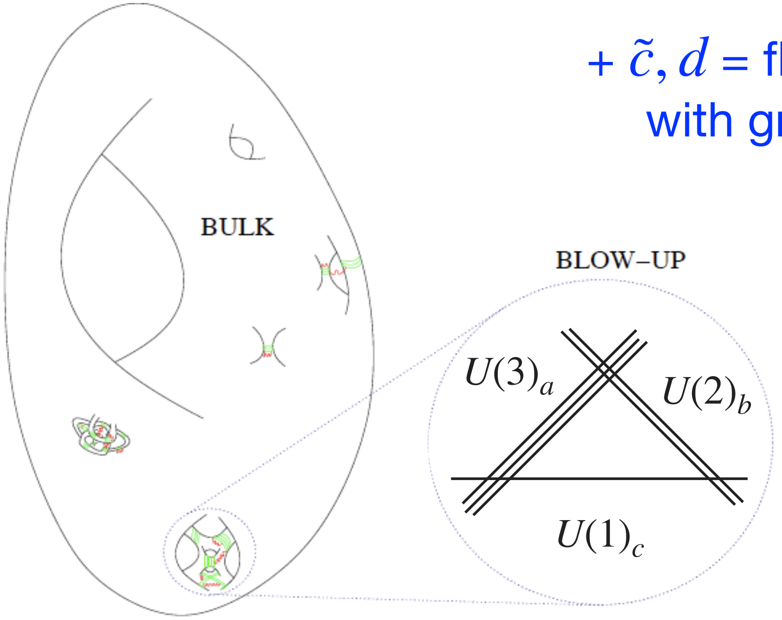
$$Q_\nu = Q_{\tilde{c}} - Q_d$$

$$g_\nu \to 0$$

Mirror type IIB picture:



+ $\tilde{c}, d$ = flavour D7-branes with growing volume

How to get small Dirac neutrino masses

Example: five-stack D-brane model

Aldazábal et al. '00, Wijnholt & Verlinde '05
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$$SU(3)\times SU(2)\times U(1)_a\times U(1)_b\times U(1)_c\times U(1)_{\tilde{c}}\times U(1)_d$$

$$Q_Y = \frac{2}{3}Q_a + \frac{1}{2}Q_b + Q_c \qquad\qquad Q_\nu = Q_{\tilde{c}} - Q_d$$

We grow the modulus that controls g_ν

$$\mathrm{Re}\, f_{\nu\nu} = u \to \infty \implies g_\nu \simeq \frac{1}{u^{1/2}} \to 0$$

Due to $U(1)_\nu$ anomaly cancellation FI-terms shrink:

$$m_{\mathrm{gon},\nu} \sim \frac{M_\mathrm{P}}{u} \sim g_\nu^2 M_\mathrm{P}$$

Yukawa $Y_{\nu,ij} H_u L^i \nu_R^j$:

$$Y_{\nu,ij} \simeq e^{-\phi_4}\left(\frac{m^i_{\mathrm{gon},\nu}}{M_\mathrm{P}}\right)^{1/2}\left(\frac{m^j_{\mathrm{gon},L}}{M_\mathrm{P}}\right)^{1/2}\left(\frac{m_{\mathrm{gon},H_u}}{M_\mathrm{P}}\right)^{1/2} \simeq \left(\frac{m^i_{\mathrm{gon},\nu}}{M_\mathrm{P}}\right)^{1/2} \simeq g_\nu$$

The neutrino scales

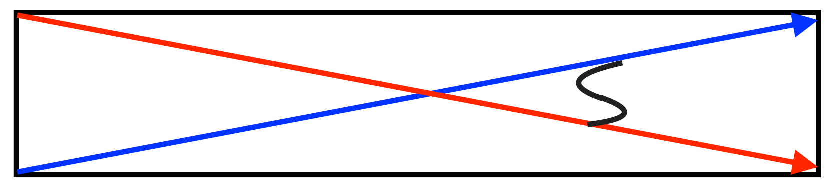
$g_\nu \sim u^{-1/2} \to 0$

$m_{\text{gon},\nu} \sim g_\nu^2 M_{\text{P}}$

$Y_{\nu,ij} \sim g_\nu$

Case in which two dimensions open up:

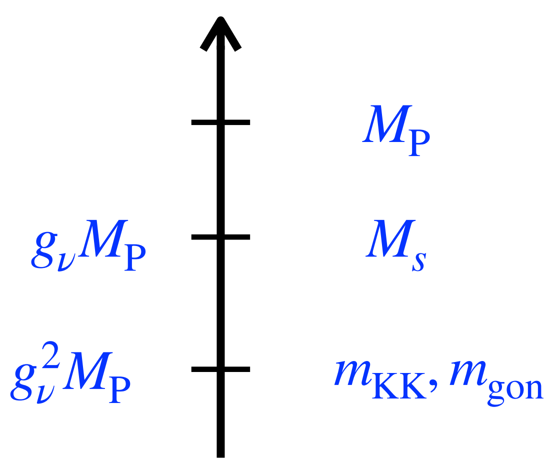
$m_{\text{KK}} \sim m_{\text{winding}} \sim g_\nu^2 M_{\text{P}}$



