The Tadpole Conjecture in non-geometric backgrounds

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Work in collaboration with

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Introduction

- Flux compactifications: building block in string pheno because of moduli stabilization

Dasgupta, Rajesh, Sethi 99

Giddings, Kachru, Polchinski 01

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(2) fluxes induce positive charges that need to be cancelled globally   Maldacena, Nuñez 00

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(1) IIB/F-theory most studied setup: flux solutions $M_{\text{ink}4} \times_w \text{CY}$

$\longrightarrow$ Drawback: odd fluxes $(H_3, F_3) \Rightarrow$ only complex structure mod stabilized

Kähler moduli not stabilized

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(2) Common lore: fluxes that have $\mathcal{O}(1)$ charge can stabilize a large number of moduli

- Tadpole conjecture: common lore not true!

The tadpole conjecture

Bena, Blåbäck, M.G., S. Lüst 20

For a large number of moduli stabilized at a generic point in moduli space, the induced charge N_{flux} satisfies

$$N_{\text{flux}} > \alpha\, n_{\text{stab}}$$

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(3) Very nice byproduct! Stay awake longer

Tadpole cancelation condition

- Fluxes induce D3-charge. In a compact space total charge should be zero

• In type IIB with 3-form fluxes

$$N_{\text{flux}} = \int F_3 \wedge H_3 \leq |Q_{O3}|$$

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• D7-branes wrapped on 4 cycles also have negative charge (and D7-moduli)

• Unified description in F-theory

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$$N_{\text{flux}} = \frac{1}{2} \int G_4 \wedge G_4 \quad \leq \frac{\chi(CY_4)}{24}$$

H_3 , F_3 and flux on D7

all the negative 3-charge from D7/O7

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H_3 , F_3 and flux on D7 (↑ G_4)

all the negative 3-charge from D7/O7 (↑ $\frac{\chi(CY_4)}{24}$)

$$\frac{\chi}{24} = \frac{1}{4}(h^{3,1} + h^{1,1} - h^{2,1} + 8)$$

c.s., dilaton and D7 moduli (can be stabilized by G_4) (↓ $h^{3,1}$)

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$$N_{\text{flux}} = \frac{1}{2}\int G_4 \wedge G_4 \leq \frac{\chi(CY_4)}{24} \sim \frac{1}{4} h^{3,1}$$

for large $h^{3,1}$

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all the negative 3-charge from D7/O7

Tadpole conjecture

$$N_{\text{flux}} > \alpha n_{\text{stab}}$$

If $\alpha > \frac{1}{4}$, cannot stabilize all moduli in F-theory (if number is large)!

Supporting examples for $\frac{N_{\rm flux}}{n_{\rm stab}} > \frac{1}{3}$ in CY

Description	$n_{\rm stab}$	$N_{\rm flux}$	$\alpha = \frac{N_{\rm flux}}{n_{\rm stab}}$	Ref
IIB at symm pt in mod space	$h^{2,1} = 128$	48	0.38	Giryavets, Kachru, Tripathy, Trivedi 03
	$h^{2,1} = 272$	124	0.46	Demirtas, Kim, Mc Allister, Moritz 19
F-theory on sextic CY at symm point	$h^{3,1} = 426$	775/4 587/4	0.45 0.34	Braun, Valandro 20 Braun, Fortin, Lopez Garcia, Villaflor Loyola 24
F-theory on $\mathbb{CP}^3$ base	$n_7 = 3728$	1638	0.44	Collinucci, Denef Esole 08
F-theory on K3xK3	$n_{\rm mod} = 57$	25	0.44	Bena, Blåbäck, M.G., Lust 20
IIB on (3,51) CY_3 at large complex structure	95	32	0.34	Coudarchet, Marchesano, Prieto, Urkiola '23

Supporting examples for linear behavior $N_{\text{flux}} > \alpha\, n_{\text{stab}}$

Description	n_{stab}	N_{flux}	$\alpha = \frac{N_{\text{flux}}}{n_{\text{stab}}}$	Ref
F-theory on any weak-Fano base	$n_7 = 58c_1^3(B) + 16$	$\frac{7}{16}(58c_1^3(B) + 15)$	0.44	Bena, Brodie, M.G. 21
F-theory on CY in asympt region (large complex structure or close to conifold)	$n_{\text{stab}} \leq n_{\text{mod}}$	$\alpha\, n$	In all exemples out of a large set $\alpha > 0.7$	M.G., Grimm, van de Heisteeg, Herraez, Plauschinn 22

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HERE!				

Non-geometric backgrounds:

mirror duals of rigid Calabi-Yau manifolds

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mirror duals of rigid Calabi-Yau manifolds

Hodge diamond of a Calabi-Yau

$$
\begin{array}{ccccccc}
 & & & 1 & & & \\
 & & 0 & & 0 & & \\
 & 0 & & h^{1,1} & & 0 & \\
1 & & h^{2,1} & & h^{1,2} & & 1 \\
 & 0 & & h^{2,2} & & 0 & \\
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On the two-dimensional (2,2) SCFT on the world-sheet of strings in CY:

$h^{2,1}$: marginal deformations in the (c,c) ring

$h^{1,1}$: marginal deformations in the (a,c) ring

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Lecher, Vafa, Warner '89

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mirror symmetry ⟷

$h^{1,1} = 0$!

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No volume form

$J \wedge J \wedge J = \text{vol}$

↑

$\in h^{1,1}$

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But perfectly fine from the world-sheet point of view

Description in terms of Landau-Ginzburg models — Vafa '89

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Description in terms of Landau-Ginzburg models Vafa '89

Standard notions in geometric flux compactifications (flux superpotential, tadpole) still apply

Becker, Becker, Vafa, Walcher '06

IIB Landau Ginzburg models with flux

- $h^{2,1}$ complex structure moduli ((c,c) marginal deformations or RR ground states in CFT)

- Add 3-form fluxes

$$\int_{\Gamma_n} F_3 = M^n \quad (\in \mathbb{Z}) \qquad \int_{\Gamma_n} H_3 = K^n \qquad n = 1, \dots, 2h^{2,1} + 2$$

basis of 3-cycles (susy cycles wrapped by A-branes ↔ bdy cond in the CFT)

- 4d $\mathcal{N} = 1$ EFT

$$G_3 = F_3 - \tau H_3$$

$$V = e^K \left(|D_I W|^2 - 3|W|^2 \right) \quad \text{with} \quad W = \int_{CY} G_3 \wedge \Omega \sim (M - \tau K) f(z)$$

Becker, Becker, Vafa, Walcher 06

exact (no perturbative or non-perturbative corrections)

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Becker, Becker, Vafa, Walcher 06

