10d Description of 4d de Sitter Vacua

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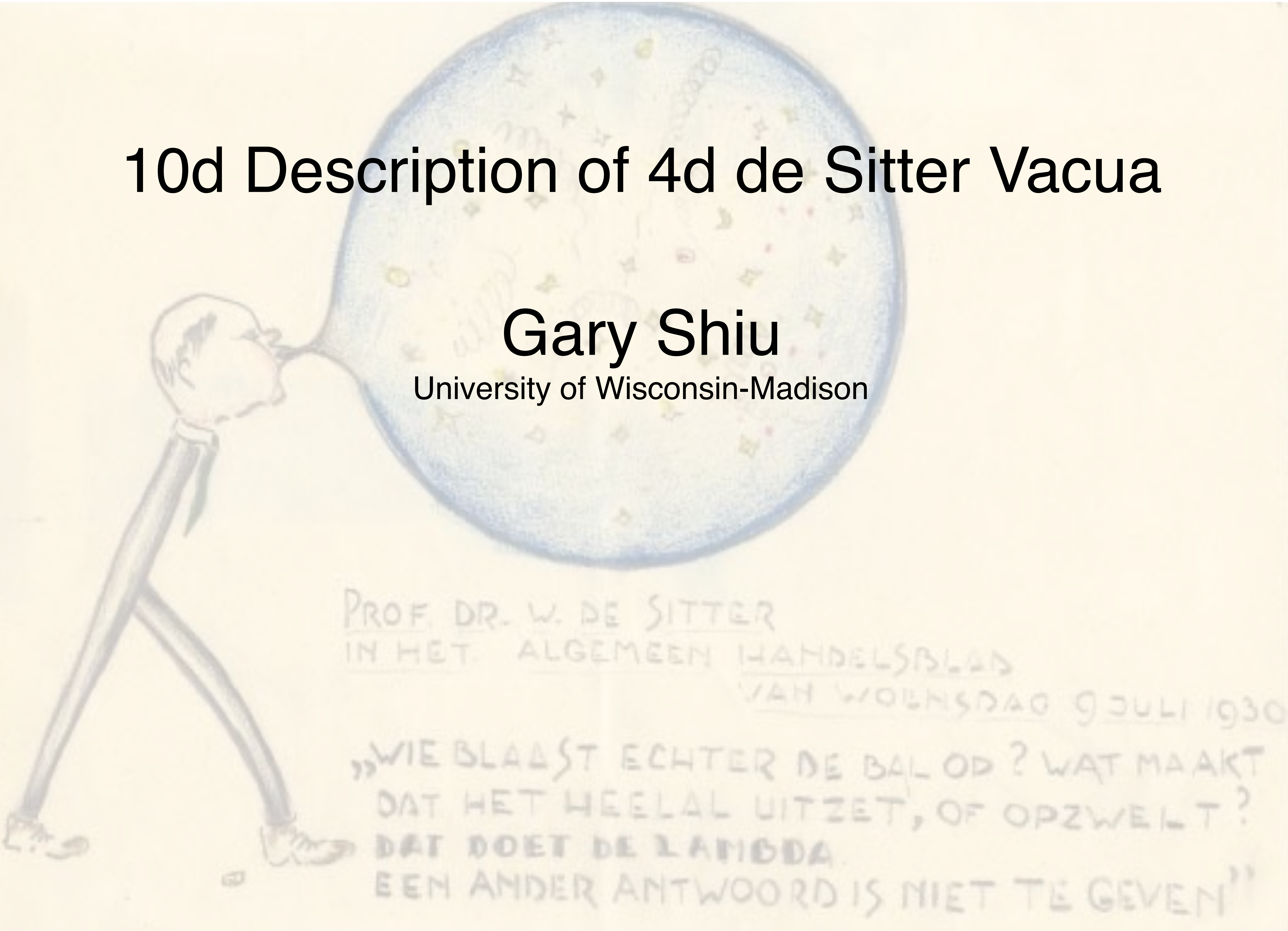

Based on work with:

Yuta Hamada

Arthur Hebecker

Pablo Soler

- “On brane gaugino condensates in 10d,'' JHEP **1904**, 008 (2019) [arXiv:1812.06097 [hep-th]].
- “Understanding KKLT from a 10d perspective,'' JHEP **1906**, 019 (2019) [arXiv:1902.01410 [hep-th]].
- + work in progress

