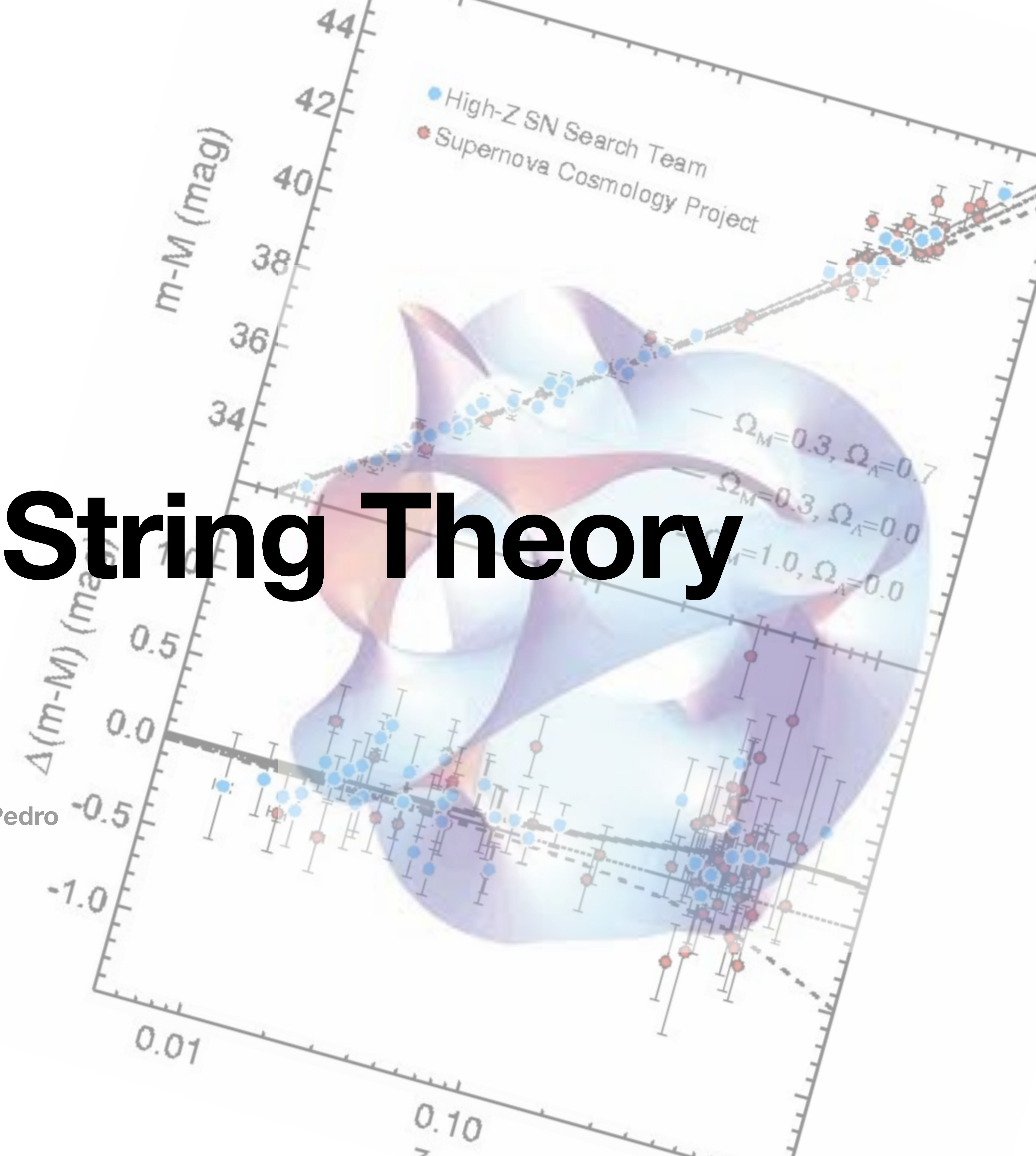
Quintessence in String Theory

Tony Padilla

Based on 2112.10783 [hep-th] and 2112.10779 [hep-th]

in collaboration with **Michele Cicoli, Francesc Cunillera-Garcia, Francisco Pedro**

University of Nottingham
UK | CHINA | MALAYSIA

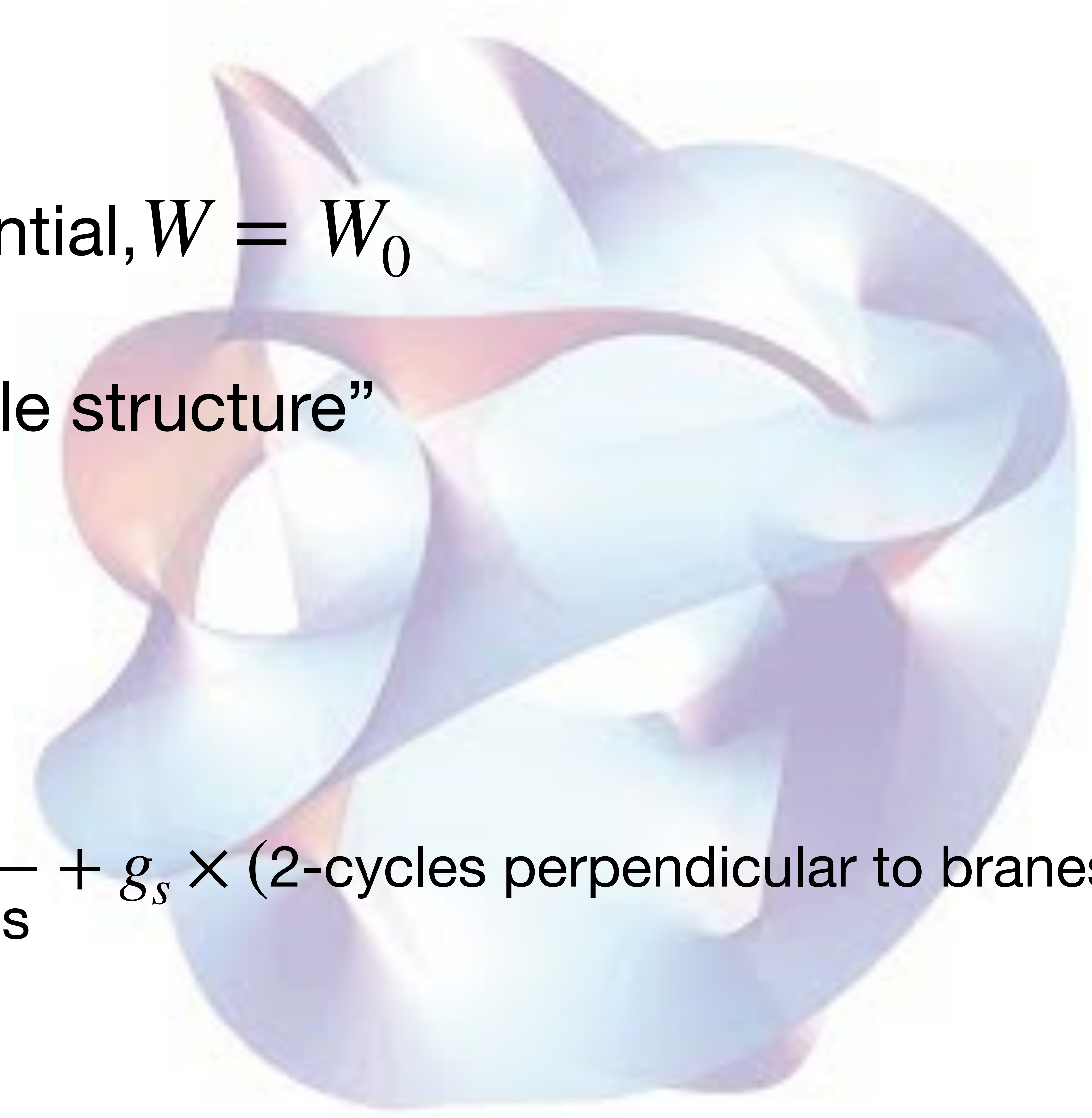


Take Home Message

Cicoli, Cunillera, Padilla, Pedro 2021

From the point of view of theoretical and phenomenological control, quintessence model building in ST is at least as challenging as search for dS vacua

Cosmology from String Theory



Model building ingredients: Type IIB strings

At “tree level” Kahler potential $K = K_0 - 2\ln\mathscr{V}$, super potential, $W = W_0$

Scalar potential ,V, vanishes identically due to famous “no scale structure”

Add corrections:

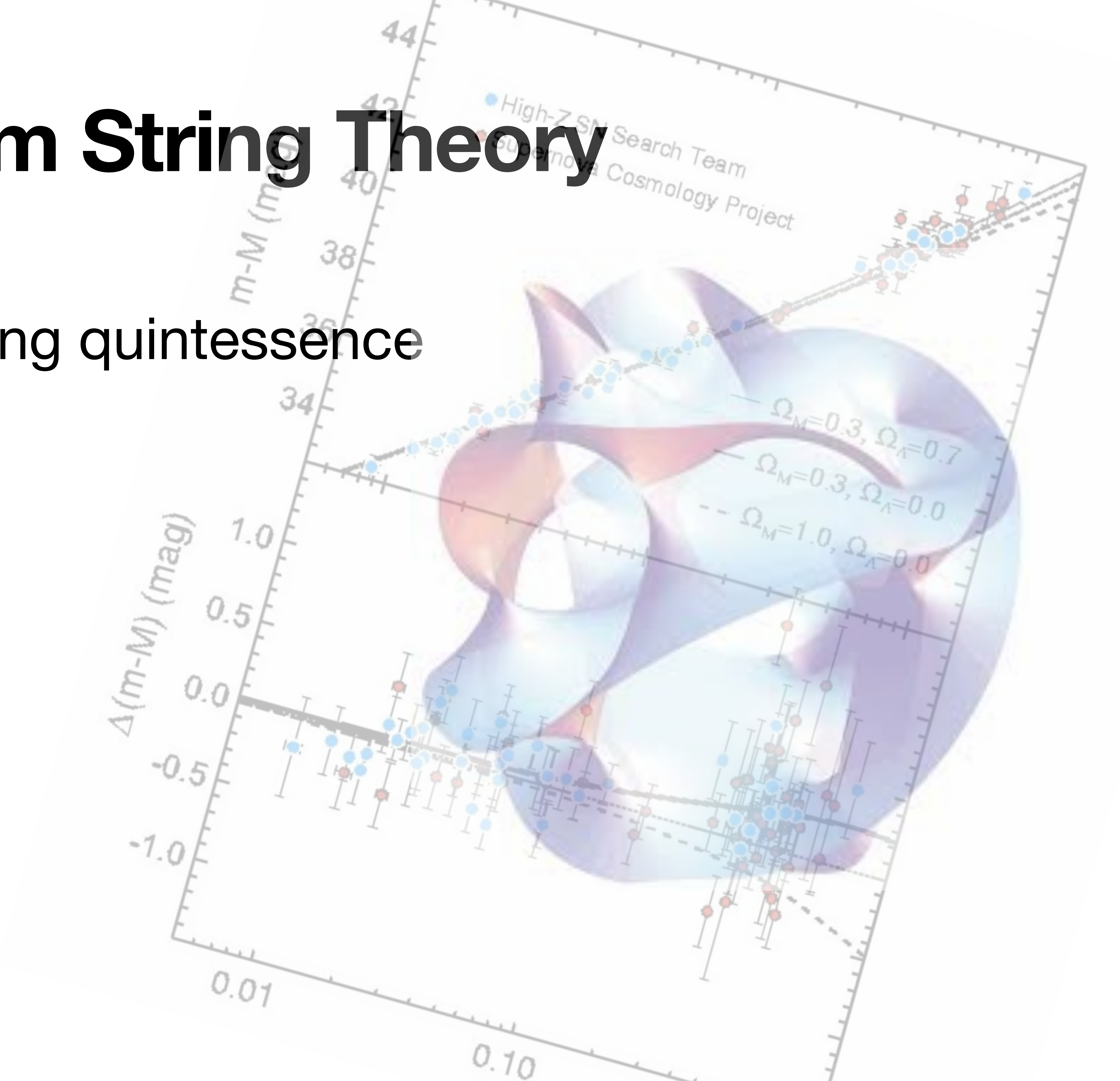
- α'^3 corrections $\delta K_{\alpha'} \sim \frac{1}{g_s^{3/2}\mathscr{V}}$
  Becker^2, Haack, Louis 2002
- Loop corrections $\delta K_{g_s} \sim \frac{1}{\mathscr{V}} \sum_{\text{2-cycles}} \left[\frac{1}{\text{2-cycles along brane intersections}} + g_s \times \text{(2-cycles perpendicular to branes)} \right]$
  Berg, Haack, Pajer 2007
- Non-perturbative corrections $\delta W_{np} \sim \sum_i A_i e^{-a_i T^i}$
  Blumenhagen et al 2009
- Higher derivative terms $\delta V_{hd} \sim \frac{1}{g_s^{3/2}\mathscr{V}^4} W_0^4 \times \text{(weighted sum over 2-cycle volume moduli)}$
  Ciupke, Louis, Westphal 2015