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Gukov, Vafa, Witten 99

exact (no perturbative or non-perturbative corrections)

IIB Landau Ginzburg models with flux

- In the 4d $\mathcal{N} = 1$ EFT $\quad V = e^K\left(|DW|^2 - 3|W|^2\right) \quad W = \int_{CY} G_3 \wedge \Omega \sim (M - \tau K) f(z^I)$

- Minima at

  - $D_I W = 0 \rightarrow$ equation for complex structure moduli: get a vev depending on M^n, K^n

$$D_I W = \int_{CY} G_3 \wedge \chi_I \qquad \Rightarrow G^{(1,2)} = 0$$

IIB Landau Ginzburg models with flux

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- Tadpole cancelation condition $\quad N_{\text{flux}} = \int F_3 \wedge H_3 = \underbrace{M^n K_n}_{> 0} \leq |Q_{O3}|$

  at Mink minimum $H_3 = \star F_3$

Landau Ginzburg models

Vafa '89

Lerche, Vafa, Warner '89

- 2d $\mathcal{N} = (2{,}2)$ theories of r chiral fields $\Phi_i,\ i = 1,\ldots,r$

$$S_{2d} = \int d^2z\, d^4\theta\, \mathcal{K}(\Phi_i, \bar{\Phi}_i) + \int d^2z\, d^2\theta\, \mathcal{W}(\Phi_i)$$

world-sheet Kähler potential

world-sheet superpotential

$$\mathcal{W}(\lambda^{\omega_i}\Phi_i) = \lambda^d \mathcal{W}(\Phi_i)$$

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E.g. $k_1 = k_2 = \ldots k_r = k$ $\quad g(\Phi_i) = e^{i\omega}\Phi_i \quad \omega = 2\pi/(k+2)$

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- Lead to 4-dimensional $\mathcal{N} = 2$ string vacua (as CY)

Landau Ginzburg orbifolds

- Can orientifold; quotient by $\Omega\,\sigma$. $\mathscr{W}(\sigma(\Phi)) = -\mathscr{W}(\Phi)$

  E.g. in k^r model $(\mathscr{W} = \sum_{i=1}^{r} \Phi_i^{k+2})$ can take $\sigma(\Phi_i) = e^{i\pi/(k+2)}\Phi_i$

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$$\begin{array}{ccccccc} & & & 1 & & & \\ & & 0 & & 0 & & \\ & 0 & & 0 & & 0 & \\ 1 & & 63 & & 63 & & 1 \\ & 0 & & 0 & & 0 & \\ & & 0 & & 0 & & \\ & & & 1 & & & \end{array}$$

2^6

$$\begin{array}{ccccccc} & & & 1 & & & \\ & & 0 & & 0 & & \\ & 0 & & 0 & & 0 & \\ 1 & & 90 & & 90 & & 1 \\ & 0 & & 0 & & 0 & \\ & & 0 & & 0 & & \\ & & & 1 & & & \end{array}$$

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With $\sigma(\Phi_1,\ldots,\Phi_9) = -(\Phi_2,\Phi_1,\Phi_3,\ldots,\Phi_9)$ $\qquad \sigma(\Phi_1,\ldots,\Phi_6) = ie^{i\pi/4}(\Phi_1,\ldots,\Phi_6)$

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$|Q_{O3}| = 12$

mirror of $\dfrac{T^6}{\mathbb{Z}_3 \times \mathbb{Z}_3}$

$|Q_{O3}| = 40$

mirror of $\dfrac{T^6}{\mathbb{Z}_4 \times \mathbb{Z}_4}$

Moduli stabilisation in these Landau Ginzburg models

Becker, Becker, Vafa, Walcher 06

Moduli Stabilization in Non-Geometric Backgrounds

Katrin Becker[a], Melanie Becker[a], Cumrun Vafa[b], and Johannes Walcher[c]

Abstract

Type II orientifolds based on Landau-Ginzburg models are used to describe moduli stabilization for flux compactifications of type II theories from the world-sheet CFT point of view. We show that for certain types of type IIB orientifolds which have no Kähler moduli and are therefore intrinsically non-geometric, all moduli can be *explicitly* stabilized in terms of fluxes. The resulting four-dimensional theories can describe Minkowski as well as Anti-de-Sitter vacua. This construction provides the first string vacuum with all moduli frozen and leading to a 4D Minkowski background.

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$\longrightarrow 1^9 \; : \; N_{\text{flux}} > \frac{1}{3} 63 = 21$

If $\quad N_{\text{flux}} > \frac{1}{3} n_{\text{stab}} \quad \Rightarrow$ to fix all moduli need

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If $N_{\text{flux}} > \frac{1}{3} n_{\text{stab}} \Rightarrow$ to fix all moduli need $\longrightarrow 1^9 : N_{\text{flux}} > \frac{1}{3} 63 = 21$ but $|Q_{O3}| = 12!$

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Moduli

- Moduli: Deformations of $\mathscr{W}$ (for concreteness all that follows for 2^6)

$$\mathscr{W} = \sum_{i=1}^{6} \Phi_i^4 + \sum_{L=1} t^L \, \Phi^{\mathbf{L-1}}$$

$$\Phi^{\mathbf{L-1}} \equiv \Phi_1^{l_1-1} \, \Phi_2^{l_2-1} \ldots \Phi_6^{l_r-1}$$

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$\Sigma\, l_i$	6	10	14	18
(p, q)	(3,0)	(2,1)	(1,2)	(0,3)

L: complex forms

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(1,1,1,1,1,1) → 6; (3,3,3,3,3,3) → 18

$\Sigma \, l_i$	6	10	14	18
(p, q)	(3,0)	(2,1)	(1,2)	(0,3)

L: complex forms

Fluxes & Moduli stabilisation

- Fluxes

$\in \mathbb{Z}$

$$\int_{\Gamma_N} F_3 = M^N \quad \int_{\Gamma_N} H_3 = K^N$$

$L = (l_1, \ldots, l_6)$ $l_i = 1,2,3$

$N = (n_1, \ldots, n_6)$ $n_i = 0,1,2$

L: complex forms

N: real cycles / forms

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- Moduli stabilisation

$$W = \int G_3 \wedge \Omega = \sum_N (M^N - \tau K^N)\,\Omega_N\,, \qquad \Omega_N = \int_{\Gamma_N} e^{-\mathscr{W}(\Phi,t)}\, d^4\Phi \sim \sum_p t_1 \ldots t_p\, i^{(L_1+\ldots+L_p)\cdot N}$$