The Elephant in the Room

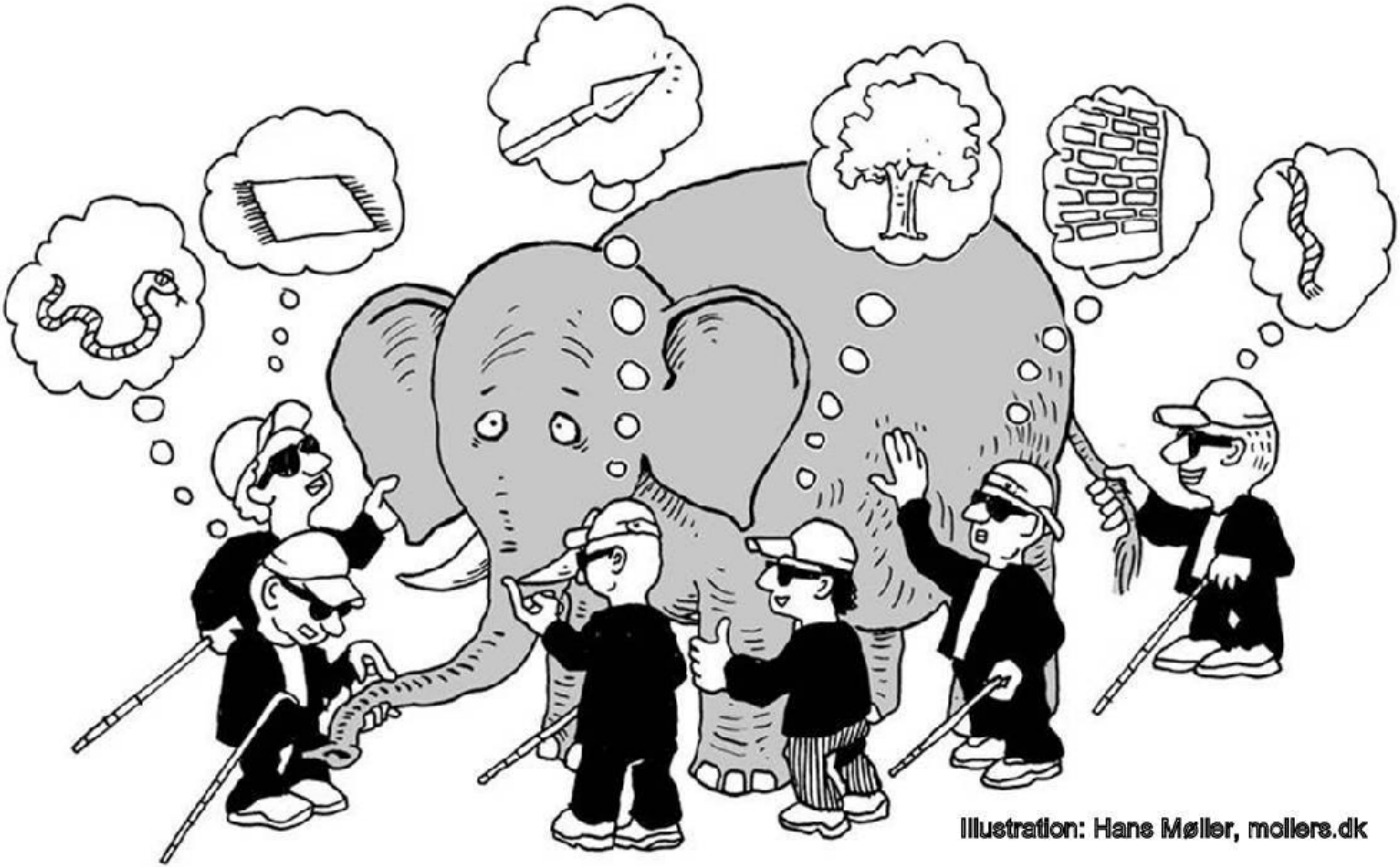

Illustration: Hans Møller, mollers.dk

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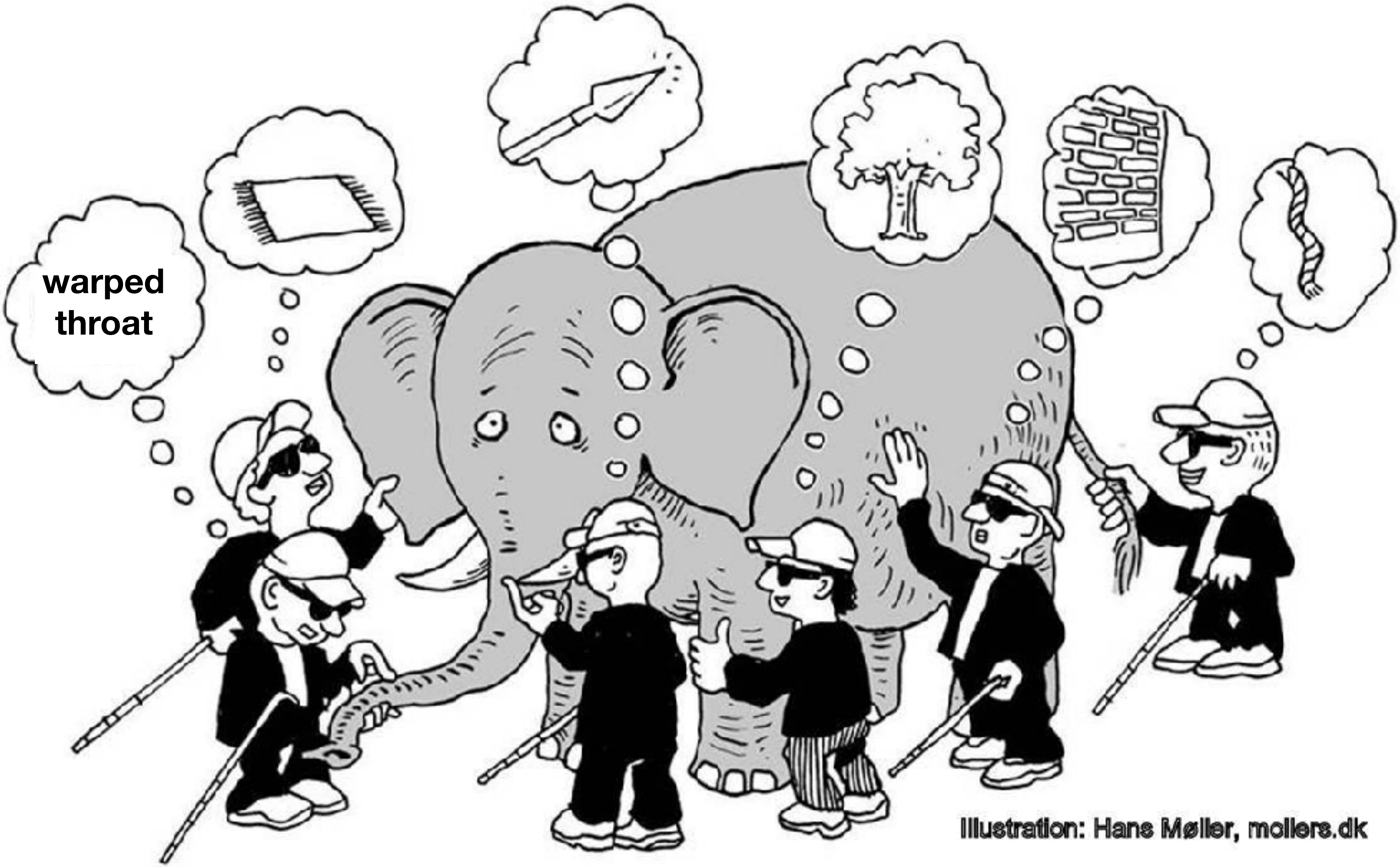

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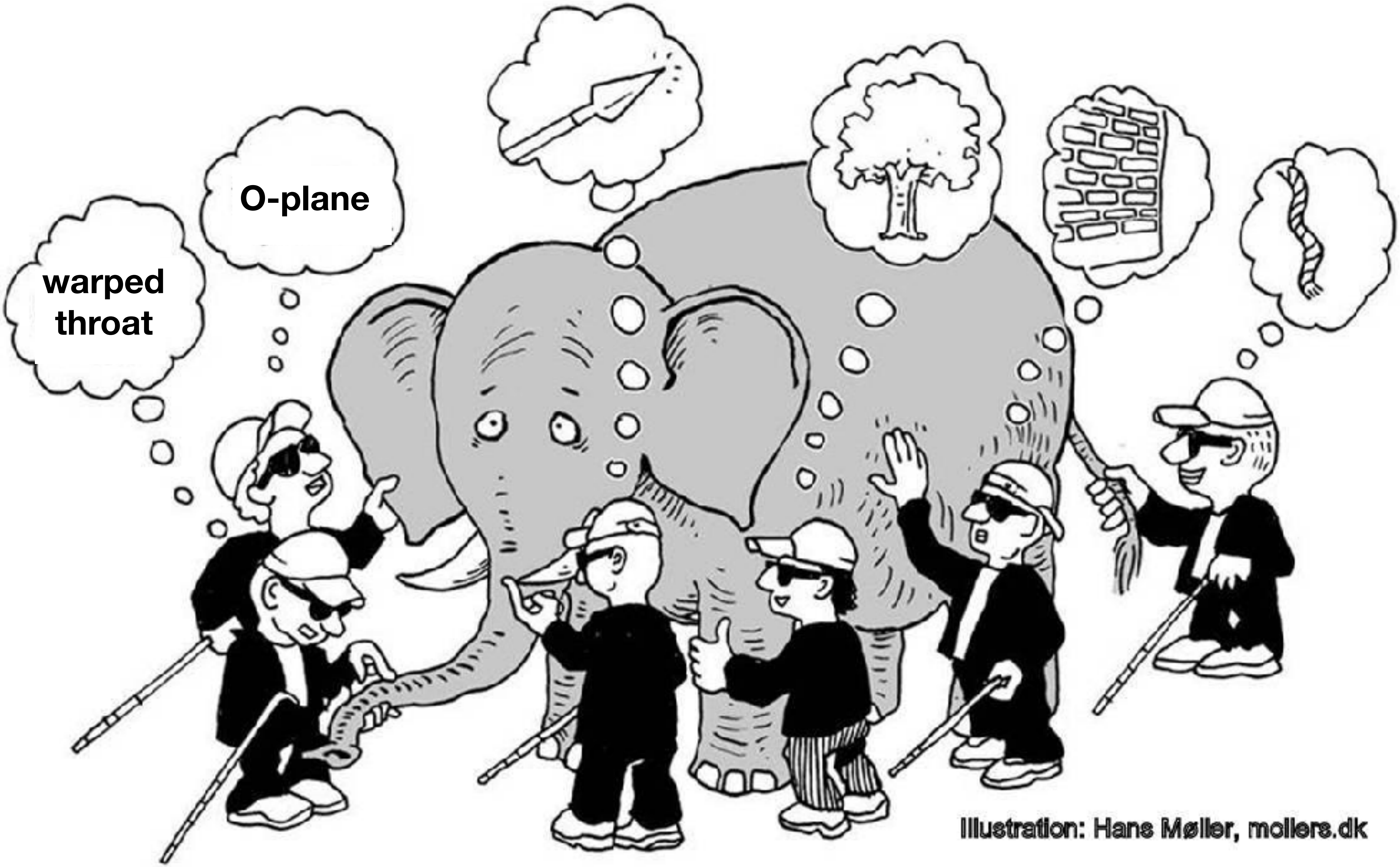