Quintessence from String Theory

Hebecker 2019

Pheno requirements on string quintessence

- light quintessence scale $m_\phi \lesssim 10^{-60} M_{pl}$
- heavy superpartners $m_{susy} \gtrsim 10^{-15} M_{pl}$
- heavy KK scale $m_{KK} \gtrsim 10^{-30} M_{pl}$
- heavy volume modulus $m_{\mathscr{V}} \gtrsim 10^{-30} M_{pl}$



Quintessence in String Theory: a blueprint

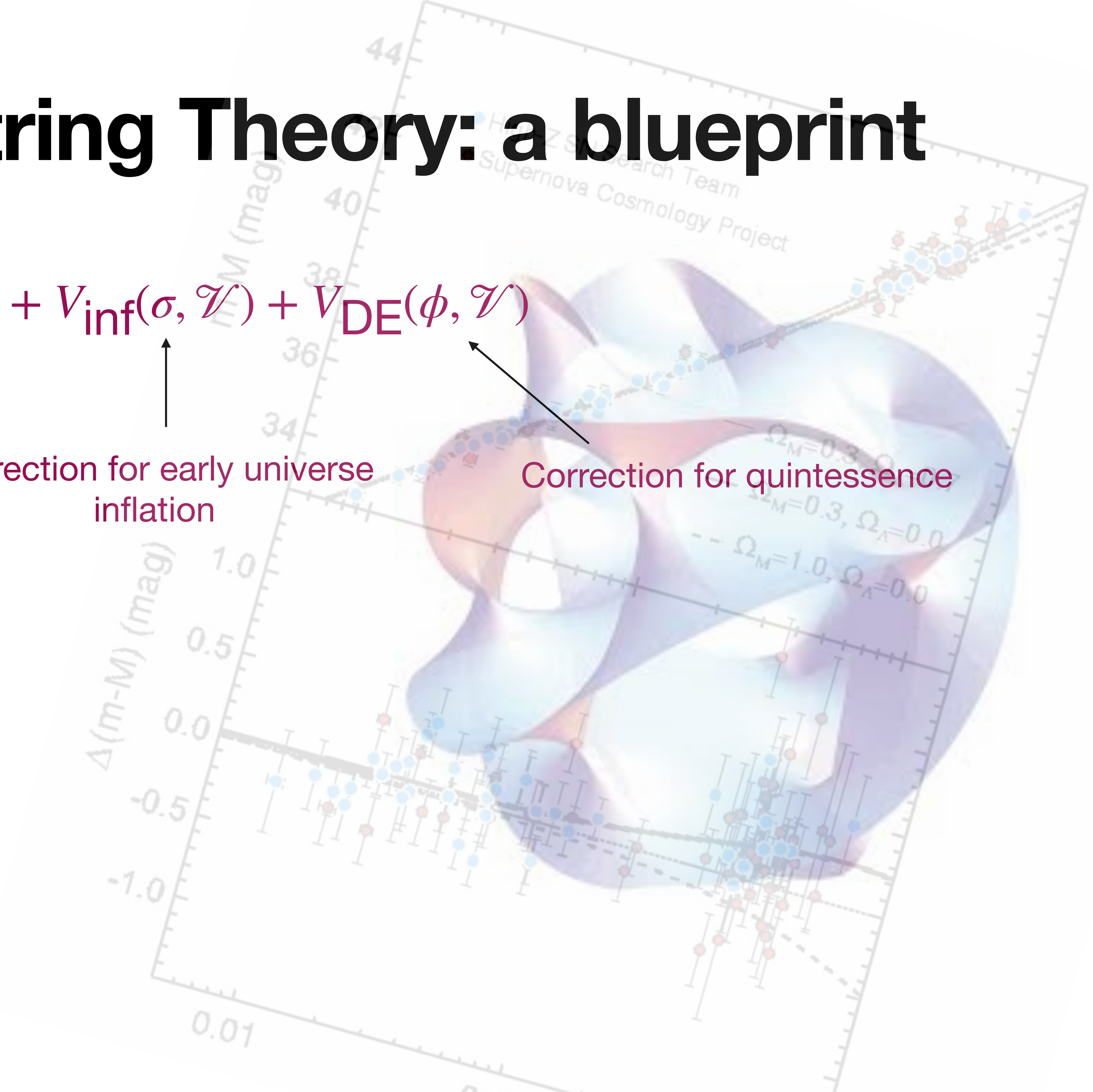
Cicoli, Cunillera, Padilla, Pedro 2021

Underlying scalar potential $V = V_{\text{vol}}(\mathscr{V}) + V_{\text{inf}}(\sigma, \mathscr{V}) + V_{\text{DE}}(\phi, \mathscr{V})$

Leading order potential for volume mode

Correction for early universe inflation

Correction for quintessence



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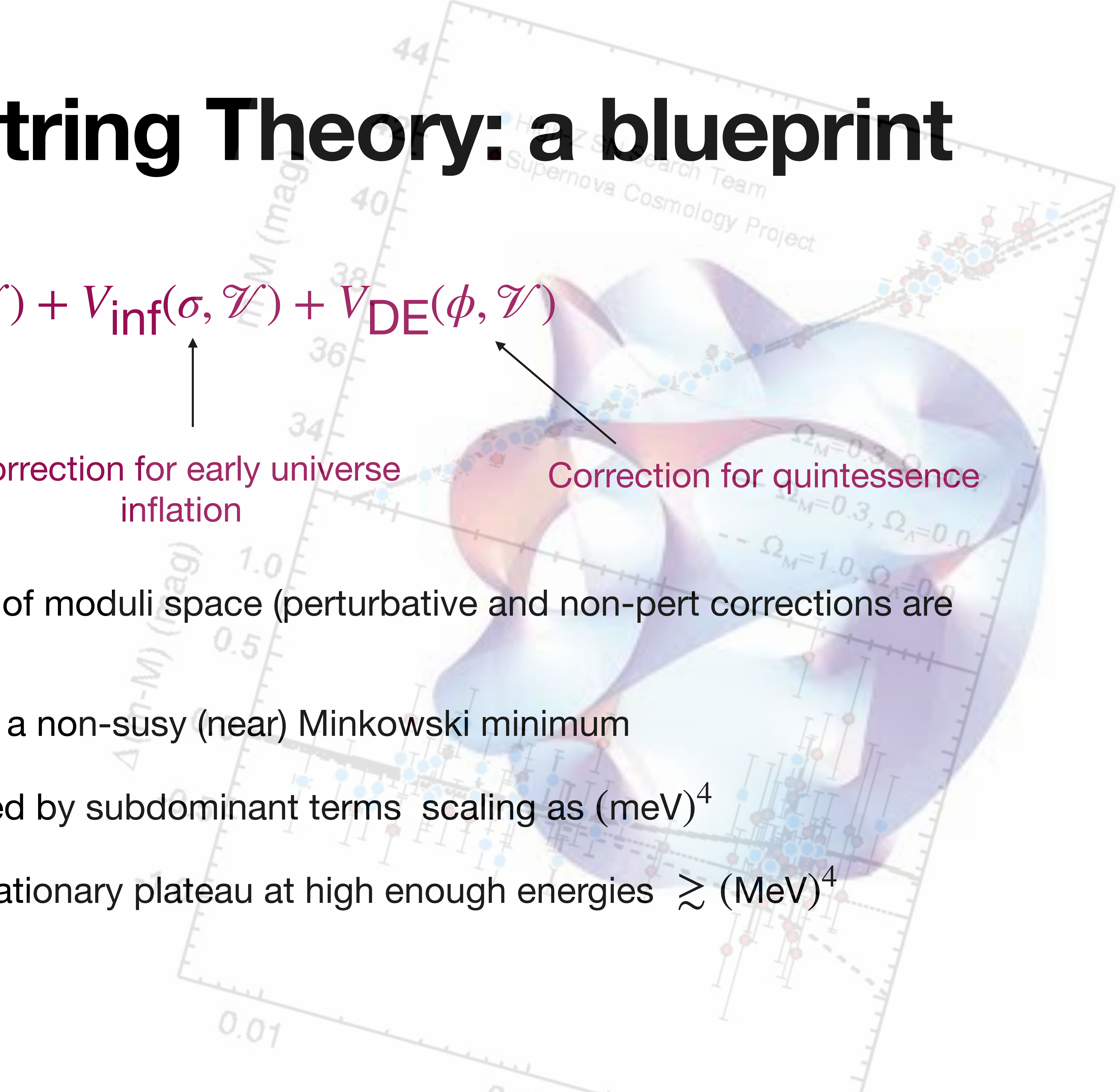

- quintessence cannot occur at boundary of moduli space (perturbative and non-pert corrections are crucial)
- at leading order $V_{\text{vol}}(\mathscr{V})$ should feature a non-susy (near) Minkowski minimum
- at leading order V_{DE} should be flat, lifted by subdominant terms scaling as $(\text{meV})^4$
- at leading order V_{inf} should contain inflationary plateau at high enough energies $\gtrsim (\text{MeV})^4$