Fluxes & Moduli stabilisation

- Massive moduli

$$\Sigma\, l_i = 10 \;\Rightarrow I$$

$$n_{\rm mass} = {\rm rank}\, M \qquad \Sigma\, l_i = 14 \;\Rightarrow \bar{I}$$

$$M = DD\, W = \begin{pmatrix} D_I D_J W & D_I D_{\bar{J}} \bar{W} \\ D_{\bar{I}} D_J W & D_{\bar{I}} D_{\bar{J}} \bar{W} \end{pmatrix}$$

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- Note!

$$n_{\text{mass}} \leq n_{\text{stab}} < 3\, N_{\text{flux}}$$

tadpole conjecture

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tadpole conjecture

- Here testing a weaker form of tadpole conjecture

Two alternative procedures

- Turn on G_3 on one, two, three,… L^I component ($\Sigma\, l_i = 10$)

  $\longrightarrow \in H^{(2,1)}$ automatic

  $\longrightarrow M^N, K^N \in \mathbb{Z}$ to be imposed

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- Can be done exhaustively (using S_6 permutations) up to ~ 8 components
- Beyond: use algorithms for smart search (start from a set of minimal length vectors)
- Compute $N_{\rm flux}$, $n_{\rm mass}$

$$N_{\rm flux} = \int F_3 \wedge H_3 = M^N K_N$$

$$N_{\rm flux} = \frac{i}{\tau - \bar{\tau}} \int G_3 \wedge \bar{G}_3 = \frac{1}{2\tau_2} \,|\, G_I |^2$$

$$n_{\rm mass} = {\rm rank}\, (\partial_I \partial_J W)$$

Results: 1^9

Becker, Gonazlo, Walcher, Wrase '22
Becker, Brady, Sengupta '23
Becker, Rajagaru, Sengupta, Walcher, Wrase '24

$$|Q_{O3}| = 12$$
$$h^{2,1} = 63$$

$$\tau = e^{2\pi i/3}$$

Not weak coupling!

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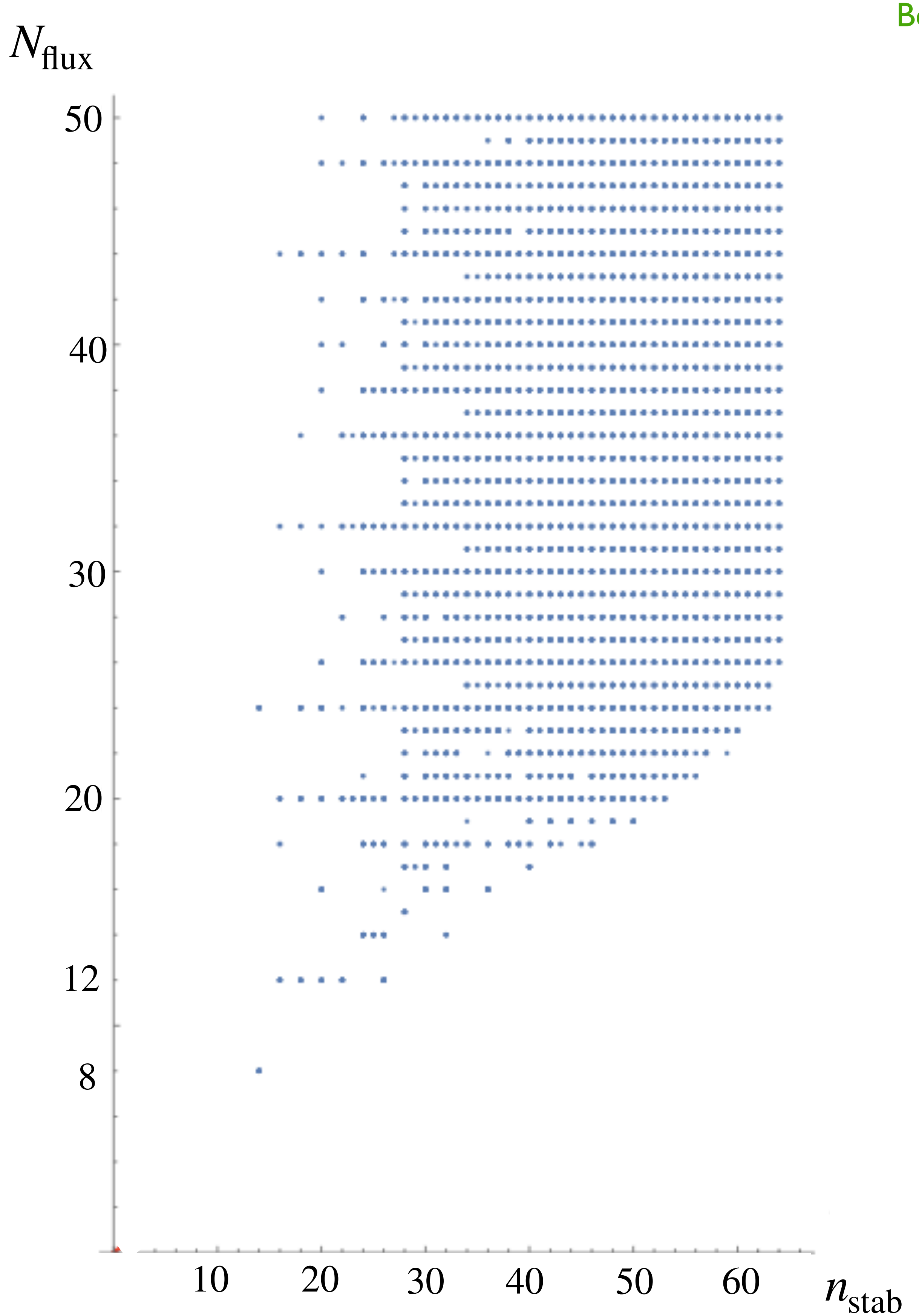