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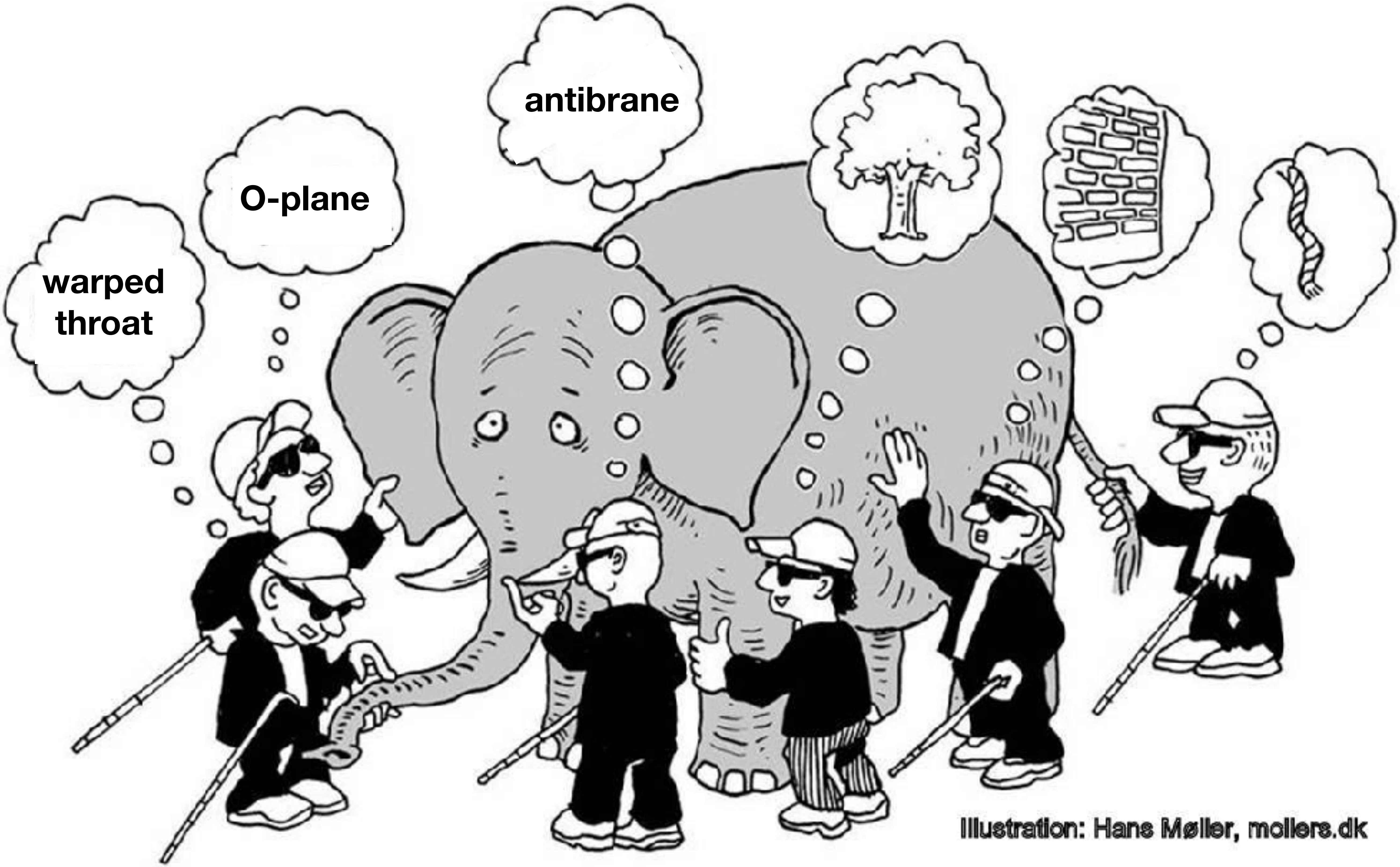

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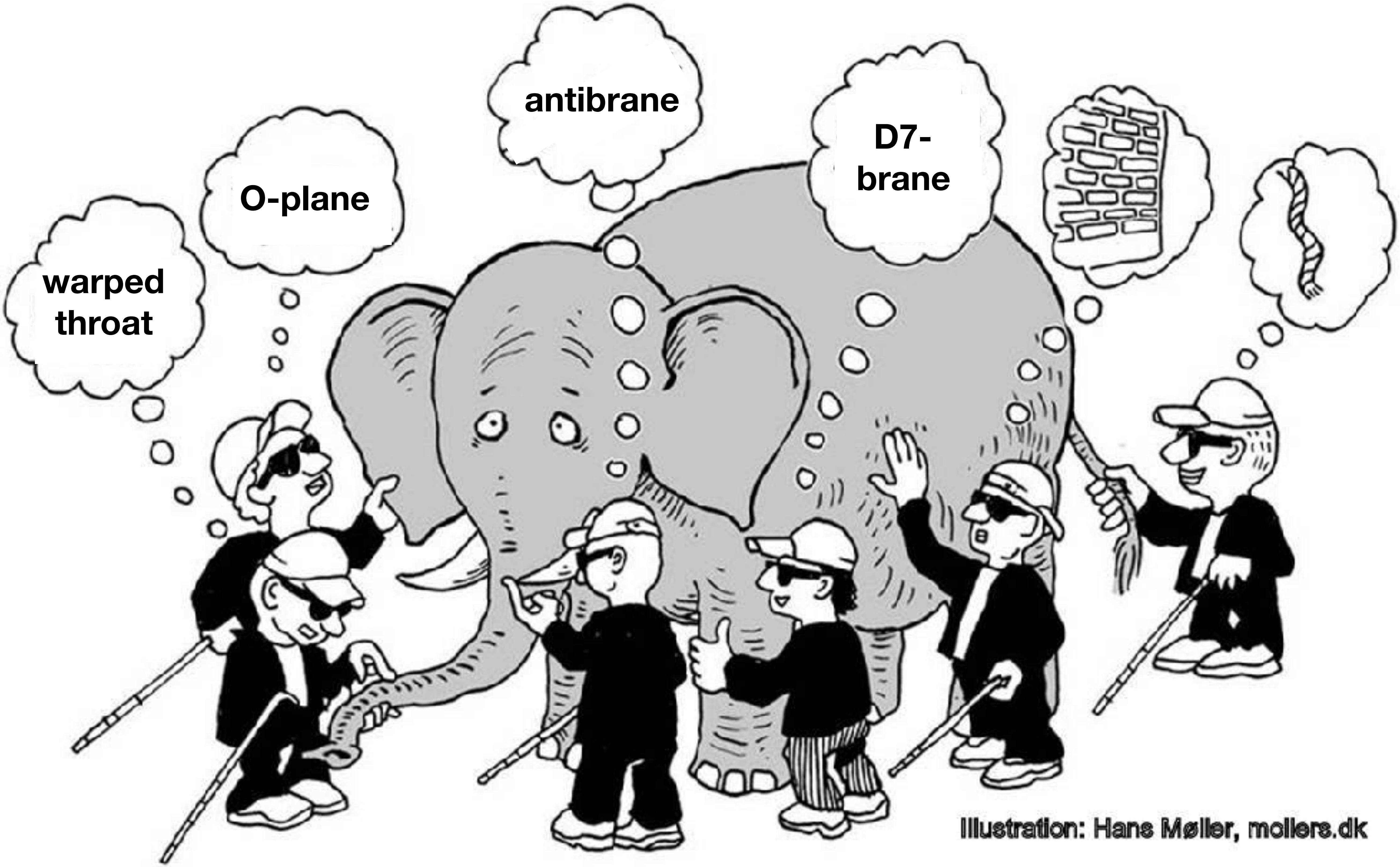

