# New perspectives on the anti-D3-brane uplift

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Based on
2208.02826, 2212.07437 with Arthur Hebecker and Gerben Venken

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- Vacuum of theory at positive energy, controlled ??

$\Rightarrow$ Study possibilities to obtain positive cc from string theory

# Outline

# Compactification

- Additional six dimensions small and compact $\Rightarrow$ escape detection
- Ansatz: $\mathcal{M}_{10} = \mathcal{M}_{1,3} \times \mathcal{Y}$, $\mathrm{d}s^2 = \eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + g_{mn}\mathrm{d}y^m \mathrm{d}y^n$

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- Expand fields $\phi$ in eigenfunctions $\psi_n$ of $\mathcal{Y}$: $\phi(x, y) = \sum_{n=0}^{\infty} \phi_n(x)\psi_n(y)$
- $\phi_0$ massless, $\phi_n$ massive *KK modes*
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Example: 5D theory of free scalar field $\varphi$ on $\mathbb{R}^{1,3} \times S^1$ with radius $R$:

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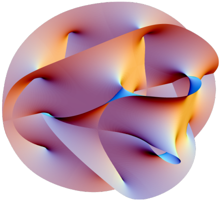
- Generalizes to compactifications on higher dim manifolds and all fields
- For 5d graviton: massless mode (*modulus*) of $g_{55}$ determines size of $S^1$!

# Compactification in string theory

$\mathcal{Y}$ typically Calabi-Yau manifold

- Solve 10D vacuum eoms since Ricci flat
- Preserve supersymmetry



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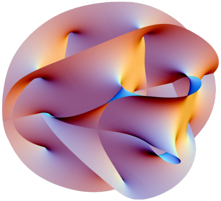
- Problem: 4D theory has many moduli (massless scalars) mediating fifth forces



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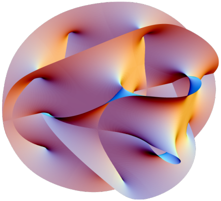

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$\Rightarrow$ Need to make moduli heavy by creating a scalar potential (*moduli stabilisation*)

# Moduli stabilisation

- Framework: type IIB string theory, effective $\mathcal{N} = 1$ supergravity in 4D
- Scalar potential $V$, $i, j = 0, \cdots, \#$cs moduli, $\alpha, \beta = 1, \cdots, \#$Kahler moduli

$$V = \mathrm{e}^{K}(K^{i\bar{\jmath}}(D_i W)(D_{\bar{\jmath}}\overline{W}) + K^{\alpha\bar{\beta}}(D_\alpha W)(D_{\bar{\beta}}\overline{W}) - 3|W|^2)$$

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  Kahler potential $K$, superpotential $W$
- Complex structure moduli stabilisation: $V = \mathrm{e}^K K^{i\bar{\jmath}}(D_i W)(D_{\bar{\jmath}}\overline{W})$
  - type IIB has 3-form flux $G_3$ living on 3-cycles
  - Intuitively: fluxes prevent cycles from shrinking
  - $W = W(G_3)$, solve $D_i W = 0$

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- General feature: Minimum of scalar potential at negative value $V_{\mathrm{AdS}} < 0$
- Minimum sets value of cc $\Rightarrow$ no accelerated expanding universe!
- Need to add source of positive energy *"uplift"*

# Anti-D3-brane uplift [Kachru et al '03]

- Anti-D3-brane contributes positive potential energy $\delta V = 2\,T_{D3}$
- Problem: Energy is too large $\Rightarrow$ runaway
- Mechanism to control size of uplift: *warped throats*

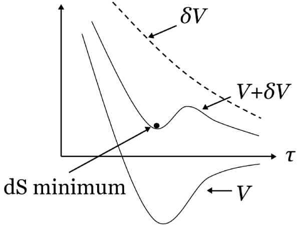
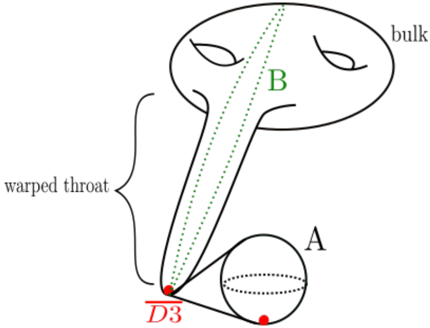



Figure: Illustration by A. Hebecker.