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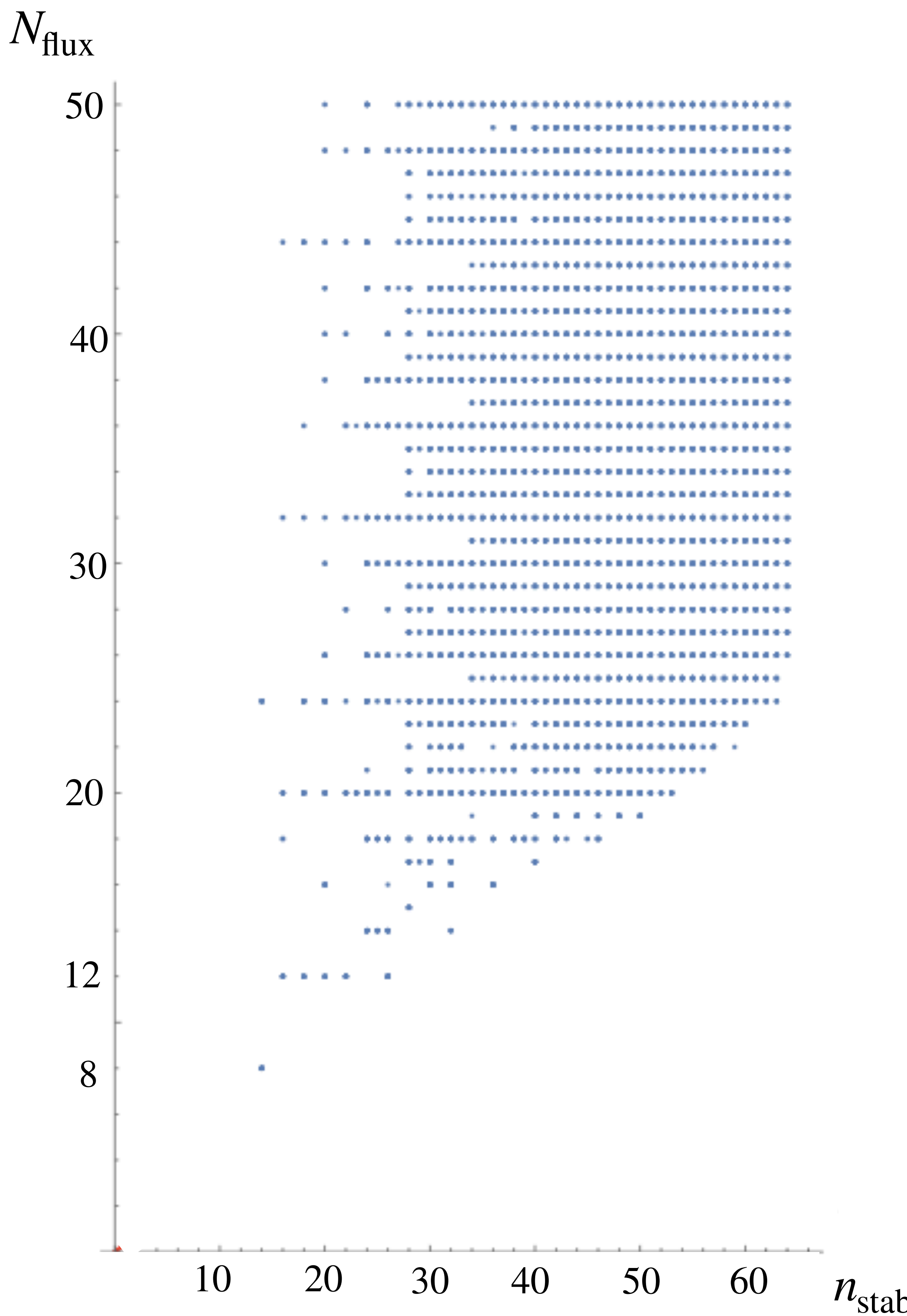

Tadpole conjecture

$$N_{\rm flux} > \alpha n_{\rm stab}$$

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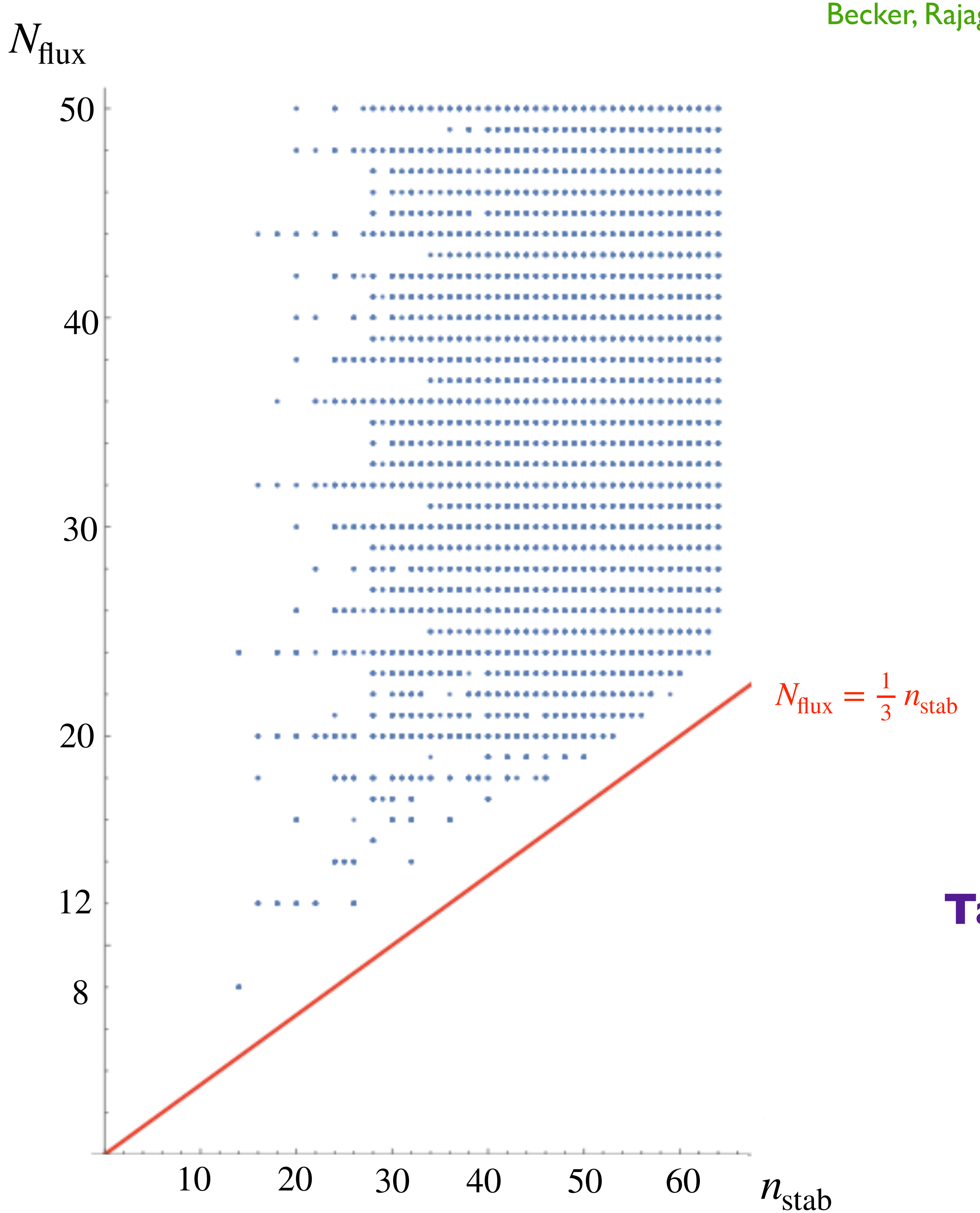