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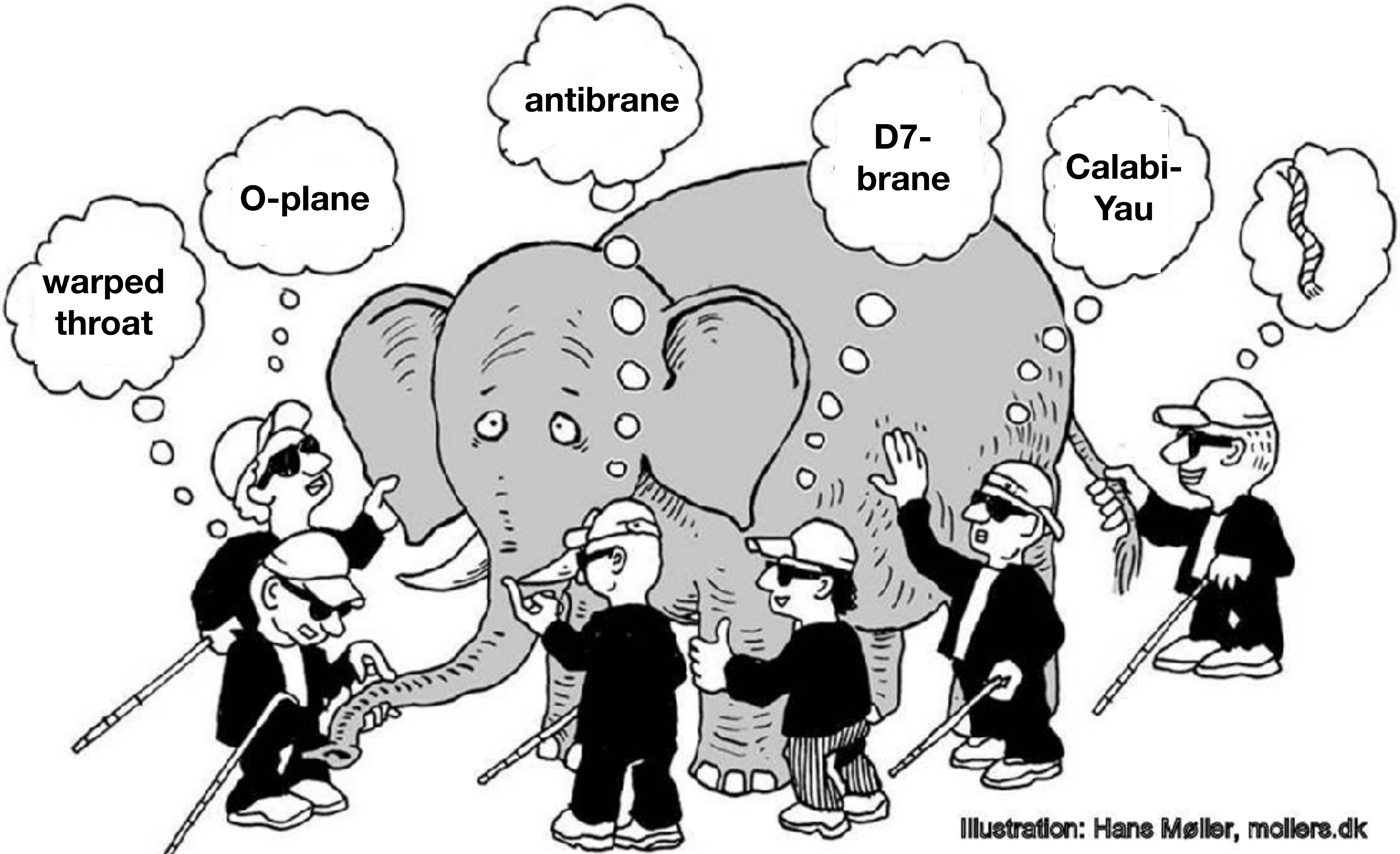

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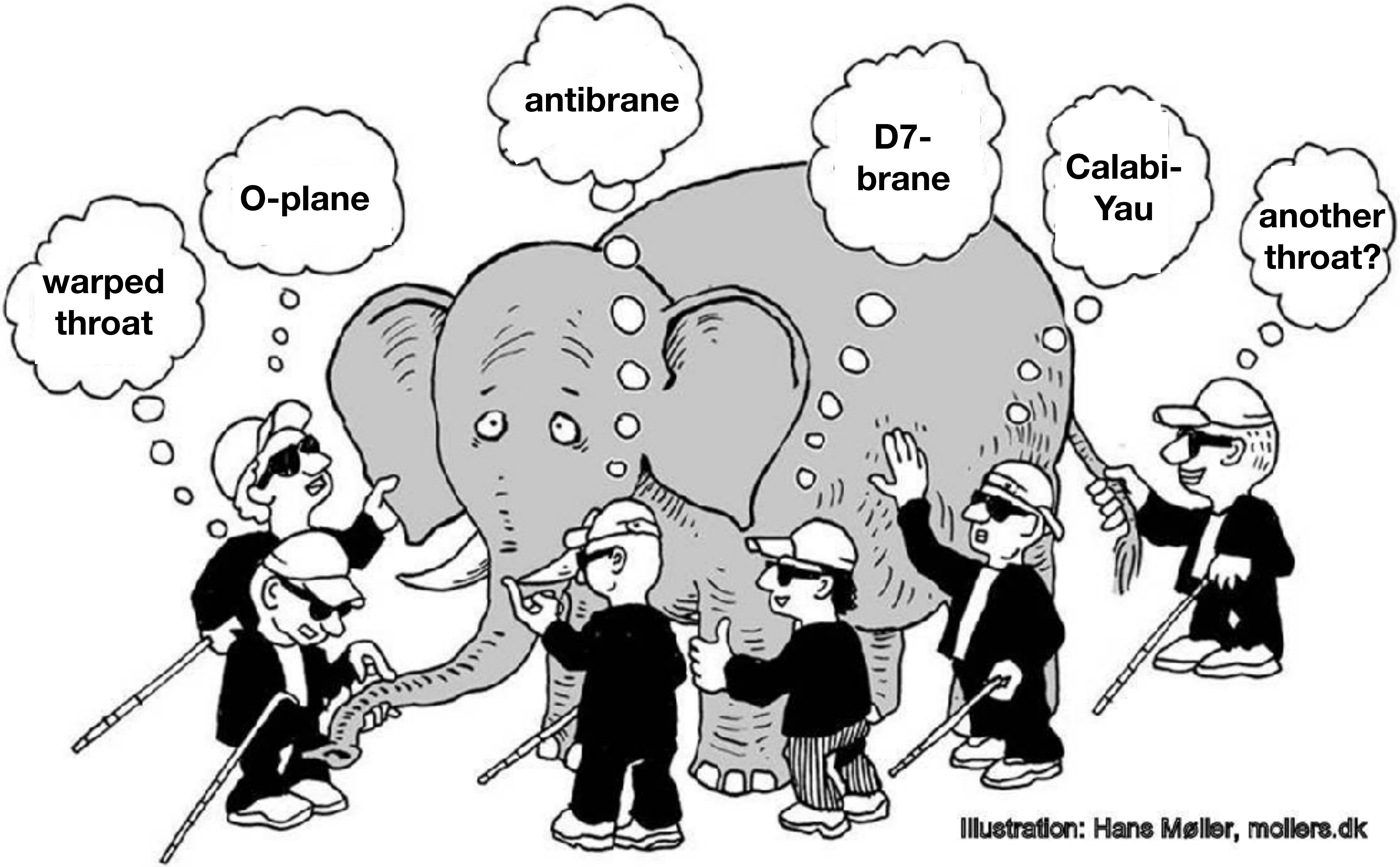
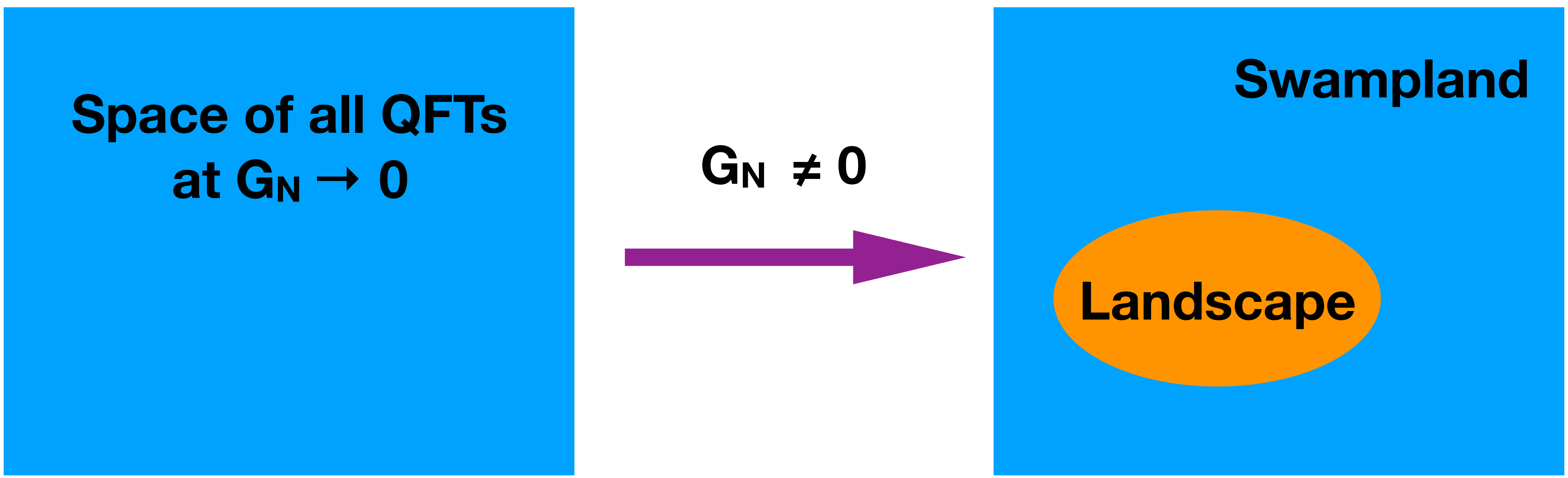