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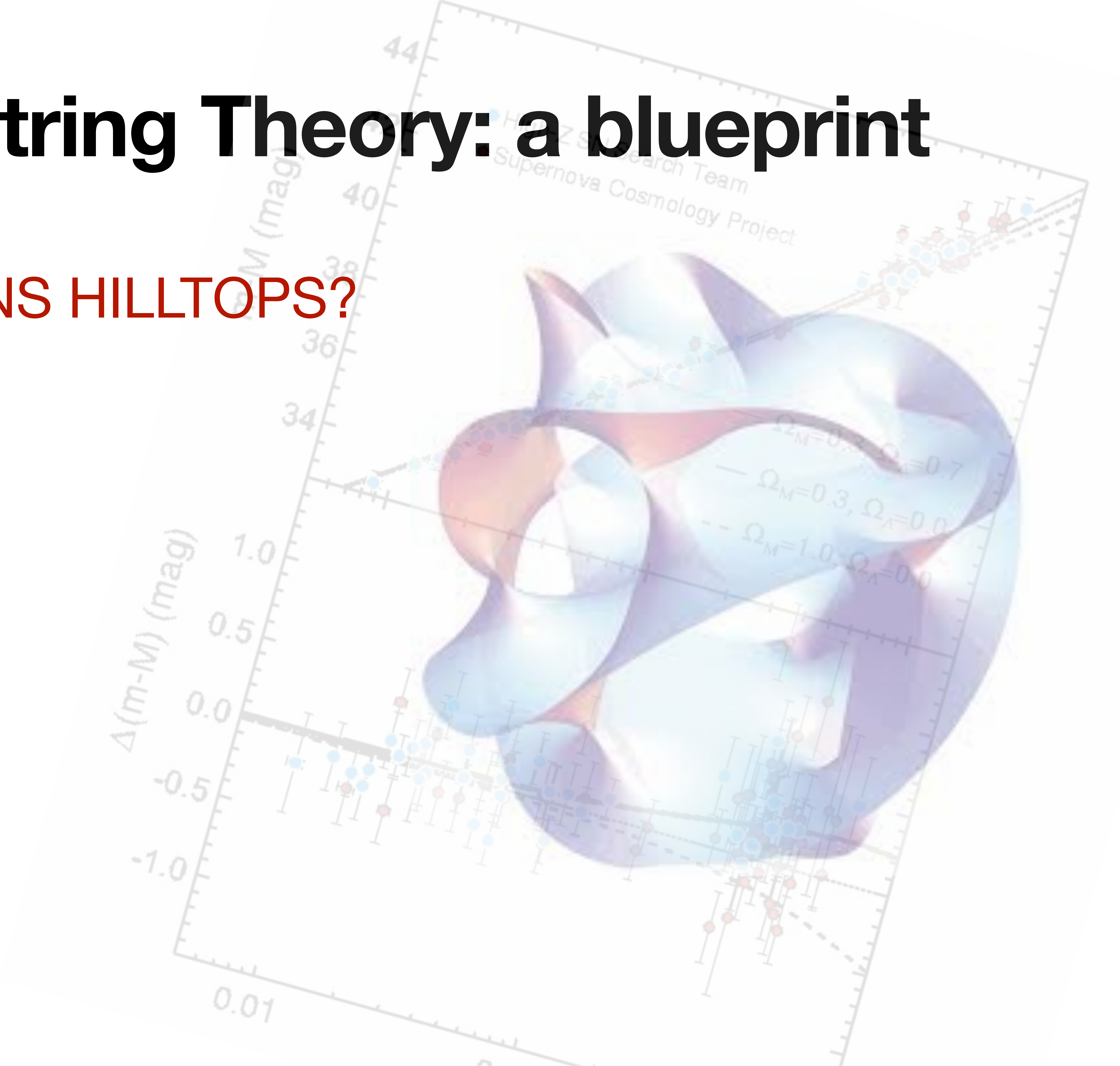
AXIONS HILLTOPS?



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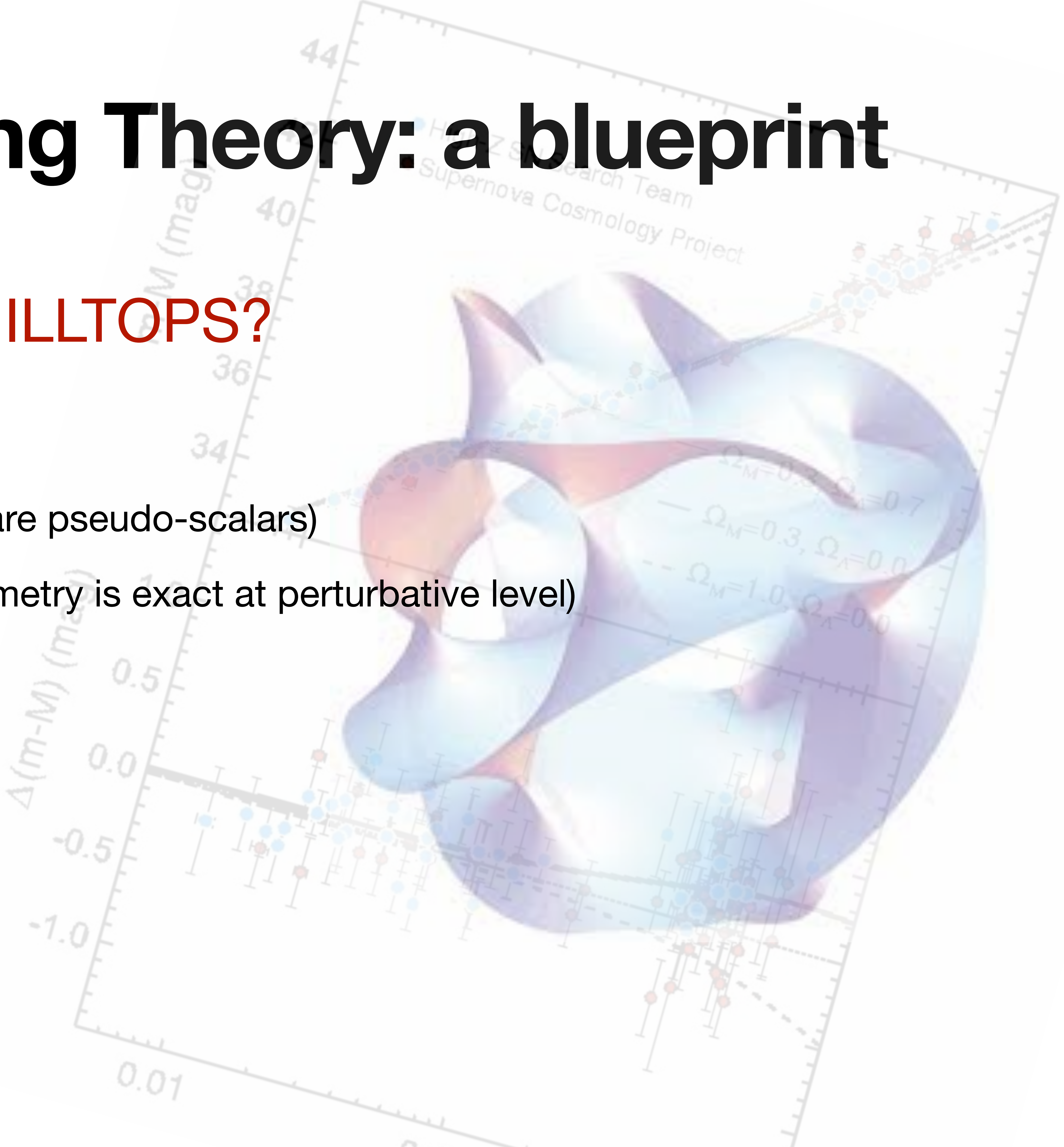
AXIONS HILLTOPS?

- axions avoid 5th force problems (since they are pseudo-scalars)
- axions are radiatively stabile (since shift symmetry is exact at perturbative level)



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AXIONS HILLTOPS?

- axions avoid 5th force problems (since they are pseudo-scalars)
- axions are radiatively stabile (since shift symmetry is exact at perturbative level)
- axion decay constants from ST tend to be sub Planckian
- initial conditions for hilltop quintessence must be very finely tuned in this case
- quantum diffusion during inflation is a problem unless in inflationary scale is very low

More problems for quintessence

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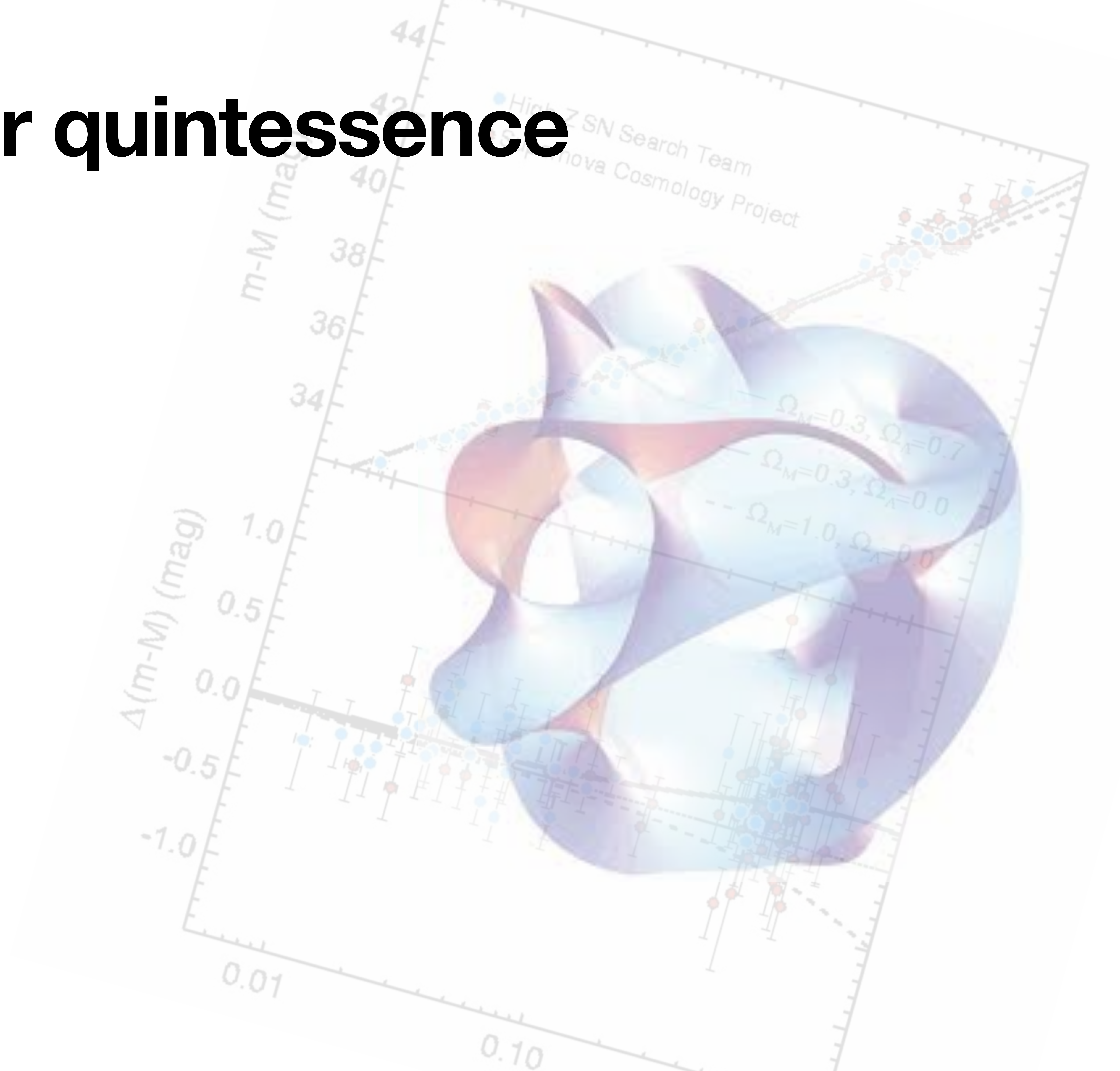