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$$N_{\text{flux}} > \frac{1}{3} n_{\text{stab}}$$

Results: 2^6

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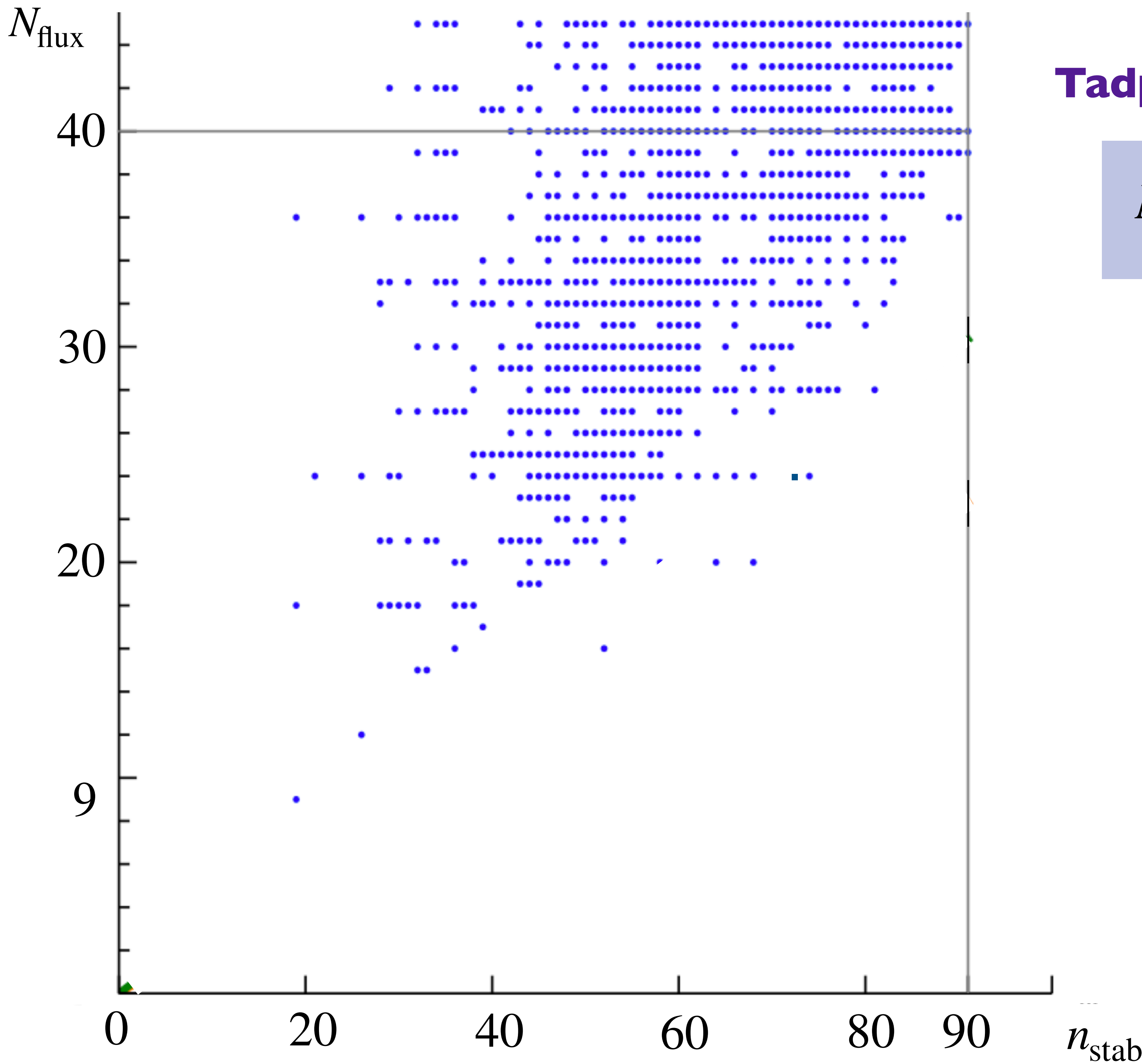

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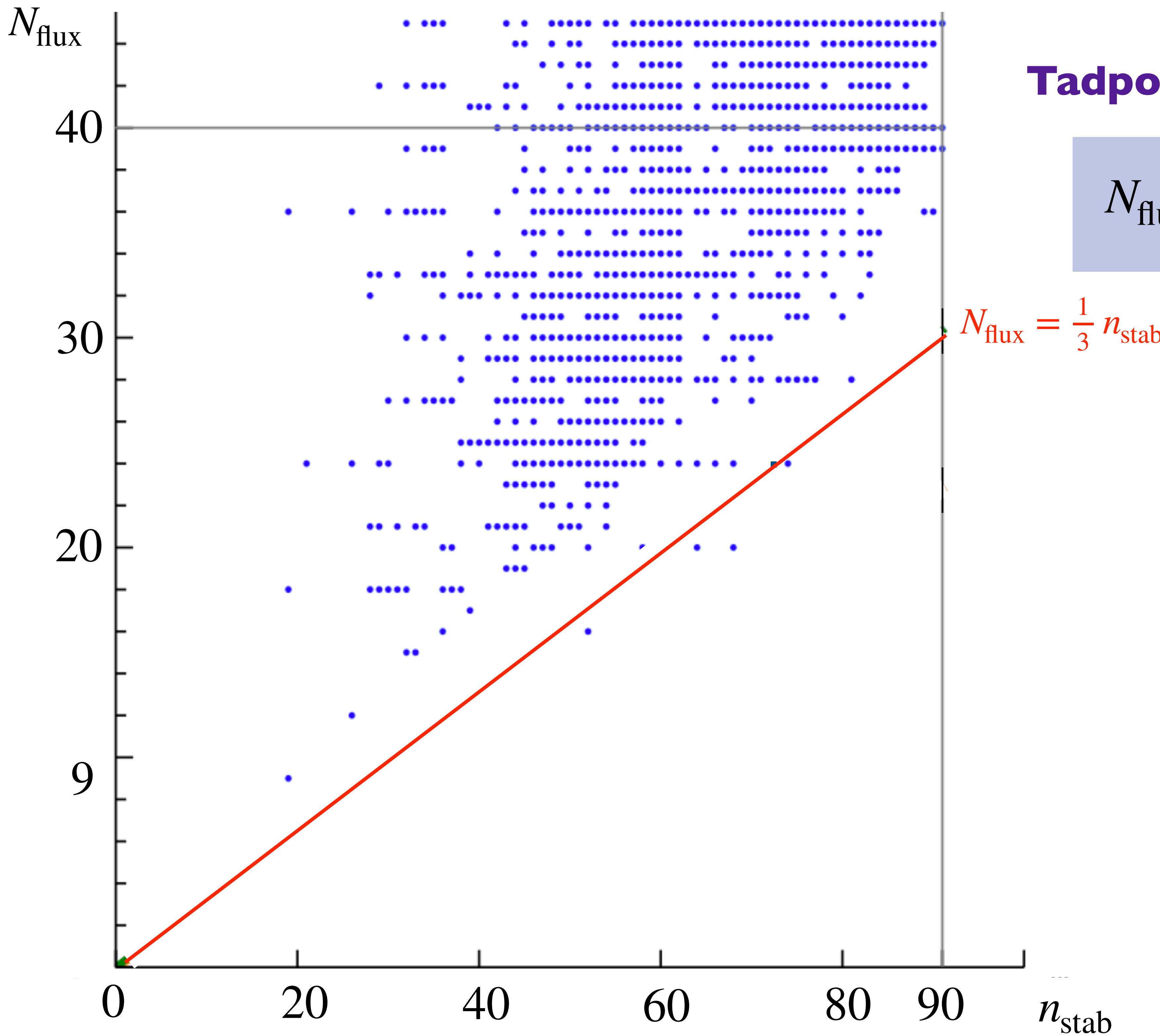