de Sitter and the Swampland

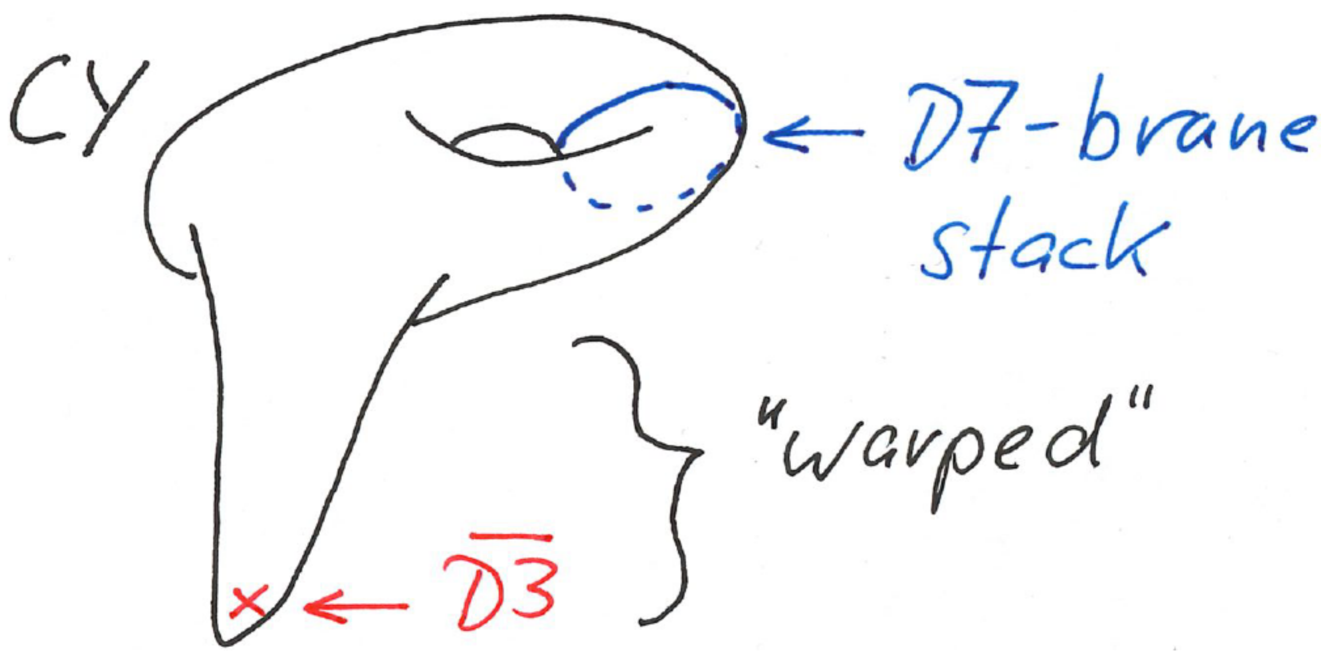
- The recent debate of whether de Sitter is in the Swampland is ***not*** about questioning **individual modules** in specific constructions or whether these constructions are *reasonable* from a **4d EFT point of view**.
- Swampland criteria **do not follow from EFT considerations alone.** Furthermore, they are **global constraints**:



- At **non-zero gravitational coupling**, these modules are not independent of each other; we must consider the **compactification in full**.

KKLT

- While de Sitter in string theory does not mean exclusively KKLT **[Kachru, Kallosh, Linde, Trivedi]**, some no-goes which plagued simple de Sitter constructions **[See Panel Discussion 5]** do not obviously apply.
- To show that KKLT is not in the swampland, we ought to show that all the modules can be consistently put together in a compactification:



- This question triggers the recent interest in understanding KKLT from a 10d perspective; a 4d analysis may obscure potential incompatibilities.

KKLT in 4d

- Type IIB on CY orientifold with all complex structure moduli ξ_a and the axio-dilaton τ stabilized by **fluxes**:

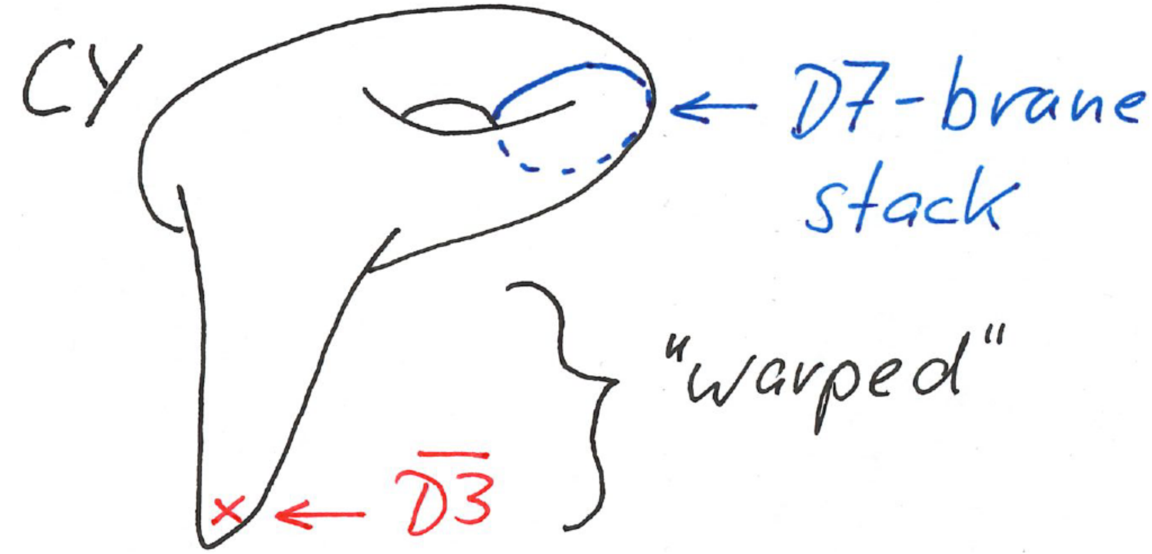
$$W = \int G_3 \wedge \Omega$$

[Gukov, Vafa, Witten]

- Assuming CY with $h_+^{1,1} = 1$, the low energy 4d EFT below the KK and complex structure moduli/axio-dilaton mass scale is described by:

$$K = -3\log(T+\overline{T}) \text{ with } T = \mathscr{V}^{2/3} + ia,$$

$$W = W_0 = \text{constant} \Rightarrow V = 0 \text{ (no scale)}$$



- **Gaugino condensate** on D7 (or ED3):

$$W = W_0 + e^{-T}$$

- **Uplift by p anti-D3** in a warped throat: $V = V_F + 2p\mu_3 e^{4A-12u}$

KKLT in 10d

- **This is a tall order!**
  - Does there exist an explicit CY orientifold which allows for an *exponentially small* $|W_0|$, a strongly warped throat, and W_{NP} ? **[Partially in Panel Discussion 4, 5]**
  - Separation of scales ? **[Panel Discussion 1]**
  - Controlled corrections ? **[Panel Discussion 1].** For one, to stay in the geometric regime, Re T ≫ 1 requires

$$\frac{\log|W_0|^{-1}}{2\pi k} \gg 1 \text{ with } k = \text{constant that increases with } h^{1,1}_{+}$$

    so far only $W_0 \approx 10^{-2}$ has been demonstrated **[Denef, Douglas, Florea].**
  - Backreaction of antibranes and metastability? **[Panel Discussion 2]**
  - Gaugino condensate and flattening? **[Panel Discussion 3]**

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KKLT and the de Sitter Conjectures