# Warped Klebanov-Strassler throat [Klebanov, Strassler '00, GKP '01]

- $\overline{D3}$ moves to tip of throat
- $M$ units of $F_3$ flux on A-cycle
- $K$ units of $H_3$ flux on B-cycle

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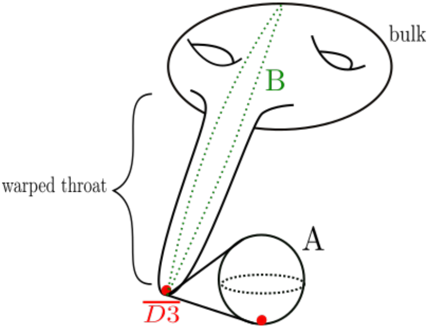
- $K$ units of $H_3$ flux on B-cycle
- $\overline{D3}$ at tip contributes $\delta V = 2T_{D3} \exp(4A(0))$
- Warp factor at tip: $\exp(4A(0)) \sim \exp(-K/(g_s M))$

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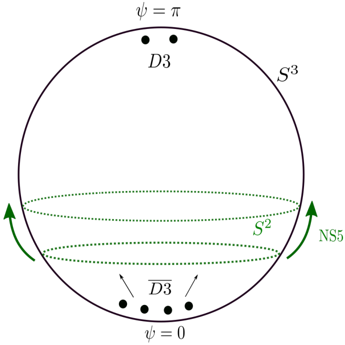
$\Rightarrow$ Tune $A(0)$ such that $|V_{\text{AdS}}| \approx \delta V$ becomes exponentially small

# Physics at the tip of the throat [KPV '01]

- Tip: A-cycle is topologically $S^3$ which is an $S^1$ (parameterized by $\psi$) fibred over $S^2$

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- Tip: A-cycle is topologically $S^3$ which is an $S^1$ (parameterized by $\psi$) fibred over $S^2$
- $p$ anti-D3-branes puff up into single NS5-brane wrapping $S^2$
- NS5 has non-trivial potential $V_{\text{KPV}}(\psi)$
- Depending on $p$ and $M$: NS5 is metastable (suitable for uplift and $\delta V = V_{\text{KPV}}(\psi_{\text{min}})\exp(4A(0)))$ or NS5 classically unstable: can slip over equator, annihilate with flux and form a supersymmetric vacuum

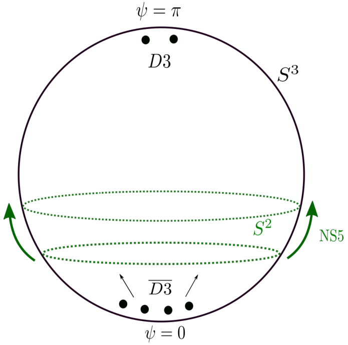


Figure: Brane-flux annihilation a la KPV.

# NS5-brane potential

$$V_{\mathrm{KPV}}(\psi) = \frac{4\pi^2 p\mu_5}{g_s} + \frac{4\pi\mu_5 M}{g_s}\left(\sqrt{b_0^4 \sin^4(\psi) + \left(\frac{\pi p}{M} - \psi + \frac{\sin(2\psi)}{2}\right)^2} - \psi + \frac{\sin(2\psi)}{2}\right)$$

- KPV analysis based on action at leading order in $\alpha'$
- $p/M < 0.08$ for metastability, then $\delta V = V_{\mathrm{KPV}}(\psi_{\min}) \exp(4A(0))$
- $V_{\mathrm{KPV}}(\psi_{\min}) \sim 2T_{\mathrm{D3}}$

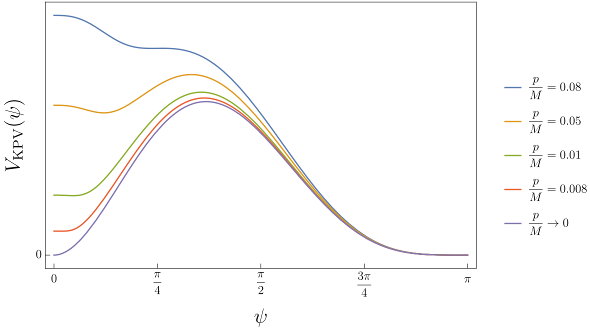


Figure: Normalized NS5-brane potential for different $p/M$.