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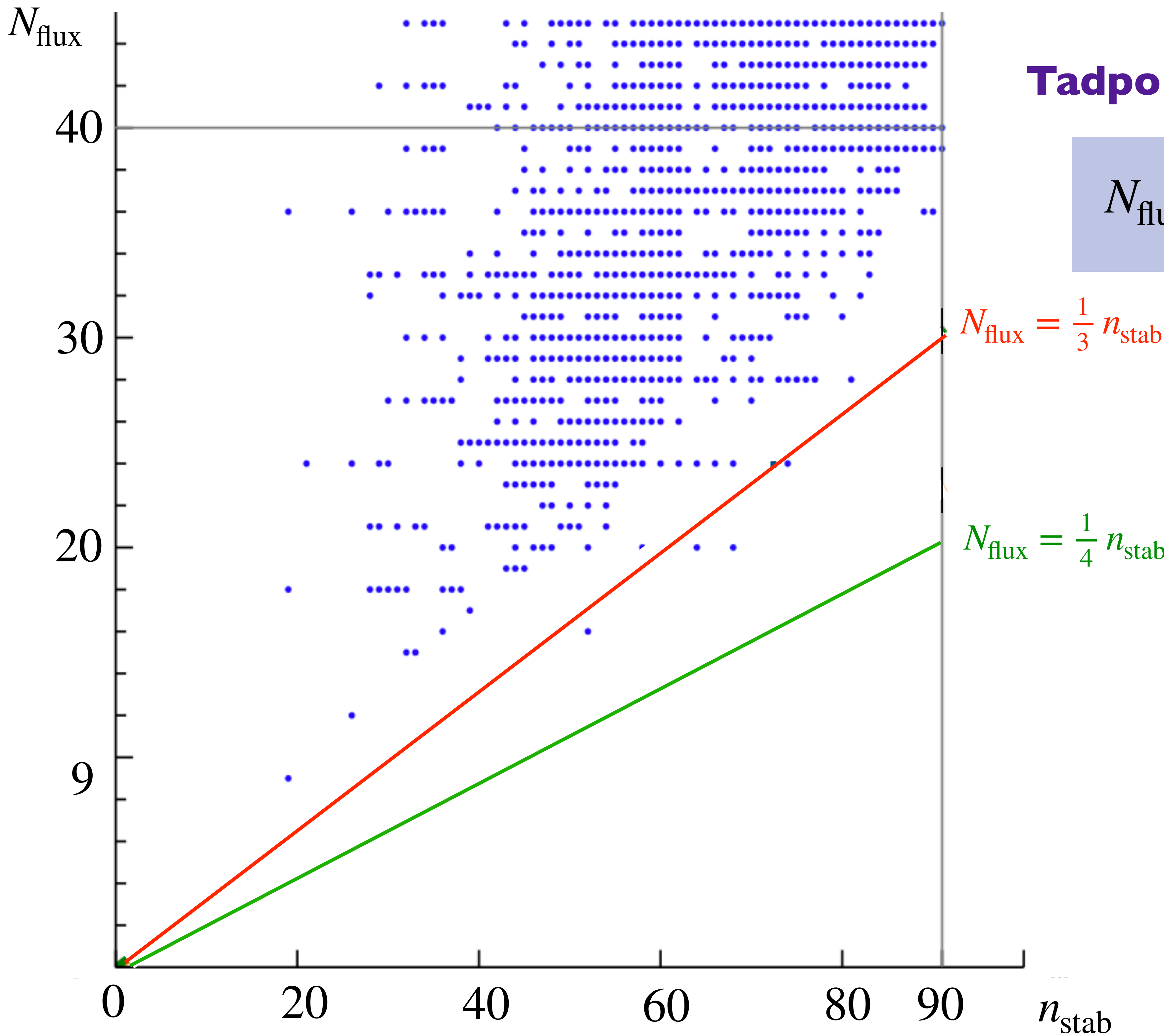