- The recent de Sitter conjectures **[Danielsson, Van Riet];[Obied, Ooguri, Spodyneiko, Vafa];[Ooguri, Palti, GS, Vafa]; [Andriot]; …** should not be seen as discouraging de Sitter constructions in string theory.
- Rather, they **open more doors** for further investigations:
  - Careful studies of string theory vacua (going beyond 4d EFT).
  - Quantifying corrections and sharpening estimate of errors.
  - Developing more powerful tools for constructing de Sitter or its alternatives.
  - …

Brane Gauginos in 10d

Trace-reversed Einstein Equation

- In a 10d approach, the trace-reversed EE + Bianchi identity gives:

$$\mathcal{V}\,\mathcal{R}_\eta = \int d^6y\sqrt{g}\left(-a\,|\partial\Phi^-|^2 - b\,\Omega^8\,\frac{|G_3^-|^2}{\mathrm{Im}(\tau)} - 2\Omega^8\Delta^{other}\right)\,.$$

includes contributions from D7 gauginos & anti D3-branes

- This is equivalent to $\mathcal{R}_4$ obtained by minimizing the 4D potential wrt the moduli **[Giddings, Maharana];[Danielsson, Haque, GS, Van Riet];[Danielsson, Haque, Koerber, GS, Van Riet, Wrase]; …**
- This **[Maldacena. Nunez]** style relation has been used to argue that an anti D3-brane does not uplift but rather flattens the potential **[Moritz, Retolaza, Westphal]; [Gautason, Van Hemelryck, Van Riet].**
- Making a definitive statement requires a precise determination of the D7-brane gaugino action **[Hamada, Hebecker, GS, Soler, '18]; [Kallosh, '19].**
- Using our regularized action, several groups have revisited KKLT **[Hamada, Hebecker, GS, Soler, '19]; [Carta, Moritz, Westphal, '19]; [Gautason, Van Hemelryck, Van Riet, Venken, '19]**

Regularizing the D7-brane Action

- This earlier concern about flattening by anti D3-branes was rooted in possibly too simplistic treatment of D7-brane-gaugino bulk coupling:

$$\mathscr{L}_{10} \supset |G_3|^2 + G_3 \cdot \Omega_3 < \lambda\lambda > \delta_{D7}$$

[Camara, Ibanez, Uranga, '04];
[Koerber, Martucci, '07];
[Baumann, Dymarsky, Klebanov, Maldacena, McAllister, '06];
[Heidenreich, McAllister, Torroba, '10], …

- G_3 backreacts, and becomes singular at the D7-brane.
- Plugging this back into the action, one gets a $(\delta_{D7})^2$ divergence.
- Without regularizing this divergence in the action, one cannot extract physically meaningful answers.

Regularizing the D7-brane Action

- Singular gaugino effects have made their appearance in other string models **[Horava, Witten, '96] (see also [Ferrara, Giradello, Nilles, '83]; [Dine, Rohm, Seiberg, Witten '85]; [Cardoso, Curio, Dall'Agata, Lust, '03], …)**

- It has been shown that SUSY implies an additional highly singular $<\lambda\lambda>^2$ term which saves the day by "completing the square".

- For the case of interest:

$$\mathscr{L}_{10} \supset |G_3 + \Omega_3 < \lambda\lambda > \delta_{D7}|^2$$

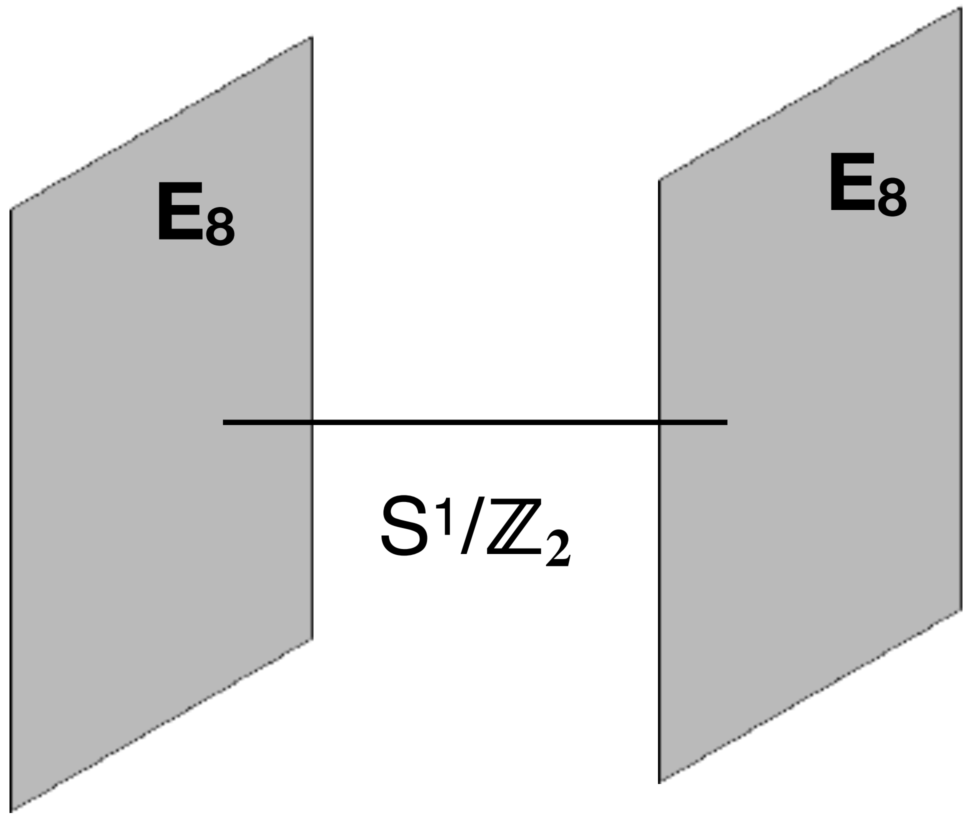
[Hamada, Hebecker, GS, Soler, '18]; (see also [Kallosh, '19])

- Very roughly speaking, one writes $\mathbf{G_3 = G_3^{flux} + \delta G_3}$ and let $\boldsymbol{\delta} \mathbf{G_3}$ cancel (most of) the $\boldsymbol{\delta}$ function.

- Schematically: $\mathscr{L}_{10} \supset |G_3^{flux} + < \lambda\lambda > |^2 \quad \rightarrow \quad |D_T W_0 + \partial_T e^{-T}|^2$

Perfect Square Structure in M-theory

- Compactifying M theory on an interval:



- We have similarly $S \sim \int_{11} G_4^2 - \delta(x^{11})(G_4)_{ABC11} j^{ABC}$ with $j^{ABC} \sim \bar{\lambda}\Gamma^{ABC}\lambda$

- It is well-known that the divergence problem is resolved by the perfect-square action (enforced by SUSY):

$$S \sim -\int_{11} \left(G_4 - \frac{1}{2}\delta(x^{11})\, j \right)^2$$

[Horava, Witten]

Warm-up: 5d Toy Model

- Better illustrated w/ a 5d toy model (inspired by **[Mirabelli, Peskin, '97]**); keeping track of the $y \equiv x^5$ dependence:

$$S = -\int_5 \big(d\varphi - j\delta(y)dy\big) \wedge * \big(d\varphi - j\delta(y)dy\big)$$

- The equation of motion:

$$d * \big(d\varphi - j\delta(y)dy\big) = 0$$

which is solved by

$$d\varphi = j\delta(y)dy + \alpha_M dx^M$$

- Crucially, $\alpha = \alpha_M \, dx^M$ is co-closed, i.e.,

$$d * \alpha = 0$$

Obtaining a Finite Action

- Neglecting x^μ dependence, the EOM reads:

$$\partial_y \left[\partial_y \varphi - j\delta(y) \right] = 0$$

- The solution is given by:

$$\partial_y \varphi = j\delta(y) + \alpha_5 \quad \text{with } \alpha_5 = \text{constant}$$