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  - Warp factor $\exp(4A(0)) \sim \exp(-K/g_s M) \sim \exp(-KM/(g_s M^2))$
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- KPV: $p/M < 0.08$ and $g_s M > 1$ (control $\alpha'$ corrections) $\Rightarrow g_s M^2 > 12$
- $R_{S^3} \sim \sqrt{g_s M \alpha'}$, curvature corrections suppressed by $R_{S^3}$
  Quantify control over $\alpha'$ corrections by explicit calculation (metric known!)
  $\Rightarrow$ more precise version for bound $g_s M > 1$

# $\alpha'$ corrections to D$p$-branes

- Many (not all!) $\alpha'^2$ correction to D$p$-branes known [Bachas, Bain, Green '99, Garousi + Jalali, Karimi, Babaei Velni, Mir, Mashhadi '09-22, Robbins, Wang '14]
- Need corrections to NS5-brane $\Rightarrow$ S-dualize ($g_s \to 1/g_s$) corrections D5
- Could also work in S-dual KS throat with D5 [Gautason, Schillo, Van Riet '16]
- Specify here to DBI-action, see [Schreyer, Venken '22] for CS

Non-vanishing corrections to DBI-action of D5-brane, schematically:

$$S_{\mathrm{DBI,D5}} \supset \frac{\mu_5}{g_s}\int_{\mathcal{M}_6} \mathrm{d}^6 x \sqrt{-(g+\alpha'\mathcal{F}_2)}\Bigg[1+\alpha'^2\Bigg((R+\Omega^2)^2+H_3^4+H_3^2 R + \Omega^4(\alpha'\mathcal{F}_2)^2+(\alpha'\mathcal{F}_2)\Omega^2\nabla H_3\Bigg)\Bigg]$$

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S-dualized D$5$-brane action:

$$S_{\mathrm{DBI,NS5}} \supset \frac{\mu_5}{g_s^2} \int_{\mathcal{M}_6} \mathrm{d}^6 x \sqrt{-(g + \alpha' g_s \mathcal{F}_2)} \Bigg[ 1 + g_s^2 \alpha'^2 \Bigg( (R + \Omega^2)^2 + (-g_s F_3)^4 + (-g_s F_3)^2 R + \Omega^4 (\alpha' g_s \mathcal{F}_2)^2 + (\alpha' g_s \mathcal{F}_2) \Omega^2 \nabla (-g_s F_3) \Bigg) \Bigg] ,$$

Looks like 2-loop term! But know from comparing to $\overline{D3}$ when shrinking $S^2 \to 0$ that there must be tree level term in $g_s$.

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Proposed NS5-brane action:

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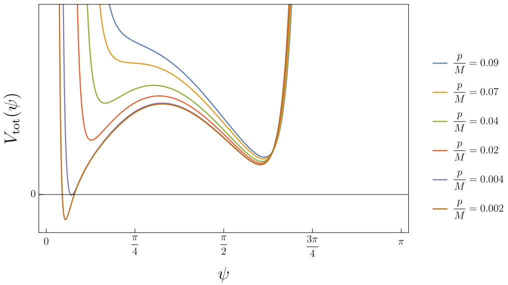
S-duality suggests a mapping of tree-level to two 2-loop for D5/NS5!

# $\alpha'^2$ corrected KPV potential [Schreyer, Venken '22]

Contribution to potential from DBI-terms

$$V_{\text{DBI}} = \frac{4\pi\mu_5 M}{g_s}\sqrt{b_0^4 \sin^4(\psi) + \left(\frac{\pi p}{M} - \psi + \frac{1}{2}\sin(2\psi)\right)^2}\left[1 + \frac{1}{(g_s M)^2}\left(c_3 - c_1\right.\right.$$
$$+ (c_4 - 2c_2)\cot^2\psi - c_2\cot^4\psi + \frac{c_5\cot^4\psi}{\sin^4\psi}\left(\frac{\pi p}{M} - \left(\psi - \frac{\sin(2\psi)}{2}\right)\right)^2$$
$$\left.\left. - \frac{c_6\cot^3\psi}{\sin^2\psi}\left(\frac{\pi p}{M} - \left(\psi - \frac{\sin(2\psi)}{2}\right)\right)\right)\right]$$

- $c_1, \cdots, c_6$ numerical constants, explicitly calculated
- Potential enjoys expansion in $g_s M$ and $p/M$



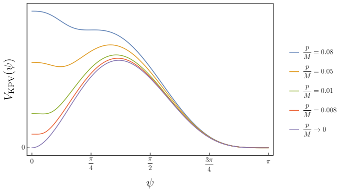
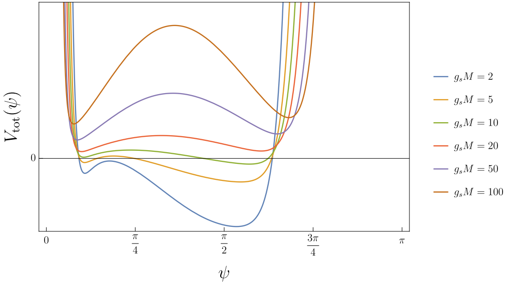




Figure: KPV potential.