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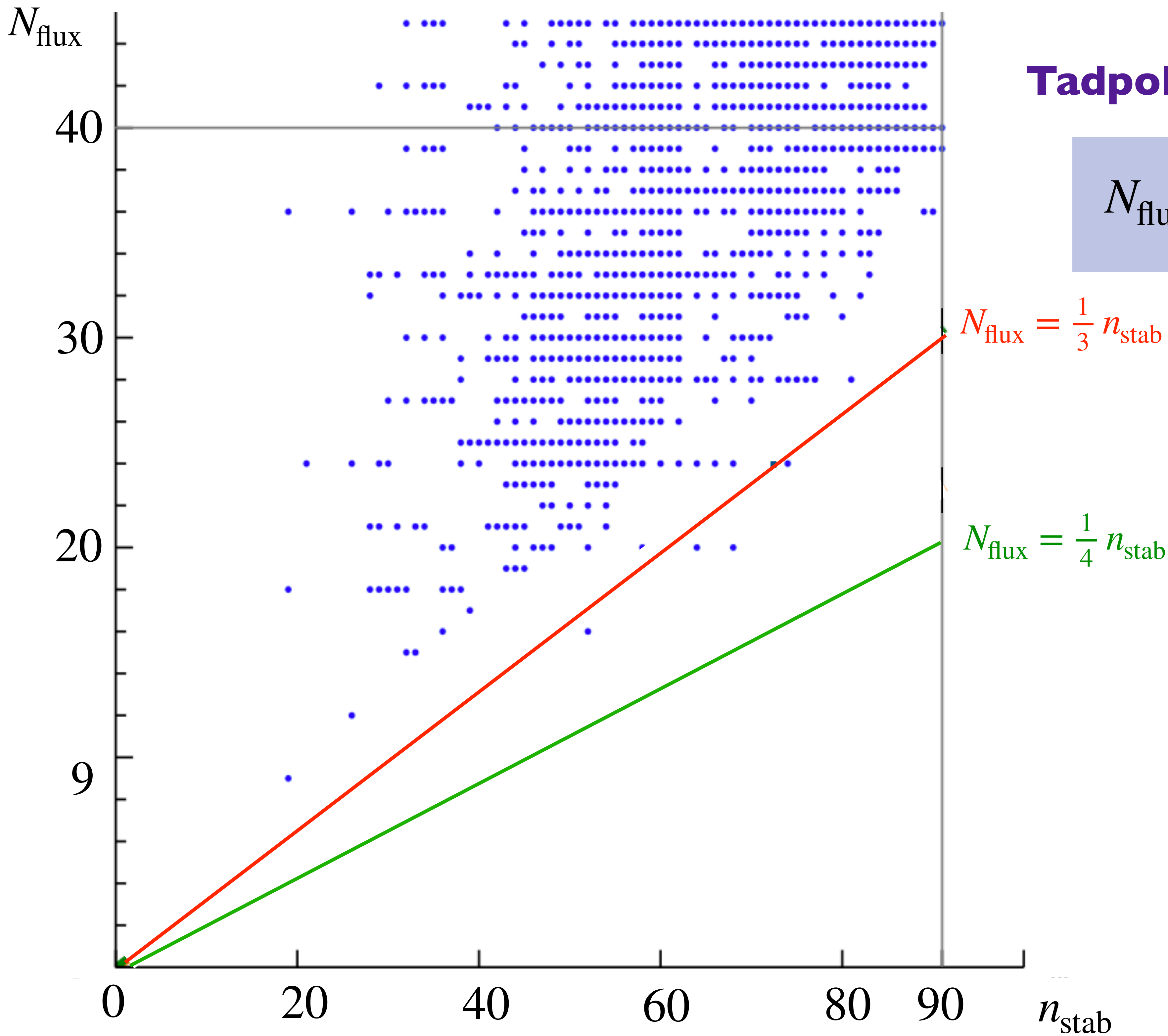

Tadpole conjecture

$$N_{\text{flux}} > \frac{1}{4} n_{\text{stab}}$$

In F-theory tadpole cond: $N_{\text{flux}} \leq \frac{\chi}{24} \simeq \frac{1}{4} n_{\text{mod}}$

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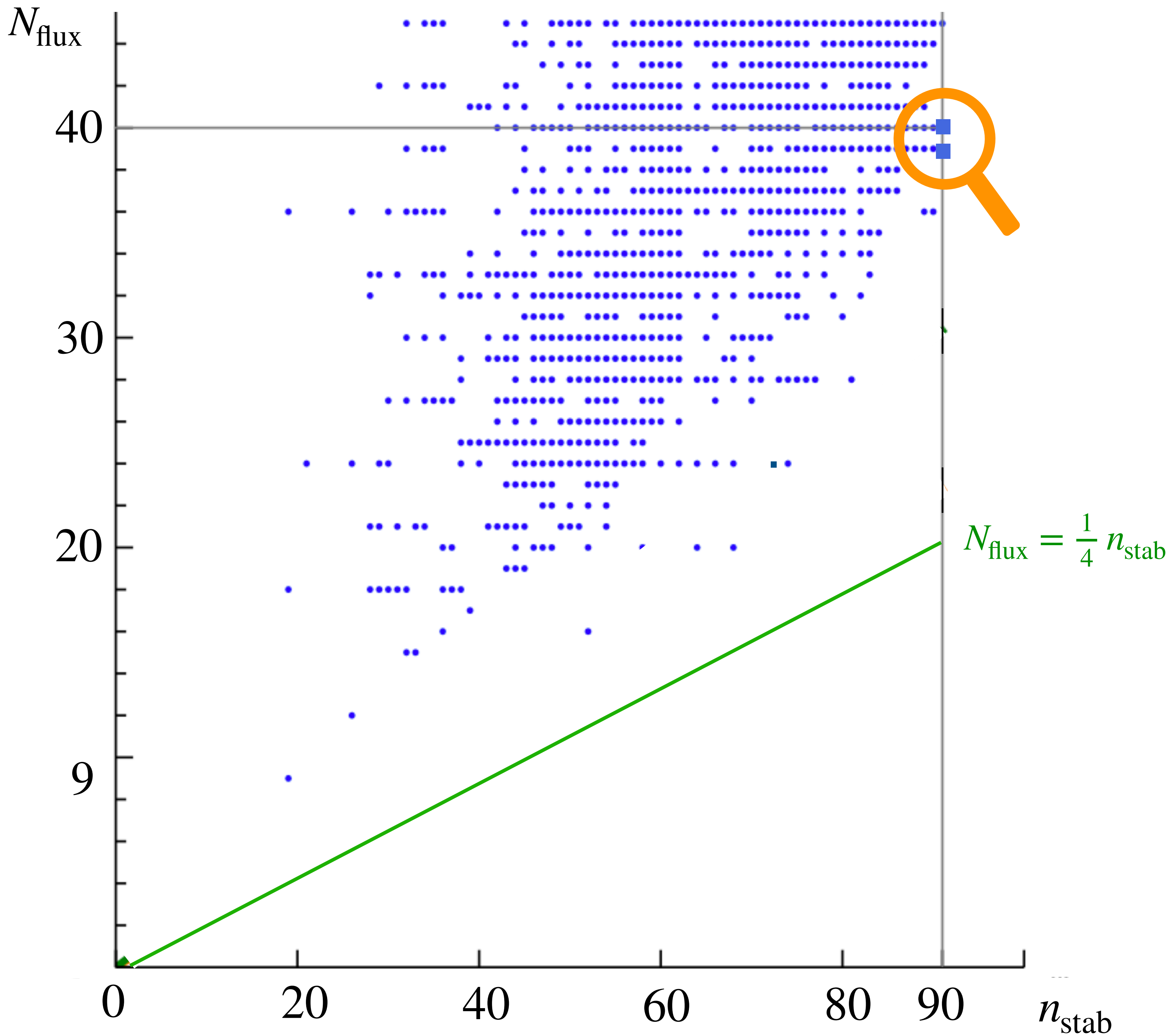