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The Kallosh Linde Problem

Kallosh Linde 2004

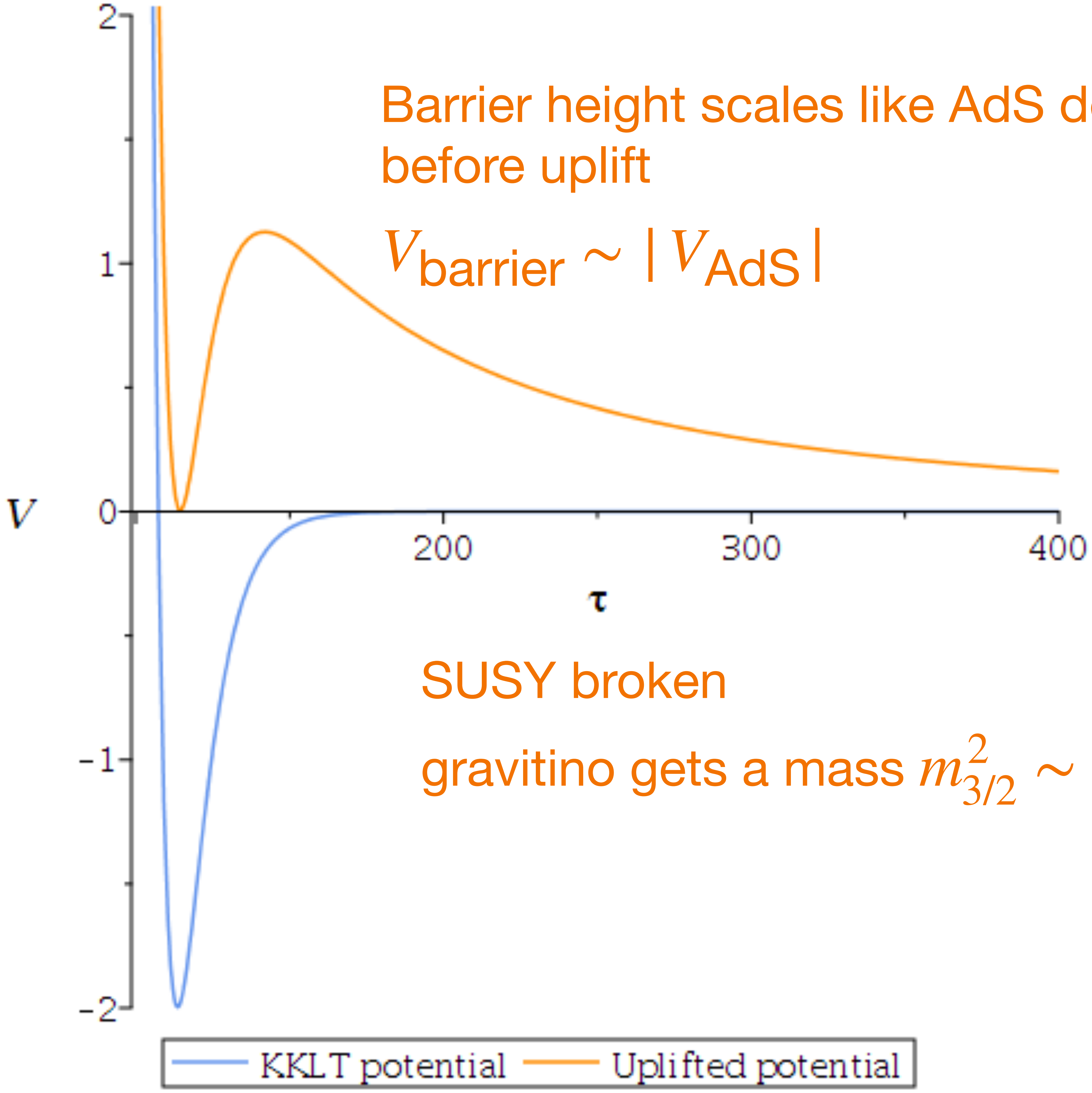
KKLT model

$$K = K_0 - 2\ln\left(\mathscr{V} + \frac{\xi}{2}\right), \qquad W = W_0 + Ae^{-aT}$$

where $\xi \propto \alpha'^3$ and $\mathscr{V} = (T + \bar{T})^{3/2}, \quad T = \tau + i\theta$

Obtain scalar potential with AdS minimum, V_{AdS}

Add an uplift $V_{\text{up}} = \dfrac{C}{\tau^2}$



Barrier height scales like AdS depth before uplift

$V_{\text{barrier}} \sim |V_{\text{AdS}}|$

SUSY broken

gravitino gets a mass $m_{3/2}^2 \sim |V_{\text{AdS}}|$

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The Kallosh Linde Problem

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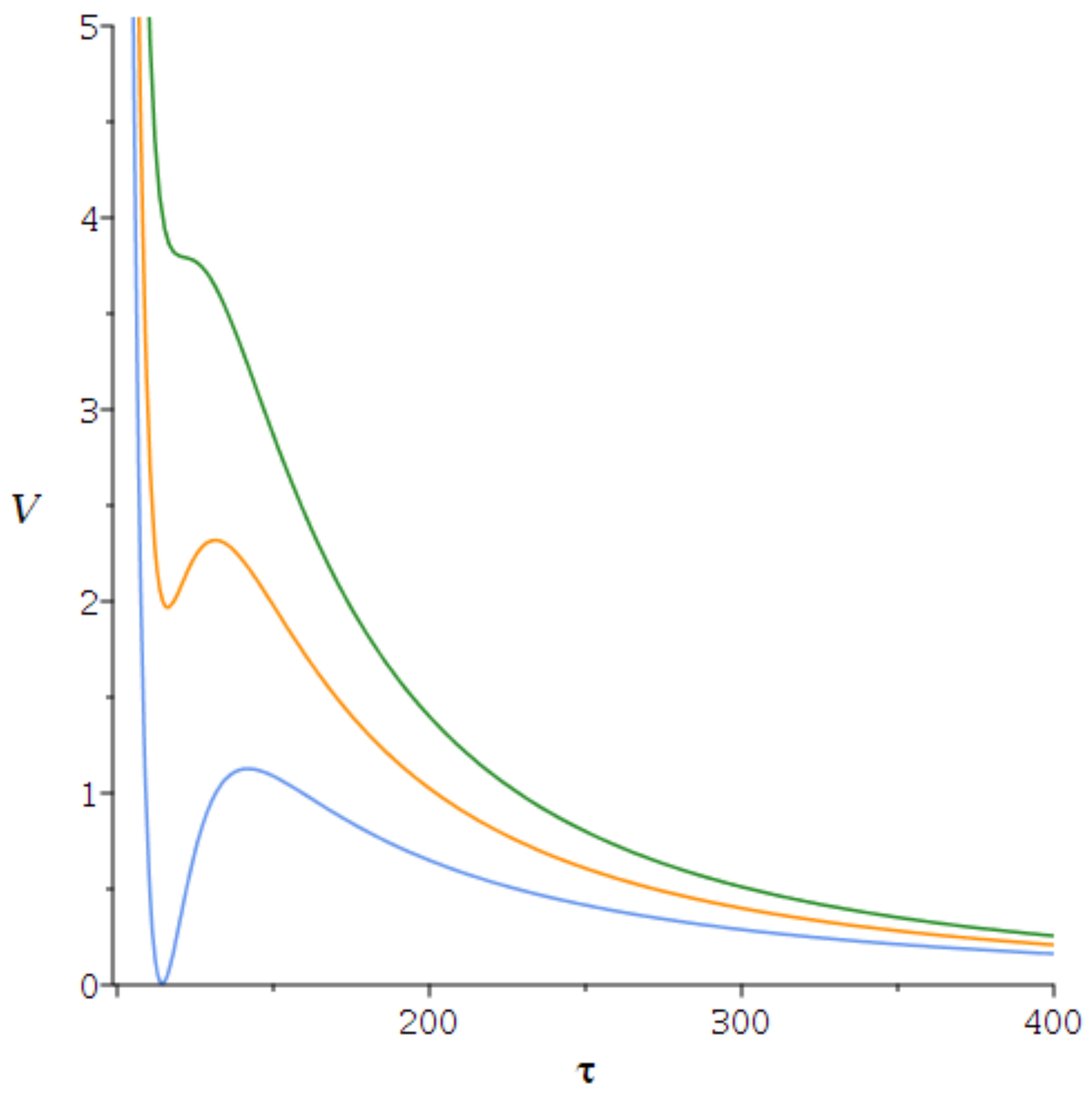
Imagine inflation driven by brane dynamics

$$V \to V_{\text{KKLT}}(\tau) + \frac{U(\sigma)}{\tau^3}$$

To avoid the runaway in volume requires

$$H_{\text{inf}}^2 \lesssim V_{\text{barrier}} \sim |V_{\text{AdS}}| \sim m_{3/2}^2$$

Sets very high scale of SUSY breaking



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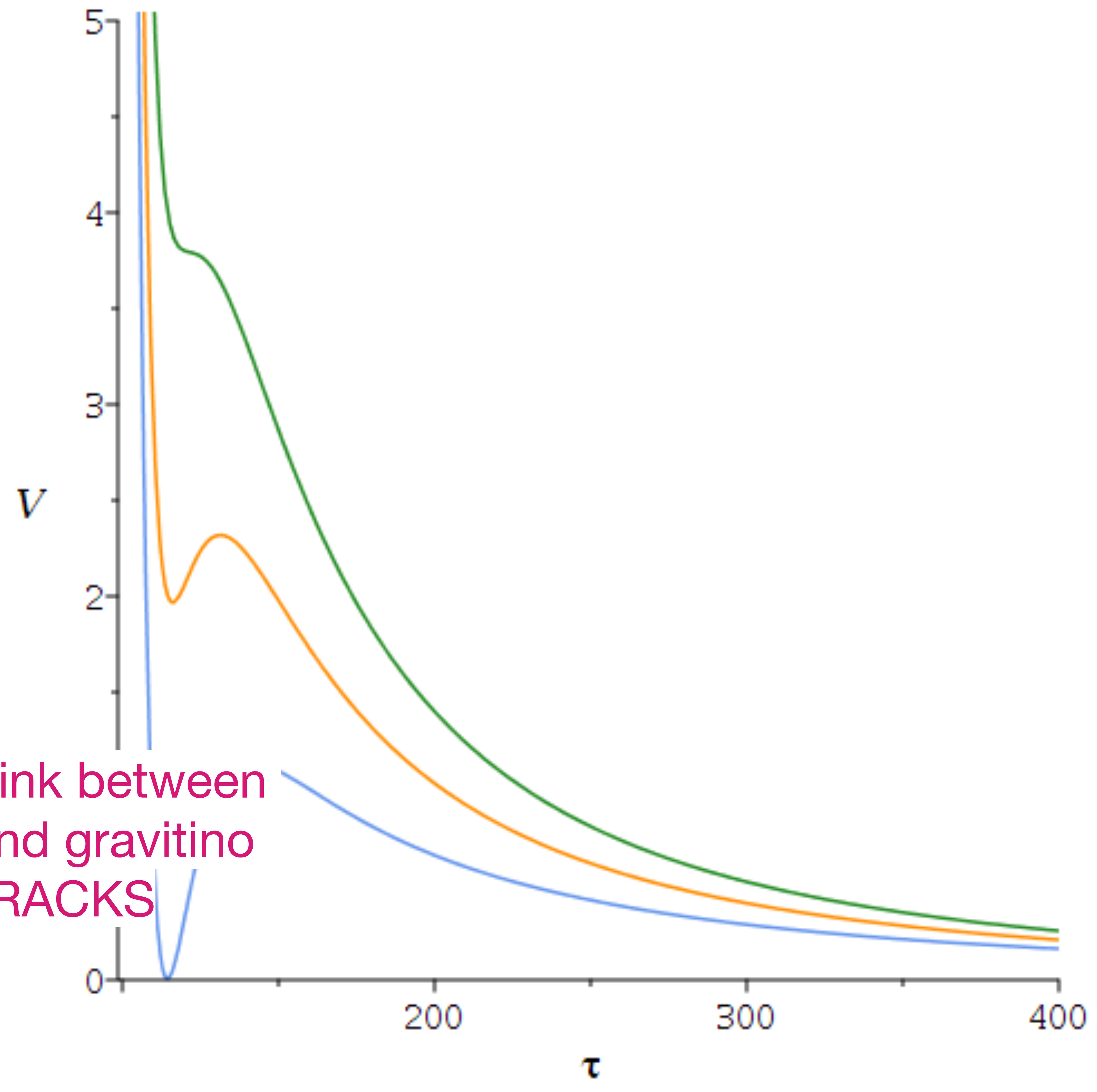
Need to break link between barrier height and gravitino mass…RACETRACKS