Figure: $\alpha'^2$ corrected KPV potential for $g_s M = 20$.

- KPV bound changes, minimum at positive, zero and negative energies



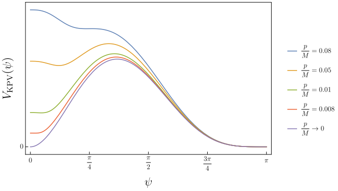




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Figure: $\alpha'^2$ corrected KPV potential for $p/M = 0.01$.

- KPV bound changes, minimum at positive, zero and negative energies

- Blue region: no metastable minimum
- Yellow region: metastable minimum at positive value
- Orange region: metastable minimum at negative value
- Minimal bound on $g_s M$: $g_s M > 3.6 \Rightarrow g_s M^2 > 144$ (compare to $g_s M^2 > 12$ from KPV!)

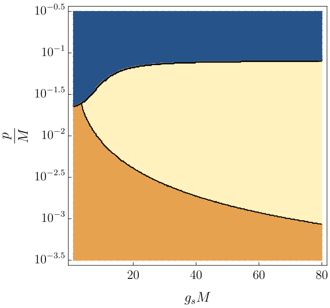
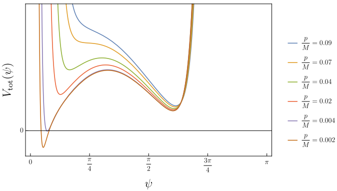



Figure: Existence of metastable minimum in $(g_s M, p/M)$ parameter space.

# Where do we trust our potential?

- $\mathcal{F}_2$ couplings special:
  $g_s\mathcal{F}_2 \sim \frac{1}{\sin^2\psi}\left(\frac{p}{M} - \psi + \frac{\sin(2\psi)}{2}\right)$.
  For $\psi \sim \mathcal{O}(1)$:
  $g_s\mathcal{F}_2 \sim -(M-p)/M \sim \mathcal{O}(1)$ when $p \ll M$.
  $\Rightarrow$ Lose trust close to equator where we anyways expect decay into SUSY minimum



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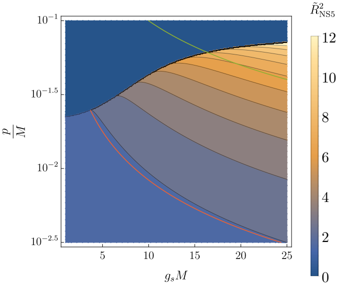
- Higher order $\alpha'$ suppressed $\Rightarrow$
  $R^2_{\mathrm{NS5}} \sim g_s M \sin^2\psi$ sufficiently large
  $\Rightarrow$ Lose trust at small $\psi$
- Weak coupling $g_s < 1$ (green line)



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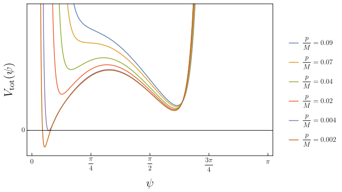
- Divergencies may be cured by summing over all $\alpha'$ corrections



# Implications for pheno

- Remember:
  - $|V_{\text{AdS}}| \approx \delta V = 2T_{\text{D3}}\,\text{exp}(4A(0)) \sim 2T_{\text{D3}}\,\text{exp}(-N/(g_s M^2))$
    $\Rightarrow$ Require much more flux in throat than expected from tree level KPV
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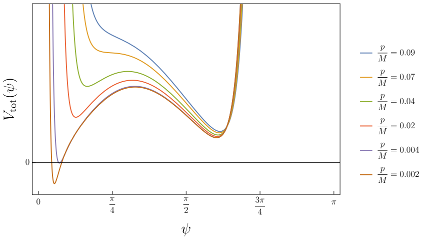
- We quantified $Q_{3,\text{min}}$ for controlled dS vacua in the LVS with $\overline{D3}$ uplift "LVS parametric tadpole constraint" [Gao, Hebecker, Schreyer, Venken '22]
- Result including bound on $g_s M^2$ from $\alpha'$ corrected KPV: $|Q_{3,\text{min}}| \sim \mathcal{O}(10^3)$
- Seems very constraining since currently highest constructed $|Q_{3,\text{min}}| = \mathcal{O}(3000)$, but higher tadpoles possible, but come with additional complications

# Uplifting without exponentially large warping

- Understand $\alpha'$ corrections as lowering effective tension of $\overline{D3}$