- Flux quantization implies:

$$\int_{S^1} dy \partial_y \varphi = j + \alpha_5 = n \in \mathbb{Z}$$

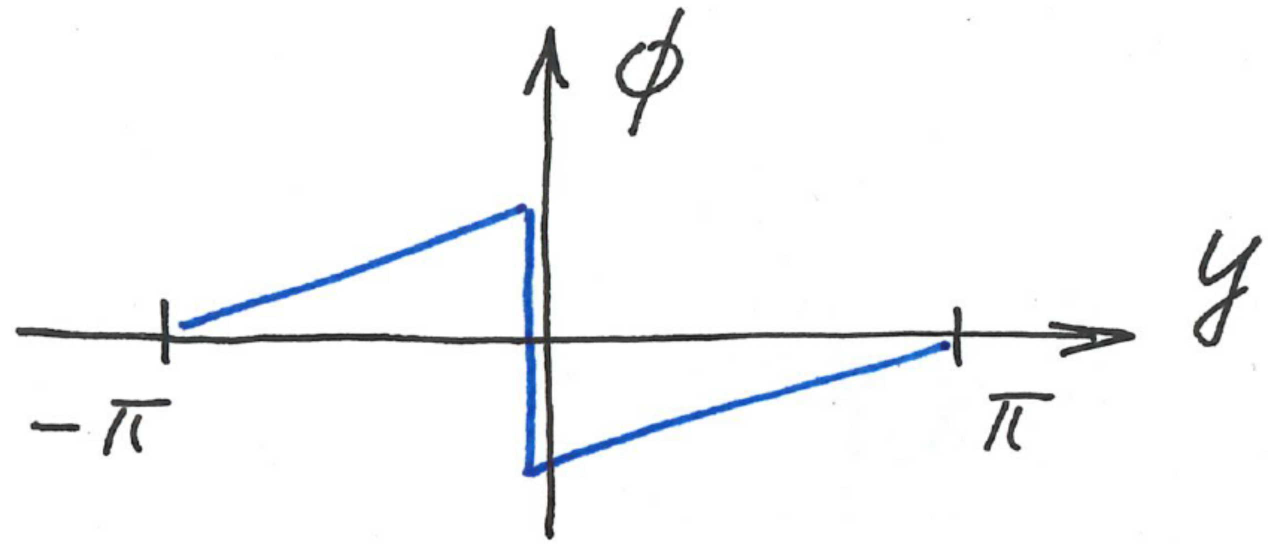
- The resulting action is:

$$S = -(n-j)^2$$

- **Upshot:** $\partial_y \varphi$ cancels the singular term and develops a finite action.

Obtaining a Finite Action (Continued)

- Illustration for n=0:



- The “step” in $\partial_y \varphi$ cancels the source term $j\delta(y)$.
- Flux quantization enforces a non-trivial slope proportional to this step.
- If $n \neq 0$, continuity is replaced by an extra step of size n at boundary:

$$\mathscr{L} = \int_R |d\varphi - j\delta|^2 = -\frac{(n-j)^2}{R}$$

restore R dependence which was previously set to 1

- **Crucial:** Radius dependence of j^2 term.

Co-dimension 2 Brane

- The case of interest is co-dimension 2 ⇒ generalize toy model to 6d
- Similar brane-bulk coupling:

$$\mathscr{L} = -\int dz^2 \left(|G_1|^2 - G_1 \cdot \bar{j}_1 + c.c. \right) \quad \text{with} \quad \bar{j}_1 = j\ dz\ \delta^2(z,\bar{z})$$

- Naively, the perfect square action for the co-dimension 2 case is:

$$\mathscr{L} = -\int d^2z\, |G_1 - \bar{j}_1|^2$$

- **BUT**: the singular source-form is **not closed** and hence cannot be compensated by G_1 (assumed to be closed):

$$d\left(j dz \delta^2(z,\bar{z})\right) \neq 0$$

Co-dimension 2 Brane (Continued)

- To allow G_1 to compensate, we project the source on the closed part using the unique decomposition:

$$\omega = \alpha + d\beta + d^{\dagger}\gamma \ ; \quad P(\omega) = \alpha + d\beta$$

- This does not change the EOMs since the inner product:

$$(G_1, d^{\dagger}\gamma) = (dG_1, \gamma) = 0$$

- Using indices h, e, c for harmonic exact, and co-exact:

$$\mathscr{L} = = \int_z - | \overline{G}_1^h + \overline{G}_1^e - j_1^h - j_1^e |^2$$

- Here the exact piece of G_1 cancels the exact piece of j_1.

From Toy Model to D7-brane Gauginos

- We are left with:

$$\mathscr{L} = -\int_z |\,\overline{G}_1^h - j_1^h\,|^2$$

- The former is the quantized flux, so it cannot compensate for the continuous

$$j_1^h \sim \lambda^2 dz/A_\perp\ , \quad A_\perp = \text{transverse volume}$$

- This perfect square of the quantized flux and the finite λ^2 term is the sole remainder in the action.
- Generalizing to the case of interest: D7-brane gauginos

$$\mathscr{L} \supset |\,\overline{G}_3 - P\left(\lambda\lambda\Omega_3\delta_{D7}\right)|^2$$

Cross-Checks with KKLT

- As before, the singular parts cancel and using $\int G_3^{(0)} \wedge \Omega \sim W_0$, one arrives at (after 4d normalization of the gauginos):

$$K^{T\overline{T}} \,|\, e^{K/2} K_T W_0 + \lambda\lambda \,|^2$$

- This is precisely the perfect square structure that one finds in the SUGRA + gauge theory formulae of Wess and Bagger.
- With the substitution $e^{-K/2}\lambda\lambda \to e^{-T}$, one arrives at (pre-uplift) KKLT:

$$e^K K^{T\overline{T}} \,|\, D_T \left(W_0 + e^{-aT} \right) |^2$$

- In the above, we neglect terms subleading in 1/T. We can recover these subleading terms by including loop corrections to the gauge kinetic function in the running from UV to IR. **[Kaplunovsky, Louis]**

Generalized Complex Geometry

- The backreaction of gaugino condensates in SUSY AdS_4 Type II flux compactification was described using GCG recently in **[Bena, Graña, Kovensky, Retolaza, '19];[Kachru, Kim, McAllister, Zimet, '19] (earlier works by [Koerber, Martucci];[Dymarsky, Martucci]; …)**
- Using the two 6d spinors η^1 η^2 define two polyforms (or bispinors):

$$\Psi_1 \sim \sum_p \eta^{2\dagger}\Gamma_{m_1\cdots m_p}\eta^1 dy^{m_1}\cdots dy^{m_p} \quad \Psi_2 \sim \sum_p \eta^{2*\dagger}\Gamma_{m_1\cdots m_p}\eta^1 dy^{m_1}\cdots dy^{m_p}$$

which encode the full metric and background field information.

- SUSY conditions (and hence EOMs) can be compactly expressed in terms of the polyforms.
- Using 4d SUSY, the AdS curvature can be related to a parameter in 10d SUSY conditions $\Rightarrow$ fully 10d-local check of pre-uplift KKLT **[Bena, Grana, Kovensky, Retolaza, '19].**

Generalized Complex Geometry

- In related work, **[Kachru, Kim, McAllister, Zimet, '19]** used GCG to discuss:
  - the cancellation of singular terms
  - a recasting of KKLT in 10d component fields
- However, a concern with this approach is that the D7-brane λ^4 term that they found by T-dualizing the known Type I action is **non-local:**

$$\mu_7 \int \sqrt{-g_8} \frac{1}{A_\perp} \lambda^4$$

- Another concern: while the cancellation of the divergence in $G_3 \lambda^2$ was discussed, the cancellation of the divergence in the kinetic term

$$\int_6 |G_3|^2 , \quad \text{with} \quad G_3 \sim \delta_{D7} + \frac{1}{z^2}$$

has not been demonstrated.

T-duality and Locality

- Starting with the manifestly local perfect square action of Horava-Witten and compactify it on an S^1, one should obtain a **local-action**.
- However, by a **9-11 flip**,

$$\text{M theory on } S^1/\mathbb{Z}_2 \times S^1 \equiv \text{IIA on } S^1/\mathbb{Z}_2 \text{ with } D8 \text{ branes at endpoints}$$

- If we try to obtain the action for the latter by T-dualizing the action for Type IIB orientifold with D9-branes (i.e., Type I), we find instead a **non-local action**.
- The original Type I action reduced on S^1 is valid in the large radius regime where the higher KK modes can be ignored.
- This theory is mapped to Type IIA on a small interval (not our regime of interest). The sum over the KK modes leads to a non-local action.

Back to our D7-brane Gaugino Action

- While the backreaction of gaugino condensates can be elegantly recast in the language of GCG, some issues remain to be better understood using our manifestly finite action.