Species scale = string scale

$\Lambda_{\text{sp}} \simeq M_s \simeq g_\nu M_{\text{P}}$

See Gonzalo F. Casas' talk



All scales fixed in terms of g_ν

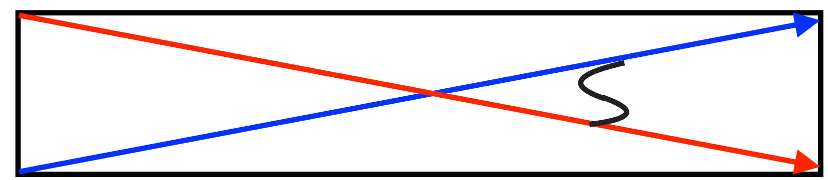
The neutrino scales

$$g_\nu \sim u^{-1/2} \to 0$$

$$m_{\text{gon},\nu} \sim g_\nu^2 M_{\text{P}} \qquad Y_{\nu,ij} \sim g_\nu$$

Case in which two dimensions open up:

$$m_{\text{KK}} \sim m_{\text{winding}} \sim g_\nu^2 M_{\text{P}}$$



Species scale = string scale $\Lambda_{\text{sp}} \simeq M_s \simeq g_\nu M_{\text{P}}$

See Gonzalo F. Casas' talk

Assuming $Y_{\nu,i} \simeq Y_\nu \simeq 7 \times 10^{-13}$:

String Scale	SM gonions	ν_R tower	large dim	Vector boson	Gravitino
M_s	$m_{\text{gon}}^{\text{SM}}$	m_{gon}^{ν}	$m_{\text{KK/w}}$	M_{V_ν}	$m_{3/2}$
$g_\nu M_{\text{P}}$	$\lesssim M_s$	$g_\nu^2 M_{\text{P}}$	$g_\nu^2 M_{\text{P}}$	$g_\nu \lvert \bar{H} \rvert - g_\nu M_{\text{P}}$	$\lesssim M_s^2/M_{\text{P}}$
$g_\nu = Y_{\nu,3}$, 700 TeV	$\lesssim$ 700 TeV	500 eV	500 eV	0.5 eV- 700 TeV	$\lesssim$ 500 eV

M_s too low for more than two large dimensions!!

The cosmological constant and neutrinos

Ibáñez, Martin-Lozano, Valenzuela'17
Hamada & Shiu'17
Gonzalo, Ibáñez, Valenzuela'21

By compactifying the SM on a circle, Swampland criteria [AdS instability and AdS distance Conjectures] provide the following bound for Dirac neutrinos:

$$m_\nu^{\rm min} \lesssim \Lambda_{\rm cc}^{1/4}$$

Using that $m_{\nu,i} \simeq Y_{\nu,i}\langle H_u \rangle \implies$ $$Y_\nu^{\rm min} \lesssim \frac{\Lambda_{\rm cc}^{1/4}}{M_{\rm EW}}$$

$\implies$ gonion tower $\implies$ two large dimensions

similar to Castellano, Ibáñez, Herráez'23

Conclusions

- In the context of SM-like type IIA orientifold compactifications, we have explored limits of small Yukawa couplings.

- Small Yukawas always come with i) a light tower of gonions (massive replicas of the chiral fields at the intersection) and ii) small gauge couplings. They appear at infinite distance boundaries of the moduli space.

- There is a wide casuistic, but things narrow down when we want to apply this setup to obtain realistic Dirac neutrino masses $\Longrightarrow$ universal scheme.

- Key model building feature: massive $U(1)_\nu$ under which right-handed neutrinos are charged, but independent of hypercharge: take $g_\nu \to 0$ (e.g. flavour 7-branes).

- All relevant scales fixed in terms of g_ν. Low string scale and two large dimensions, close to possible test in future colliders.

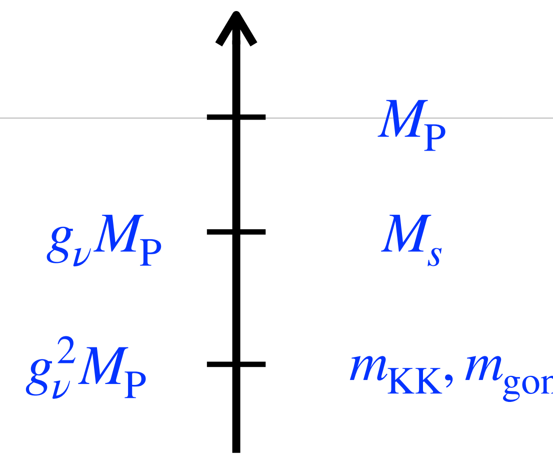

Thank you!

Backup Slides

Neutrino scales

$$g_\nu \sim u^{-1/2} \to 0$$

$$Y_{\nu,i} \sim g_\nu \delta^i \qquad i = 1,2,3$$



String Scale	SM gonions	ν_R tower	large dim	Vector boson	Gravitino
M_s	$m_{\mathrm{gon}}^{\mathrm{SM}}$	m_{gon}^{ν}	$m_{\mathrm{KK/w}}$	M_{V_ν}	$m_{3/2}$
$g_\nu M_{\mathrm{P}}$	$\lesssim M_s$	$g_\nu^2 M_{\mathrm{P}}$	$g_\nu^2 M_{\mathrm{P}}$	$g_\nu \lvert\bar{H}\rvert - g_\nu M_{\mathrm{P}}$	$\lesssim M_s^2/M_{\mathrm{P}}$
$g_\nu = Y_{\nu,3}$, 700 TeV	$\lesssim$ 700 TeV	500 eV	500 eV	0.5 eV- 700 TeV	$\lesssim$ 500 eV
$g_\nu = Y_{\nu,1}$, 10 TeV	$\lesssim$ 10 TeV	0.1 eV	0.1 eV	10^{-3} eV- 10 TeV	$\lesssim$ 0.1 eV

Table 3: Spectrum of masses and scales from imposing Dirac character to neutrino masses in string theory. Numerical results are shown for two limiting cases with $g_\nu \simeq Y_{\nu,3} \simeq 7 \times 10^{-13}$ and $g_\nu \simeq Y_{\nu,1} \simeq 10^{-14}$.