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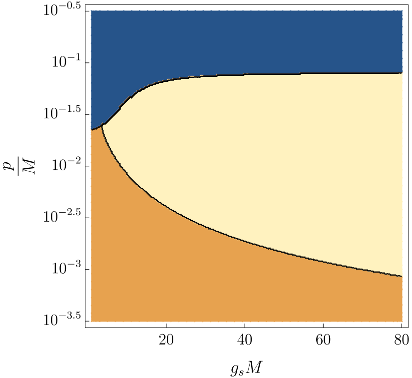

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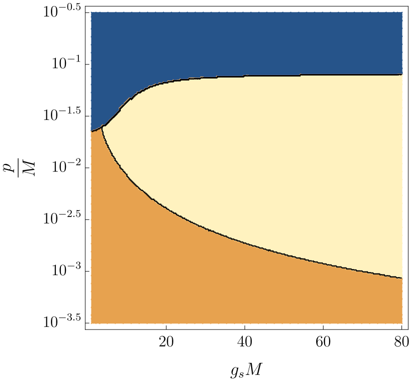
- Tuning $\alpha'$ corrections by $g_s M$, $p/M$ tunes value of potential at metastable minimum!
  $\Rightarrow$ No need to warp down $T_{\mathrm{D3}}$, as itself tunable to exponentially small value!
  $\Rightarrow \delta V = V(\psi_{\mathrm{min}})$
- No large flux and large $|Q_3|$ necessary



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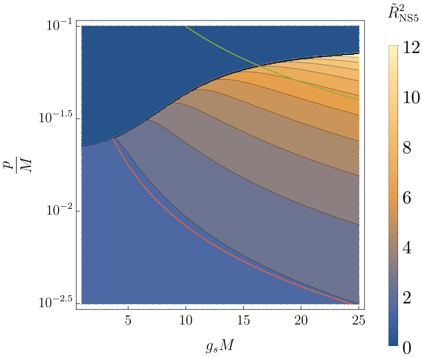
- Problem: control over higher order $\alpha'$ as $g_s M \sin^2 \psi \approx 1$



# Open questions

- Improve control by calculating higher order $\alpha'$ corrections
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- Holographic picture is controlled for $g_s M \ll 1$ where $\alpha'$ expansion breaks down
  $\Rightarrow$ Way of proving new uplifting mechanism by establishing metastable AdS vacuum for $g_s M < 1$
- Interplay backreaction effects

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## Thank you!

# Flux prevents cycle from shrinking

- $p$-form fluxes: higher dim generalization of 2-form fluxes known from Maxwell
- In compact space: Live on $p$-cycles $c_p$, take quantized values

$$\oint_{c_p} F_p = 2\pi n$$

Example: compact space is $S^1_A \times S^1_B$

- Can put one unit of 1-form flux on $S^1_B$ 1-cycle: i.e. $\int \mathrm{d}y_B F_1 = 1$, hence $F_1 \sim 1/R_B$
- Contribution to action:

$$S \supset -\int \mathrm{d}^4x \int \mathrm{d}y_A \mathrm{d}y_B F_1 \wedge *F_1 \sim -\int \mathrm{d}^4x (R_A R_B) \cdot \frac{1}{R_B^2} \sim -\int \mathrm{d}^4x \frac{R_A}{R_B}$$

- For $R_B \to 0$, $V \to \infty \Rightarrow$ flux prevents cycle from shrinking
- Putting fluxes on various cycles $\Rightarrow$ tend to stabilize shape of manifold

# $\alpha'^2$ corrected KPV potential

$$
\begin{aligned}
V_{\text{tot}} = \frac{4\pi\mu_5 M}{g_s}\sqrt{b_0^4 \sin^4(\psi) + \left(p\frac{\pi}{M} - \psi + \frac{1}{2}\sin(2\psi)\right)^2} \times \Bigg[1 + \frac{1}{(g_s M)^2}\Bigg(c_3 - c_1 \\
+ (c_4 - 2c_2)\cot^2\psi - c_2\cot^4\psi + \frac{c_5\cot^4\psi}{\sin^4\psi}\left(\frac{\pi p}{M} - \left(\psi - \frac{\sin(2\psi)}{2}\right)\right)^2 \\
- \frac{c_6\cot^3\psi}{\sin^2\psi}\left(\frac{\pi p}{M} - \left(\psi - \frac{\sin(2\psi)}{2}\right)\right)\Bigg)\Bigg] \\
+ \left[\frac{4\pi^2 p\mu_5}{g_s} - \frac{4\pi\mu_5 M}{g_s}\left(\psi - \frac{\sin(2\psi)}{2}\right)\right]\left(1 + \frac{c_7}{(g_s M)^2} + \frac{c_8\cot\psi}{(g_s M)^2\sin\psi}\right)
\end{aligned}
$$