More problems for quintessence

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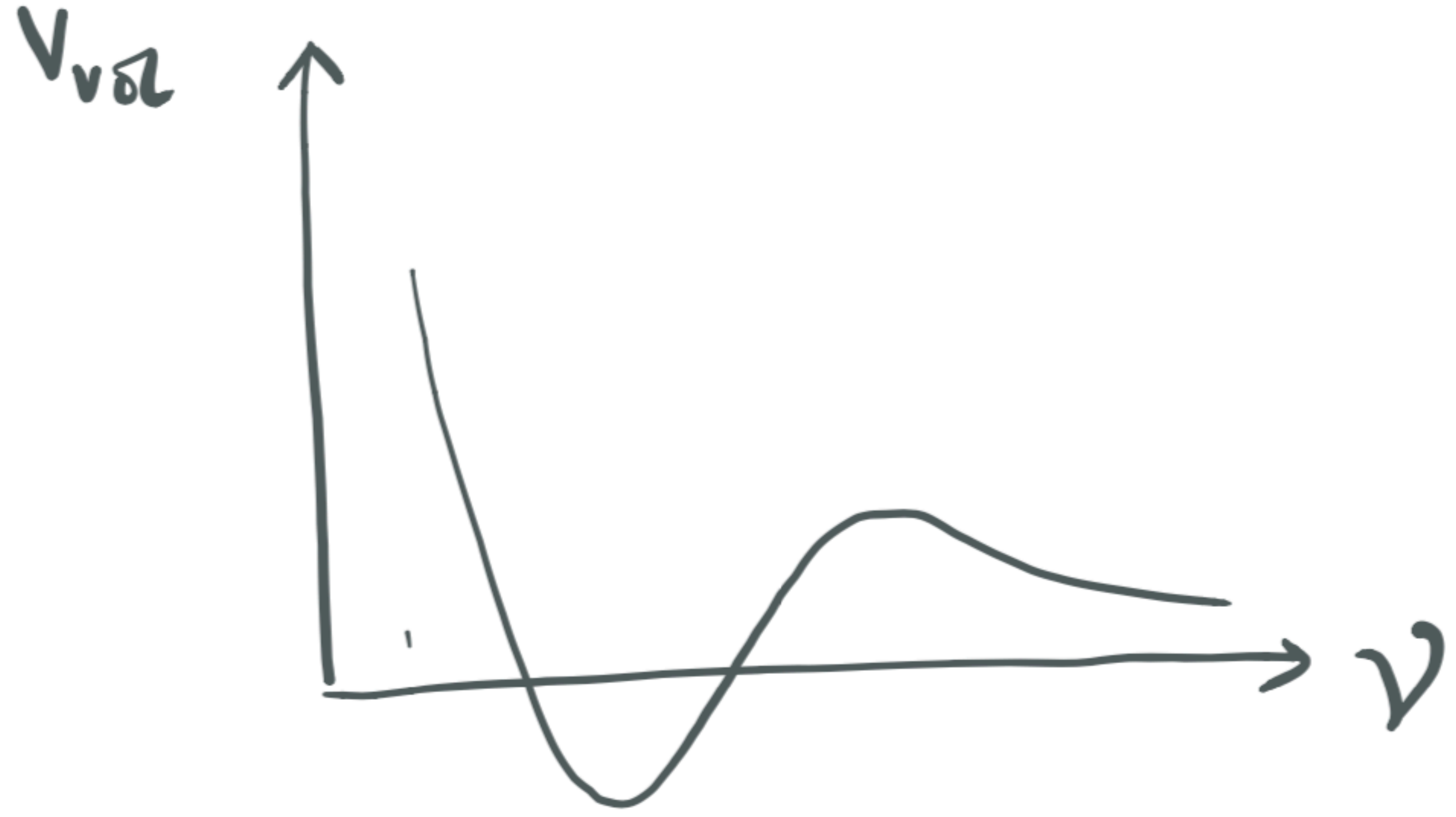
The KL Problem for Quintessence

$$V = V_{\text{vol}}(\mathscr{V}) + V_{\text{inf}}(\sigma, \mathscr{V}) + V_{\text{DE}}(\phi, \mathscr{V})$$

At late times, potential is
$V_{\text{late}}(\phi, \mathscr{V}) = V_{\text{vol}}(\mathscr{V}) + V_{\text{DE}}(\phi, \mathscr{V})$

At early times, during inflation, we pick up the inflationary correction

$$V_{\text{early}} = V_{\text{late}}(\phi, \mathscr{V}) + \frac{U(\sigma)}{\mathscr{V}^{\frac{4}{3}}}$$



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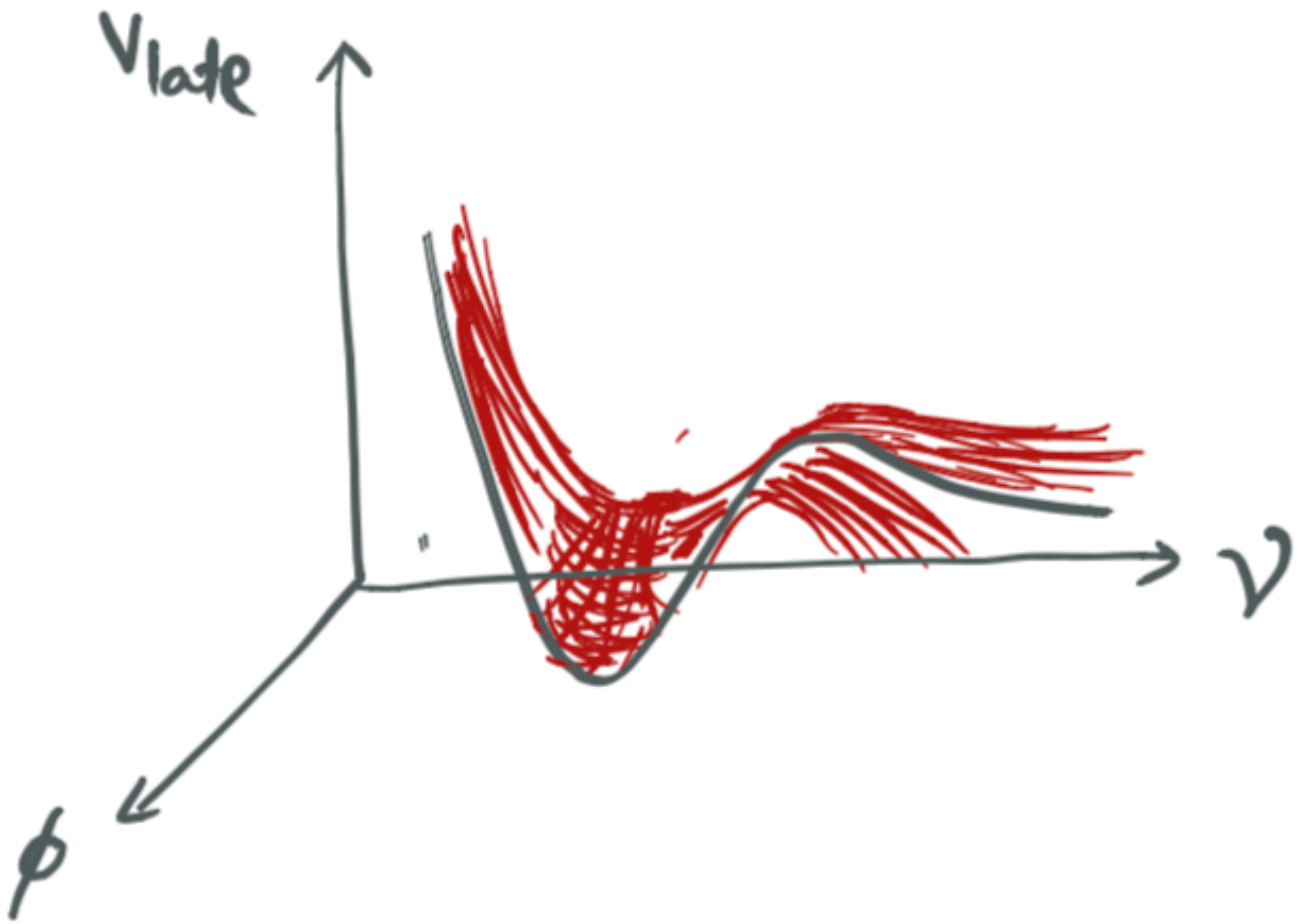

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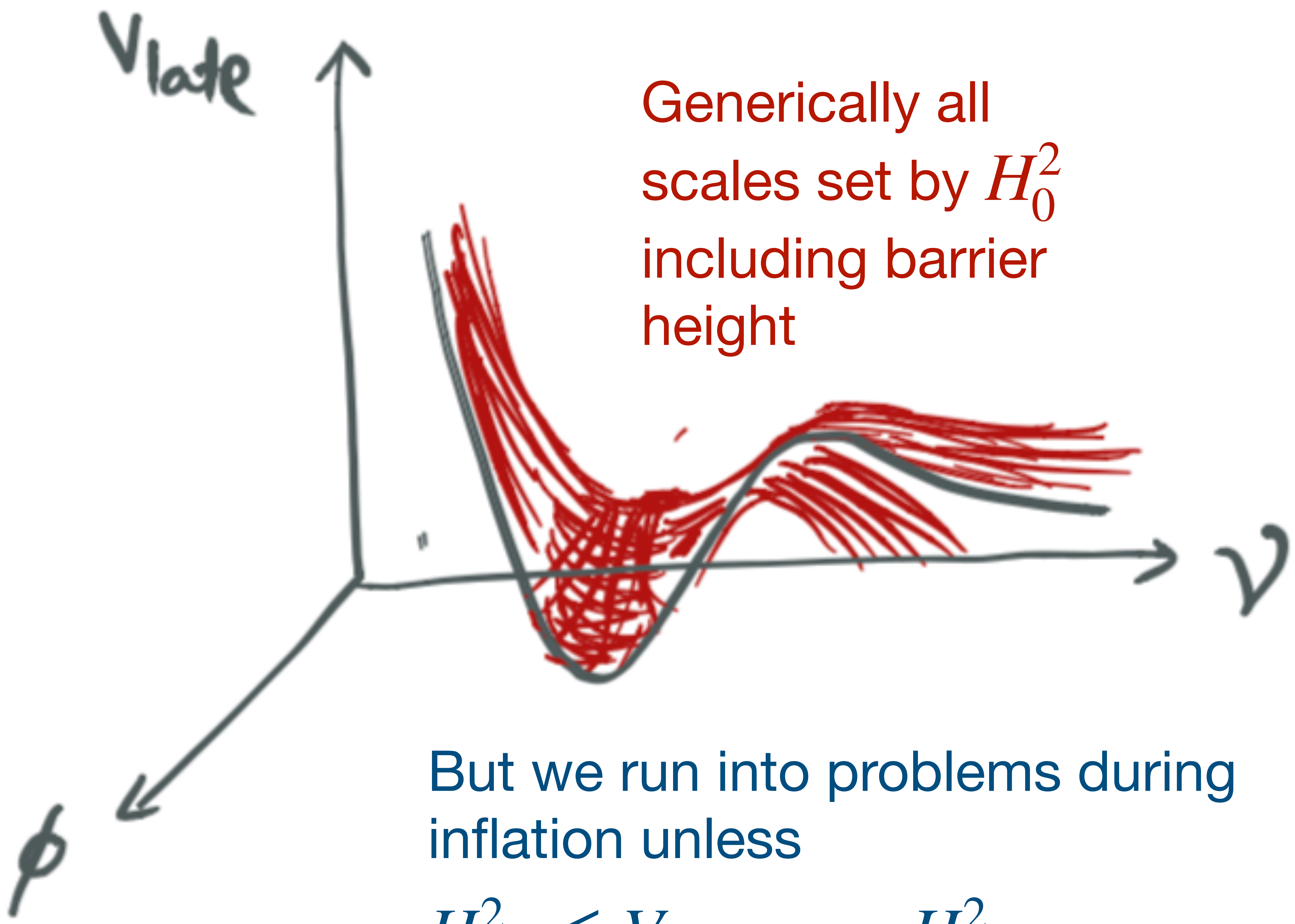

Generically all scales set by H_0^2 including barrier height

But we run into problems during inflation unless

$$H_{\text{inf}}^2 \lesssim V_{\text{barrier}} \sim H_0^2$$

which is obviously not satisfied!