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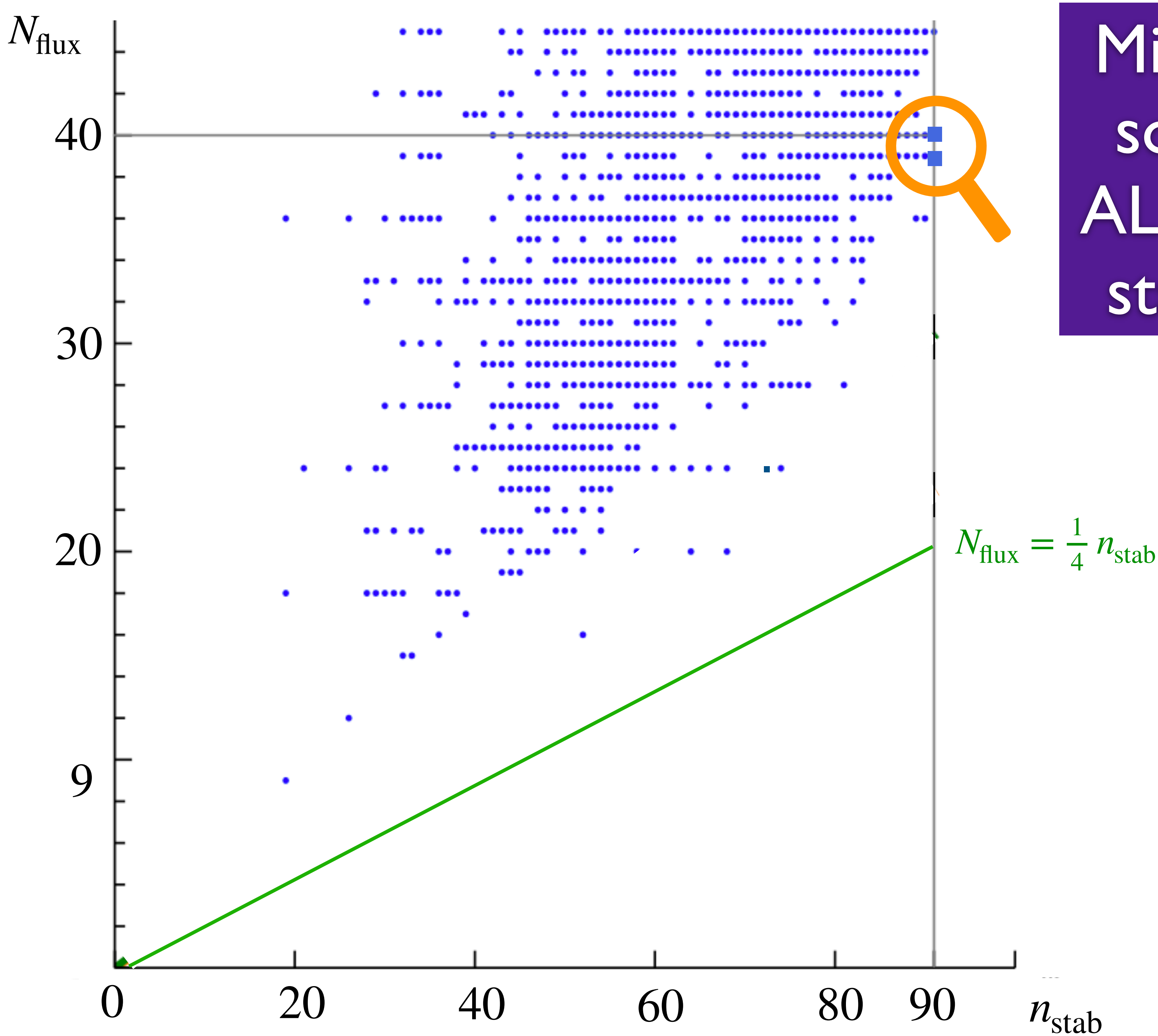

Minkowski sols. with ALL moduli stabilised!

One solution with all moduli stabilised with $N_{flux} = 40$

$$
\begin{aligned}
G = \frac{1}{128} [& -2i\chi_{111133} + (1+i)\chi_{111232} - (1+i)\chi_{112231} + 2i\chi_{113131} - (1+i)\chi_{121321} \\
& - \chi_{122212} + i\chi_{122221} + (1-i)\chi_{123121} - 2i\chi_{123211} + 2i\chi_{131311} - 2i\chi_{132112} \\
& + (1-i)\chi_{132211} + 2\chi_{133111} + (1+i)\chi_{211123} - \chi_{211222} + (1-i)\chi_{211321} + \chi_{212212} \\
& + 2i\chi_{213211} + \chi_{221212} + i\chi_{222112} + i\chi_{222211} - 2\chi_{223111} + 2i\chi_{231112} - 2\chi_{232111} \\
& - 2\chi_{311113} - (1+i)\chi_{311212} + 2i\chi_{311311} - 2i\chi_{312211} - 2i\chi_{321112} + 2\chi_{322111}]
\end{aligned}
$$

Conclusions

- Found the first Minkowski solutions with ALL moduli stabilised!

  -Massless Minkowski conjecture (always some massless modulus) does not apply beyond supergravity

  Andriot, Horer, Marconnet 22

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  -Coefficient $\alpha > \frac{1}{4}$ (vs original value $\frac{1}{3}$)

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We/many others checked massive, but results in 1^9 and 2^6 at higher order indicate also true with n_{stab}

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→ Does it apply beyond tadpole bound?

Yes!

Conclusions

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Probably yes $$M|_{DW=0} = \begin{pmatrix} D_I D_J W & g_{I\bar{J}} \bar{W} \\ g_{\bar{I}J} W & D_{\bar{I}} D_{\bar{J}} \bar{W} \end{pmatrix}$$

Shown e.g $W_0 \neq 0$ sol at point with discrete symmetry with $\frac{N_{\text{flux}}}{n_{\text{stab}}} = \frac{3}{1052}$

S.Lust, Wiesner22

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$N_{\rm flux} > \frac{1}{4}\, n_{\rm stab}$ at generic pt

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→ What does generic point mean?

A point where non-Abelian gauge symmetries is not generic (K3 x K3)

Bena, Blåbäck, M.G., Lüst 20

Braun, Fraiman, MG, Lust, Parra de Freitas 23

A point with discrete symmetries (Fermat) satisfies tadpole conjecture

Generic = no non-Abelian gauge symmetries?

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THANK YOU!