- In our approach, the cancellation of the divergence in the flux kinetic term is manifest, but locality is not (though in a milder way). In projecting the source, we drop the co-exact piece:

$$|j_3^C|^2 \supset \left(\frac{1}{z^2}\right)^2$$

  which has a non-local tail. In contrast the full source $j_3 = j_3^h + j_3^e + j_3^c$ is completely D7-localized.

- A direct derivation of the perfect square action by completing the action under SUSY transformations would settle these issues **[work in progress].**

Electro-Magnetic Interpretation

- The non-local tail of the projected source may be a red herring as the Type IIB action used is not manifestly EM duality invariant.
- Consider the brane-bulk coupling

$$G_3 \wedge *\bar{j}_3 = G_3 \wedge *\left(\bar{j}_3^h + \bar{j}_3^e + \bar{j}_3^c\right)$$

the exact & co-exact pieces are the **electric** & **magnetic** currents:

$$G_3 \wedge *\bar{j}_3^c \sim *G_3 \wedge \bar{j}_3^c \sim G_7 \wedge \bar{j}_3^c \sim dA_6 \wedge \bar{j}_3^c \sim A_6 \wedge J_{mag}$$

- The exact piece would not have contributed since it is exact. Likewise, the co-exact piece couples to A_2 but not to A_6.
- The usual Type IIB action keeps only p-forms with p ≤ 5 and with self-duality of the 5-form imposed.

Electro-Magnetic Interpretation (Continued)

- If instead G_3 is sourced by both electric and magnetic currents, we do not need to project the source:

$$\left| G_3 + j_3 \right|^2 \quad \text{with} \quad j_3 \sim \lambda^2 \delta_{D7} \overline{\Omega}$$

as the EOMs are:

$$dG_3 = J_{mag} \equiv d\bar{j}_3^e \quad \text{and} \quad d * G_3 = J_{el} \equiv d\bar{j}_3^c$$

The non-flux part of G_3 would cancel all but the harmonic part of j_3.

- We have a completely local action throughout and still find a finite result:

$$\left| G_3^{(0)} + j_3^h \right|^2 \sim \left| G_3^{(0)} + \lambda^2 \Omega / A_\perp \right|^2$$

[work in progress]

Revisiting KKLT

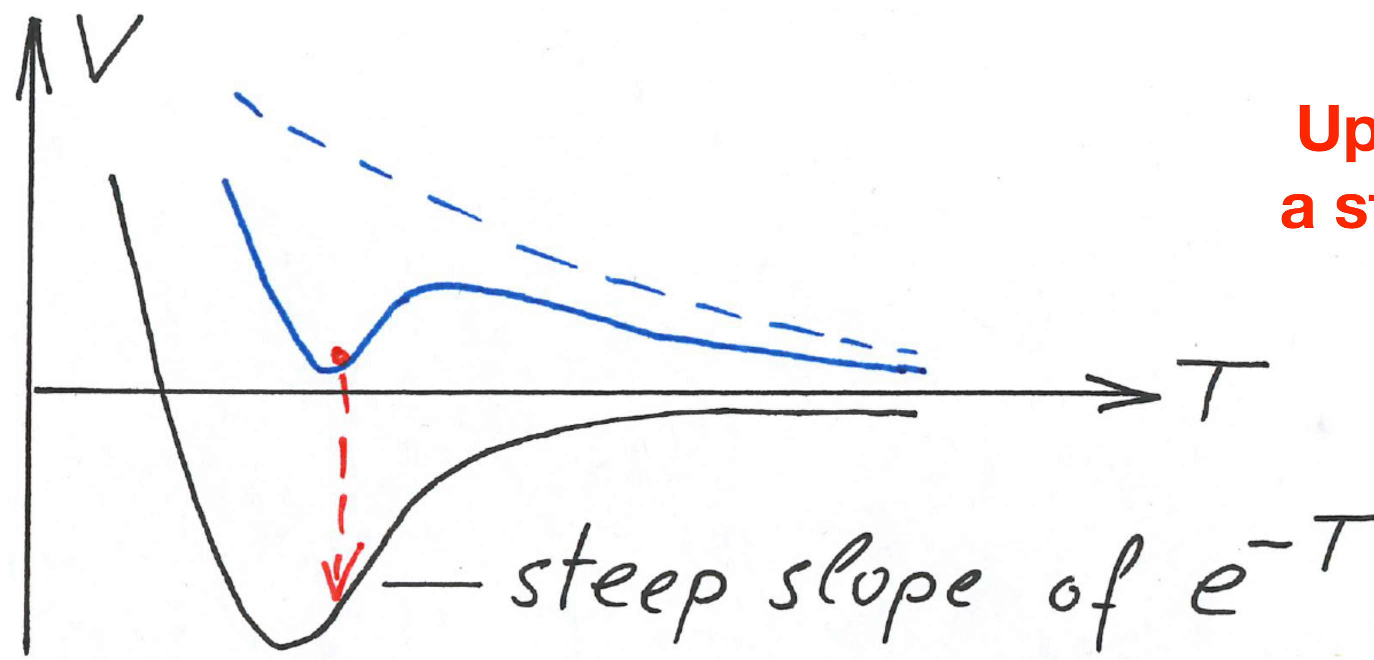
- Concerning KKLT, the above are fine points. In the end, one has (possibly without the need for the projection):

$$\mathscr{L} \supset \left| \overline{G}_3 - P\left(\lambda\lambda\Omega_3\delta_{D7}\right) \right|^2$$

- **4d Approach:** From this action, we can derive the 4d effective potential (with or without the anti-D3 uplift) in agreement with KKLT.
- **10d Approach:** One can also plug this action into the 10d Einstein equations, and again obtain the 4d curvature (with or without uplift).
- Our results are in agreement with **[Carta, Moritz, Westphal]** but in some (partial) disagreement with **[Gustason, Van Hemelryck, Van Riet, Venken].**

Revisiting KKLT (Continued)

- As we have shown, 4d EOMs imply the integrated 10d Einstein eqs. and so the match with the 4d description of KKLT should work.



Uplift is due to shift of T along a steep slope by anti D3-brane.

[Hamada, Hebecker, GS, Soler];[Carta, Moritz, Westphal]

- The disagreement with **[Gautason, Van Hemelryck, Van Riet, Venkens]** is on the treatment of the T dependence in the 10d energy-momentum tensor, which we now briefly comment.

Treatment of 10d Stress Tensor of Gaugino Condensate

- Our approach:

$$g_{mn}\frac{\delta}{\delta g_{mn}}S_{eff} \rightarrow T\frac{\partial}{\partial T}S_{eff} \rightarrow T\frac{\partial}{\partial T}e^{-T}$$

- The derivative acting on e^{-T} gives the crucial dominant term that stops the runaway to large volume.

- The approach of Gautason et al (disregarding the red part):

$$T\frac{\delta}{\partial T}S_{class} \quad \text{with} \quad S_{class} \supset T\left[G_3\lambda^2 + \left(F_{\mu\nu}\right)^2\right]$$

- Subsequent quantum averaging gives $< \lambda^2 > \sim e^{-T}$ but the T-derivative never gets to act on the exponent.

- We believe the later treatment misses some key effects from say terms like $\langle G_3\lambda^2\left(F_{\mu\nu}\right)^2\rangle$ (see “Note added” in v3 of our paper).

Conclusions

KKLT in 10d

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  - Backreaction of antibranes and metastability? **[Panel Discussion 2]**
  - Gaugino condensate and flattening? **[Panel Discussion 3]**

Summary

- The recent de Sitter conjectures have significantly elevated the level of discussion on de Sitter vacua in string theory.
- Many of the issues currently being discussed/debated were not anticipated before; opening new doors for future investigations.
- Our regularized D7-brane gaugino action has alleviated one of the concerns of KKLT, but more remains to be done (e.g., direct SUSY derivation of λ^4 term, …) **[Hamada, Hebecker, GS, Soler, in progress]**
- New concerns have been raised **[Carta, Moritz, Westphal]; [Das, Haque, Underwood];[Bena, Dudas, Grana, Lust]; [Blumenhagen, Klaewer, Schlechter]; [Dasgupta, Emelin, Faruk, Tatar]; …**
- It is sometimes said that the same level of rigor is not achieved in realizing the SM + Einstein gravity in string theory (with all moduli fixed), are we aiming too high? IMHO, this is not a fair comparison.
- Hopefully, these efforts will bring us closer to a genuine string theoretical understanding of de Sitter vacua in string theory.