More problems for quintessence

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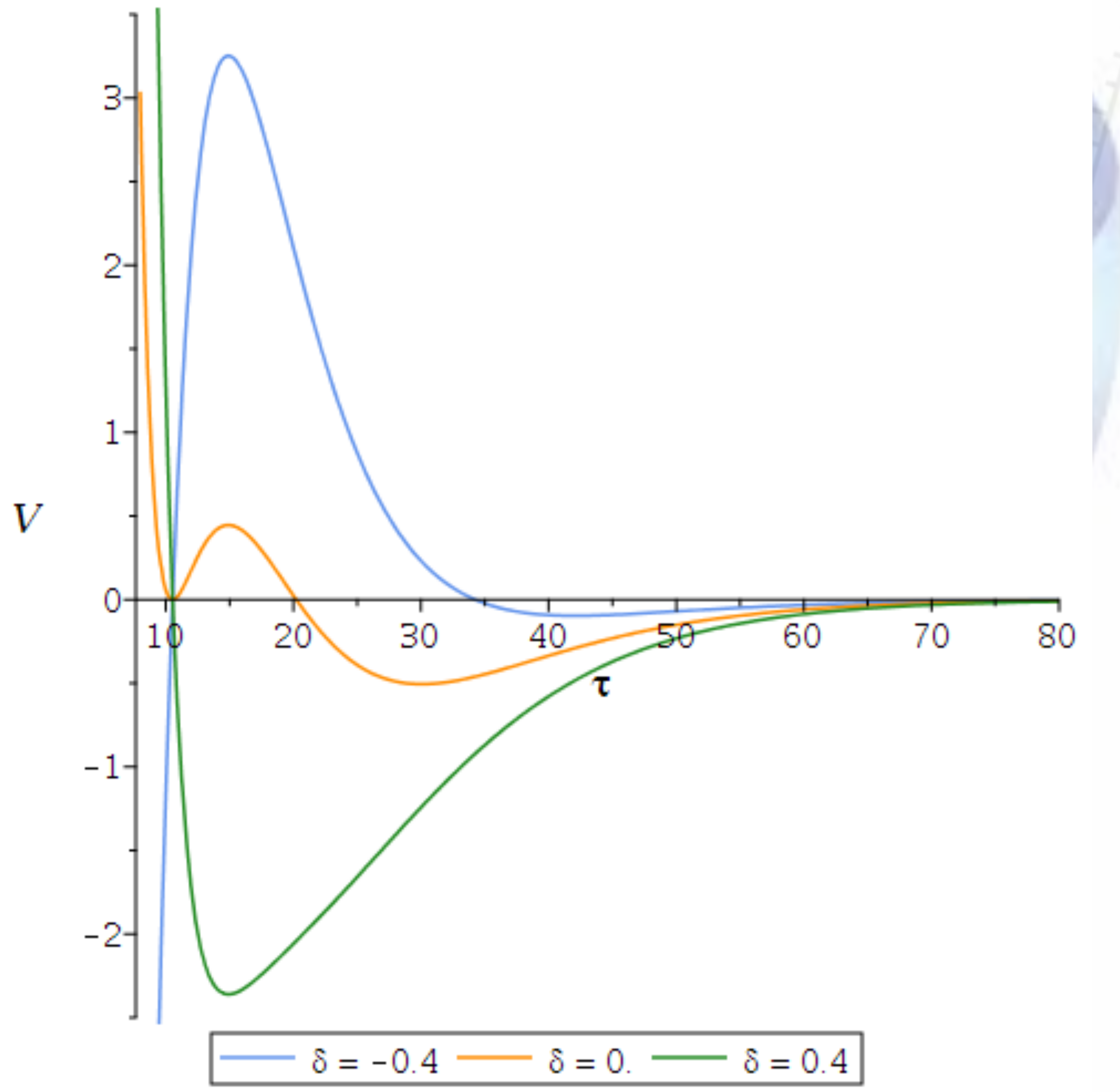
The KL Problem for Quintessence - a racetrack solution?

Racetracks break the link between barrier height and gravitino mass $m_{3/2} \sim H_0$

KKLT with two instantons $W \to W_0 + Ae^{-aT} - Be^{-bT}$

Model admits SUSY vacuum for critical choice of W_0



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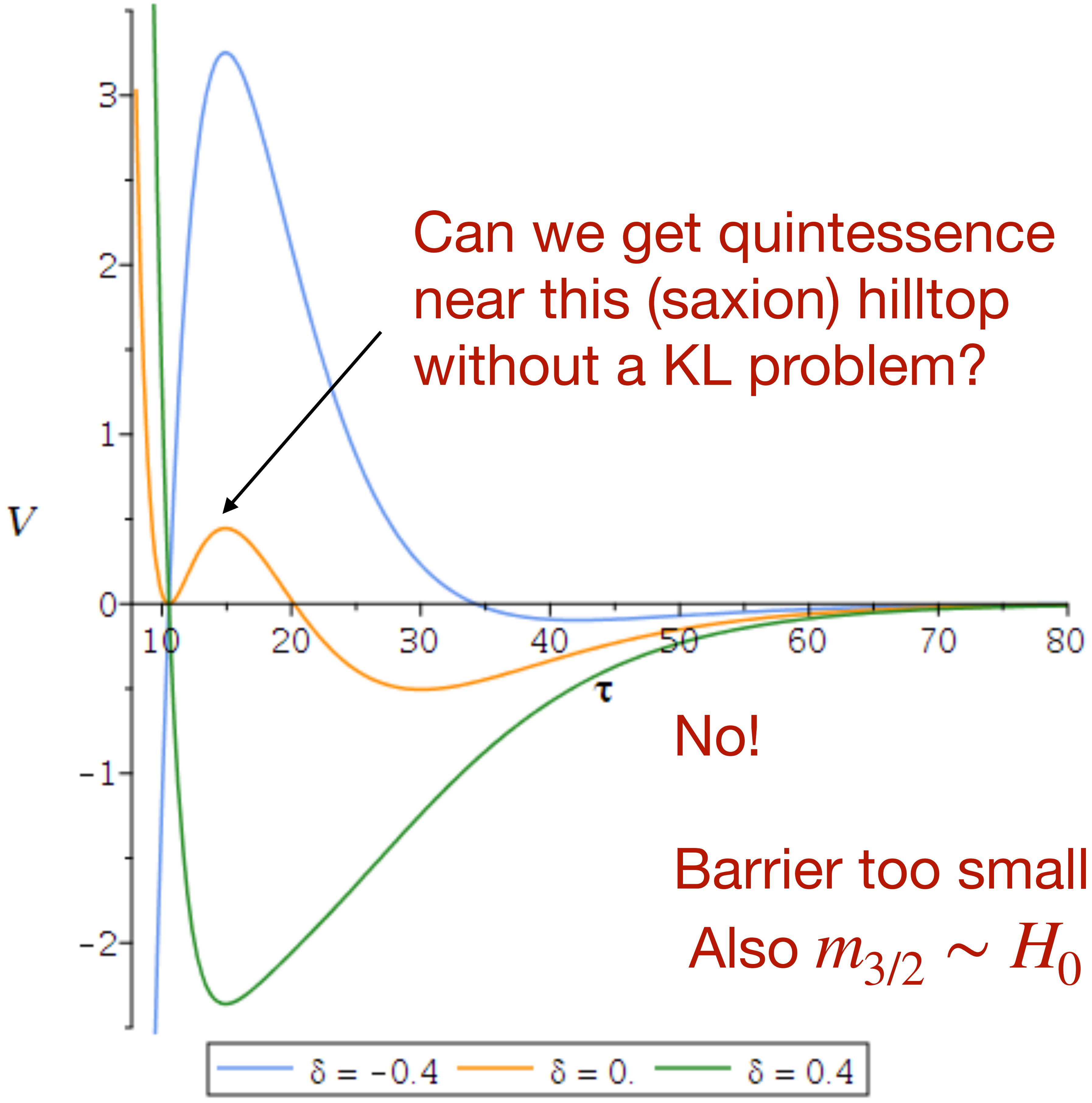

Can we get quintessence near this (saxion) hilltop without a KL problem?

No!

Barrier too small

Also $m_{3/2} \sim H_0$

More problems for quintessence

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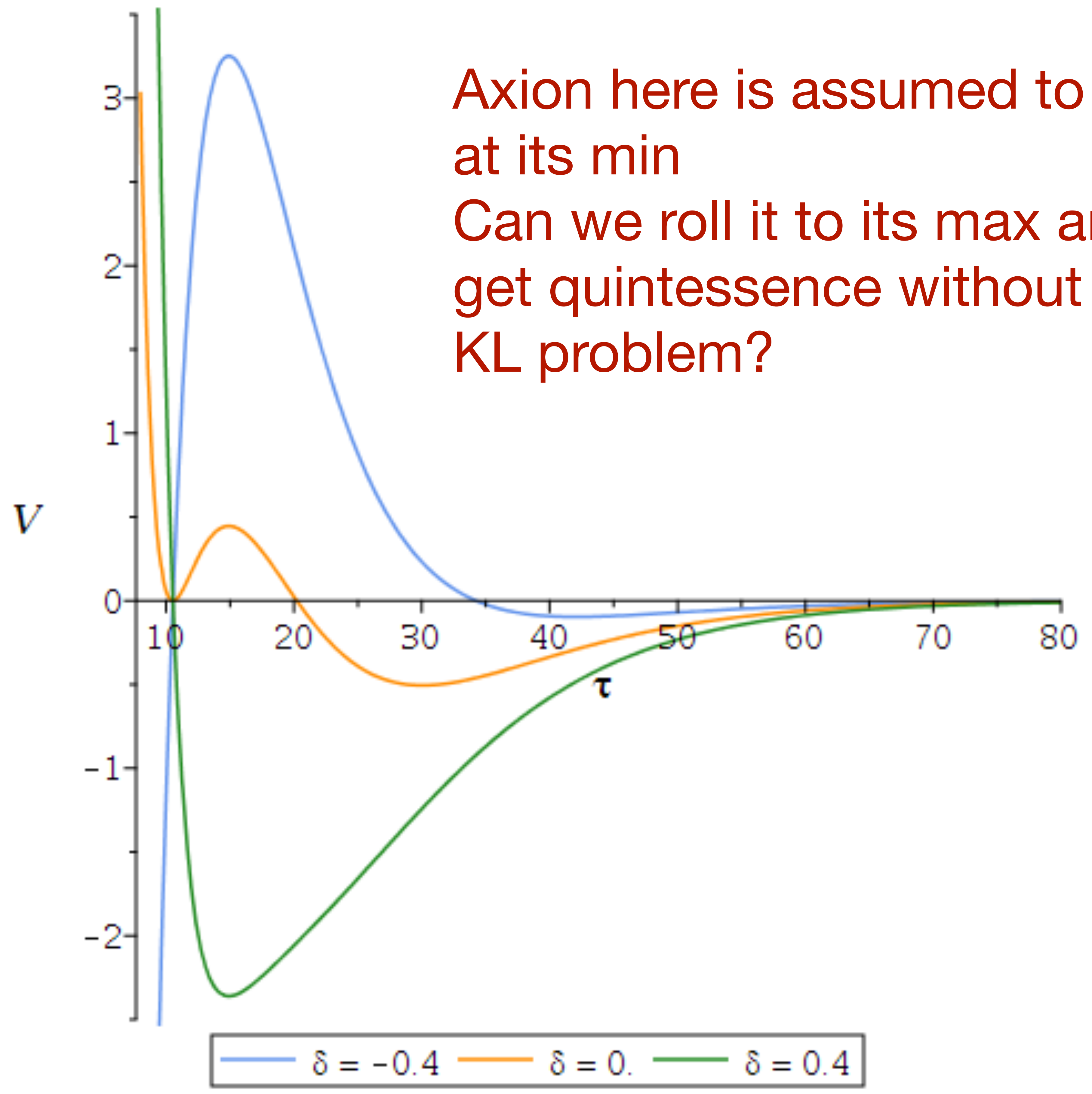

Axion here is assumed to be at its min
Can we roll it to its max and get quintessence without a KL problem?

More problems for quintessence

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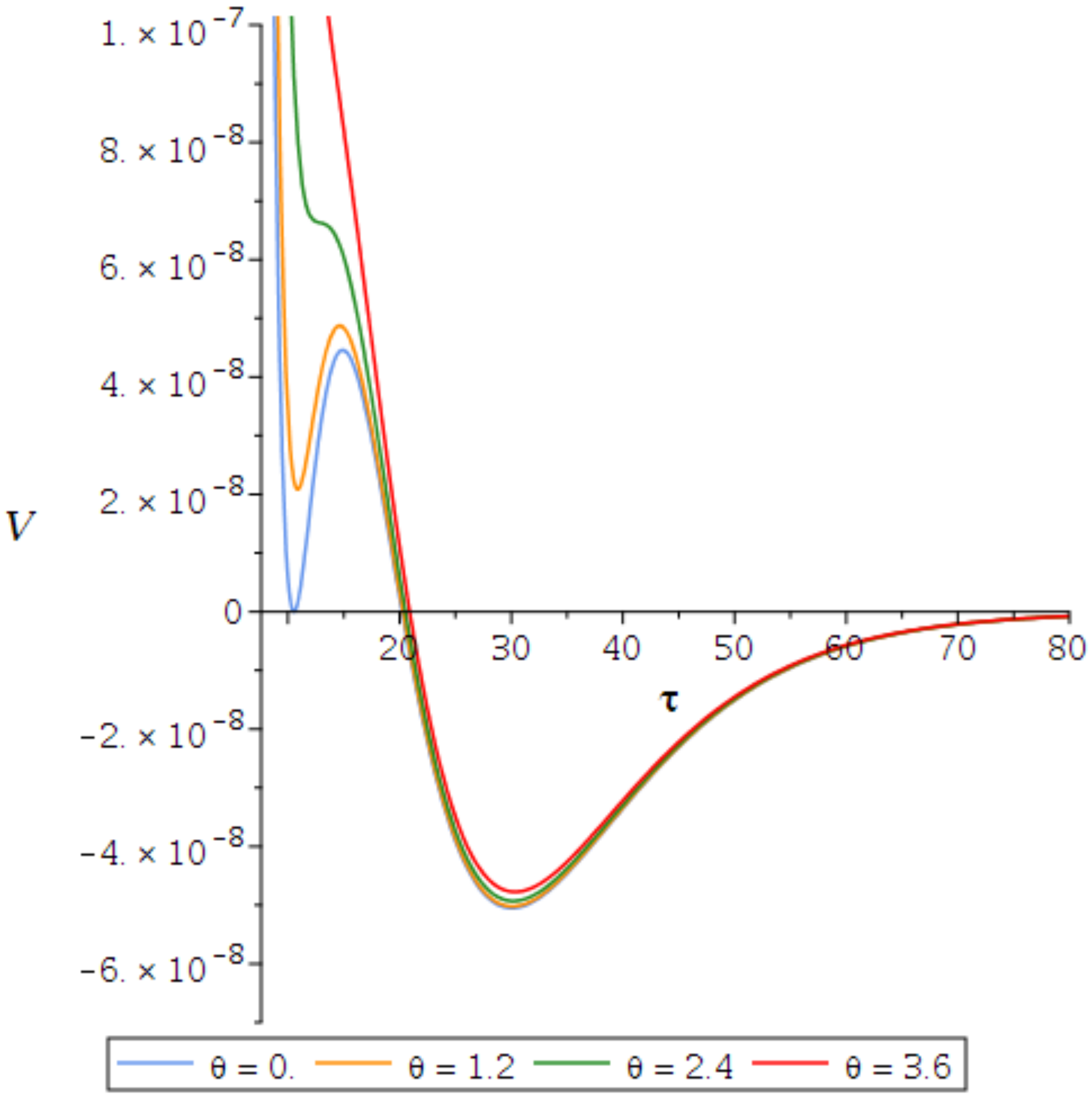

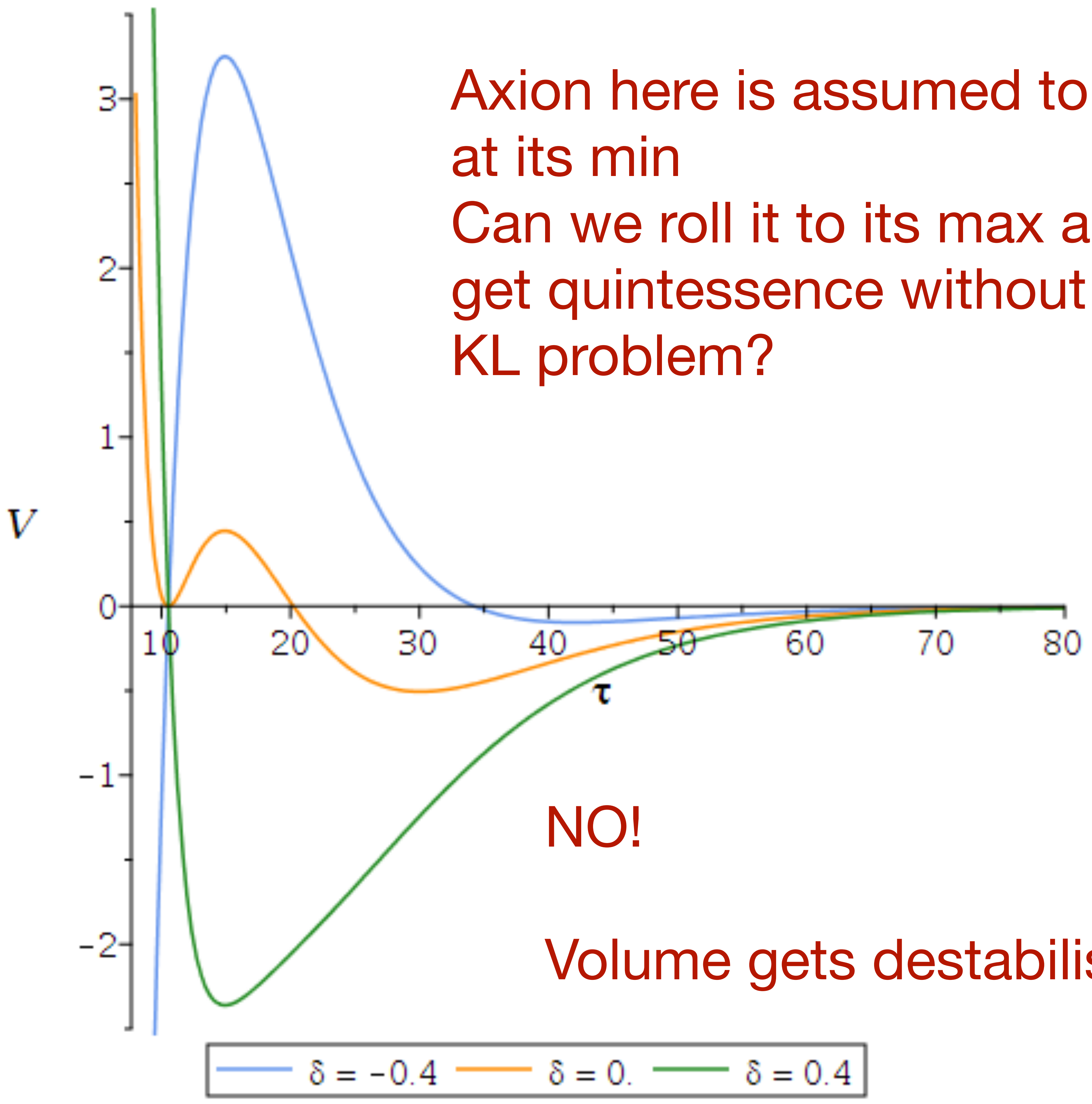

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NO!

Volume gets destabilised

Quintessence in String Theory: a blueprint

Cicoli, Cunillera, Padilla, Pedro in progress

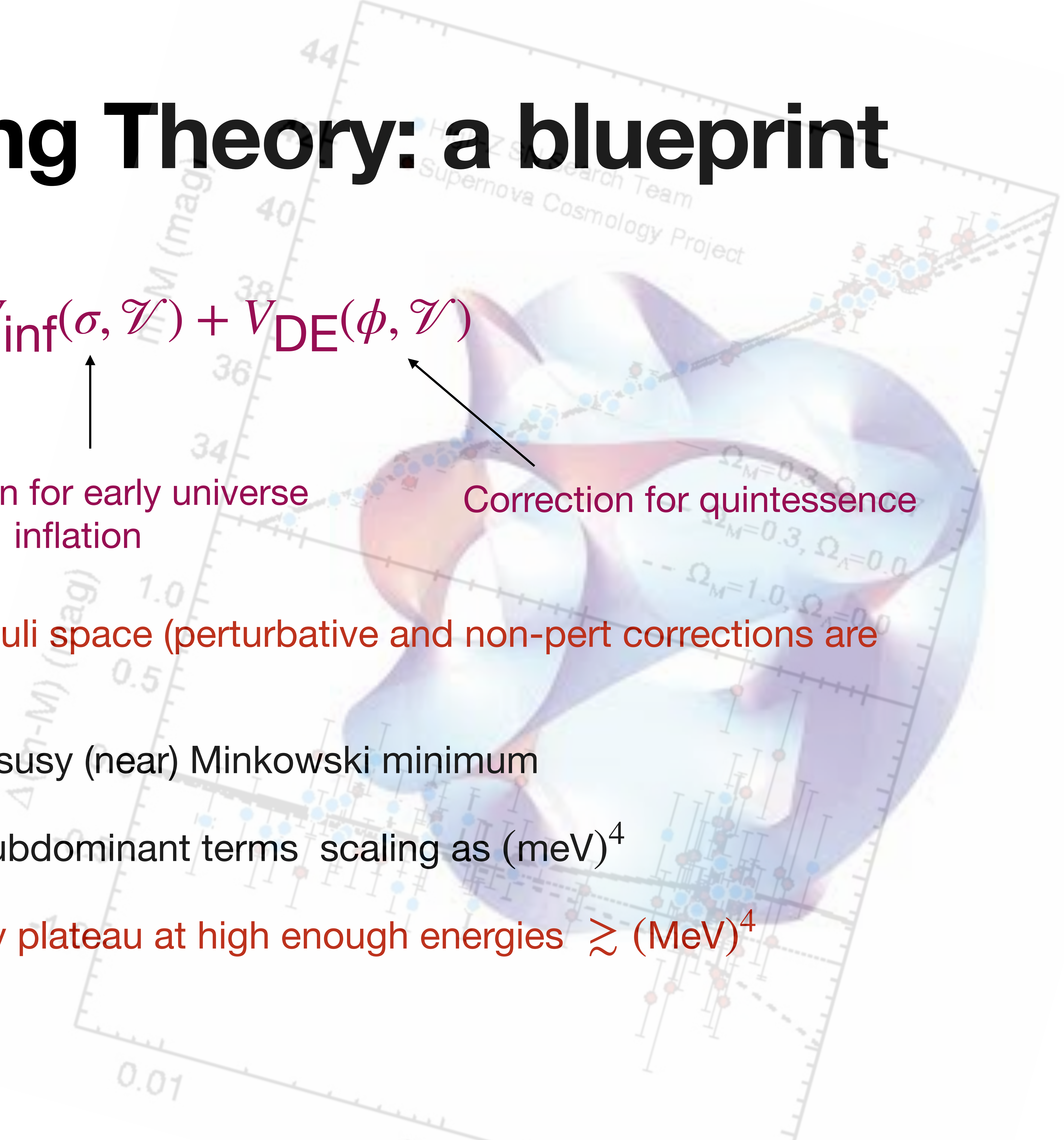
- Stabilisation of volume must see the high inflationary scale to avoid KL problem.

- Vacuum should admit a flat direction (axions) at leading order
- Vacuum should be near Minkowski so that subleading effects can lift to positive energy
- Vacuum should break SUSY so that gravitino mass is decoupled from DE scale

- Dynamics of low scale DE must be generated separately to decouple it from volume

Quintessence in String Theory: a blueprint

Cicoli, Cunillera, Padilla, Pedro 2021



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Leading order potential for volume mode

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Axion hilltops

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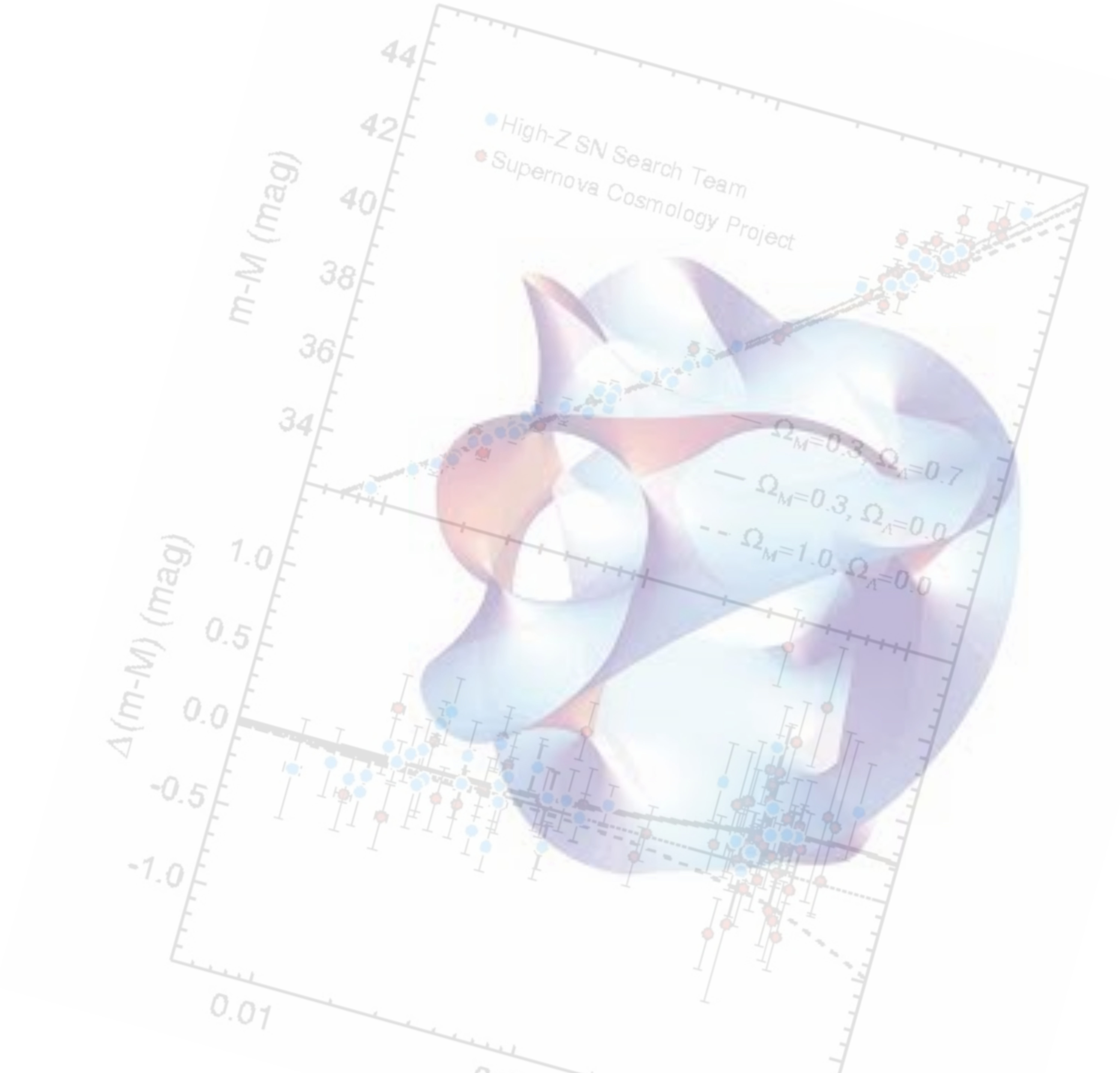

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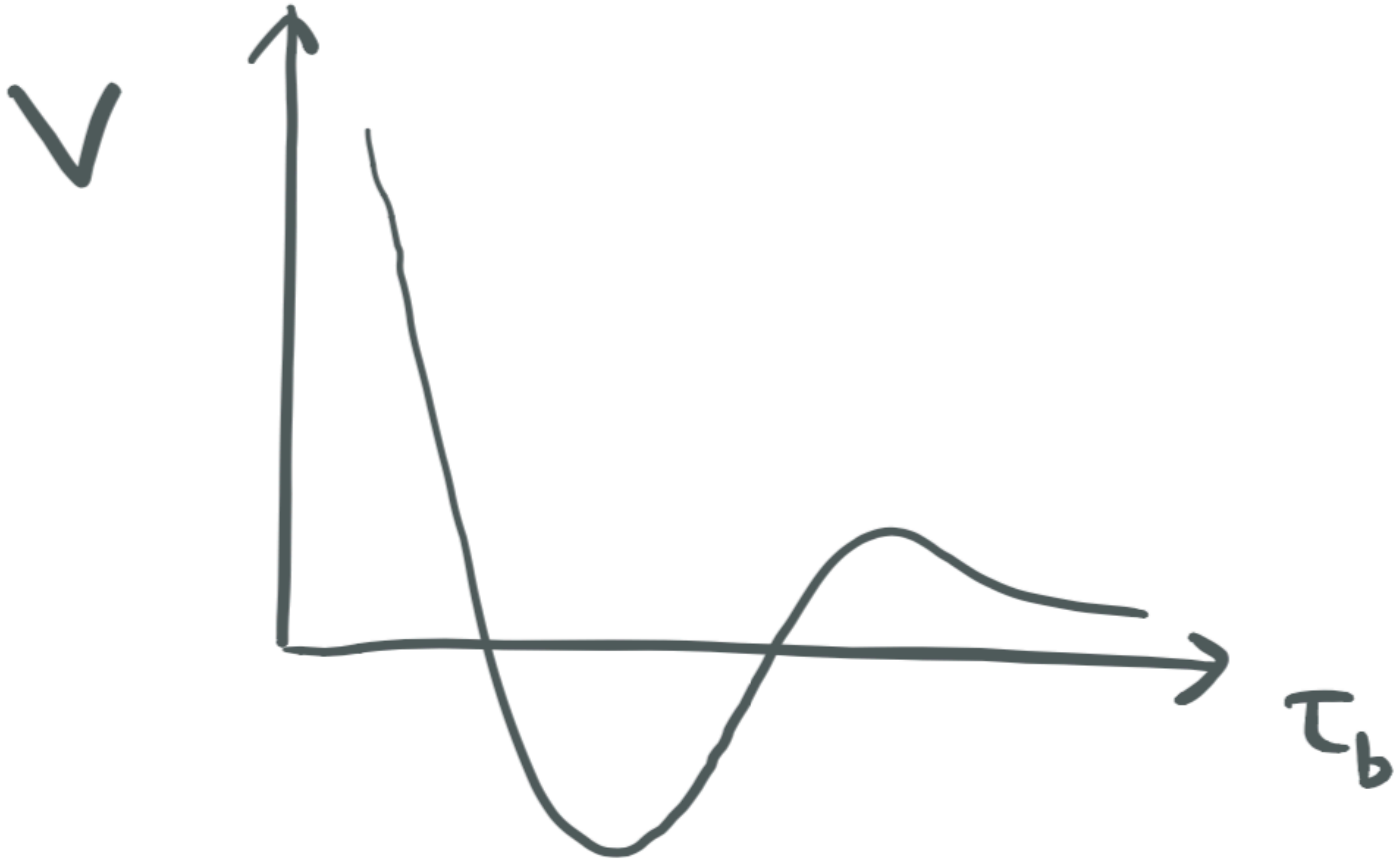
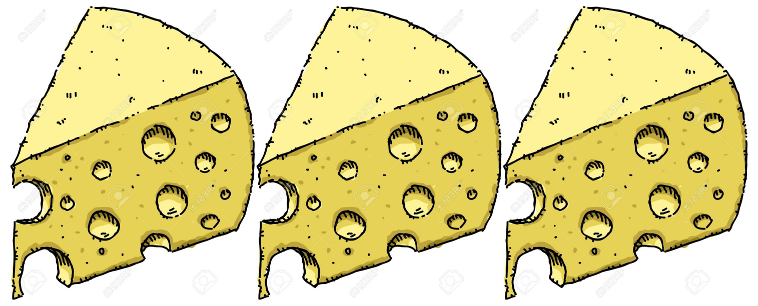


LVS model with two Kahler moduli $T_b = \tau_b + i\theta_b$ and $T_s = \tau_s + i\theta_s$



$$K = K_0 - 2\ln\left(\mathscr{V} + \frac{\xi}{2}\right), \qquad W = W_0 + A_s e^{-a_s T_s} + A_b e^{-a_b T_b}$$

where $\xi \propto \alpha'^3$ and $\mathscr{V} = \tau_b^{3/2} - \tau_s^{3/2}$

Obtain scalar potential with (non SUSY) AdS minimum, $V_{\text{AdS}} \sim -\dfrac{\xi\,|W_0|^2}{a_s\langle\tau_s\rangle\mathscr{V}^3}$

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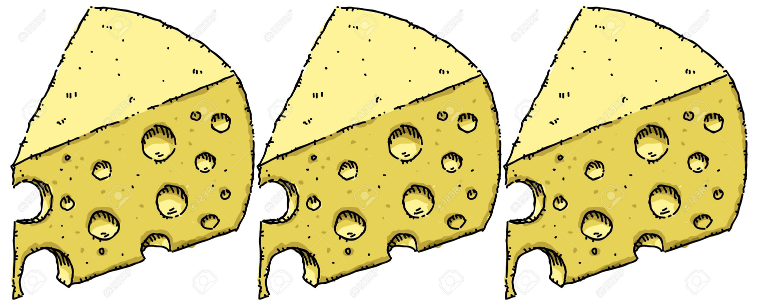

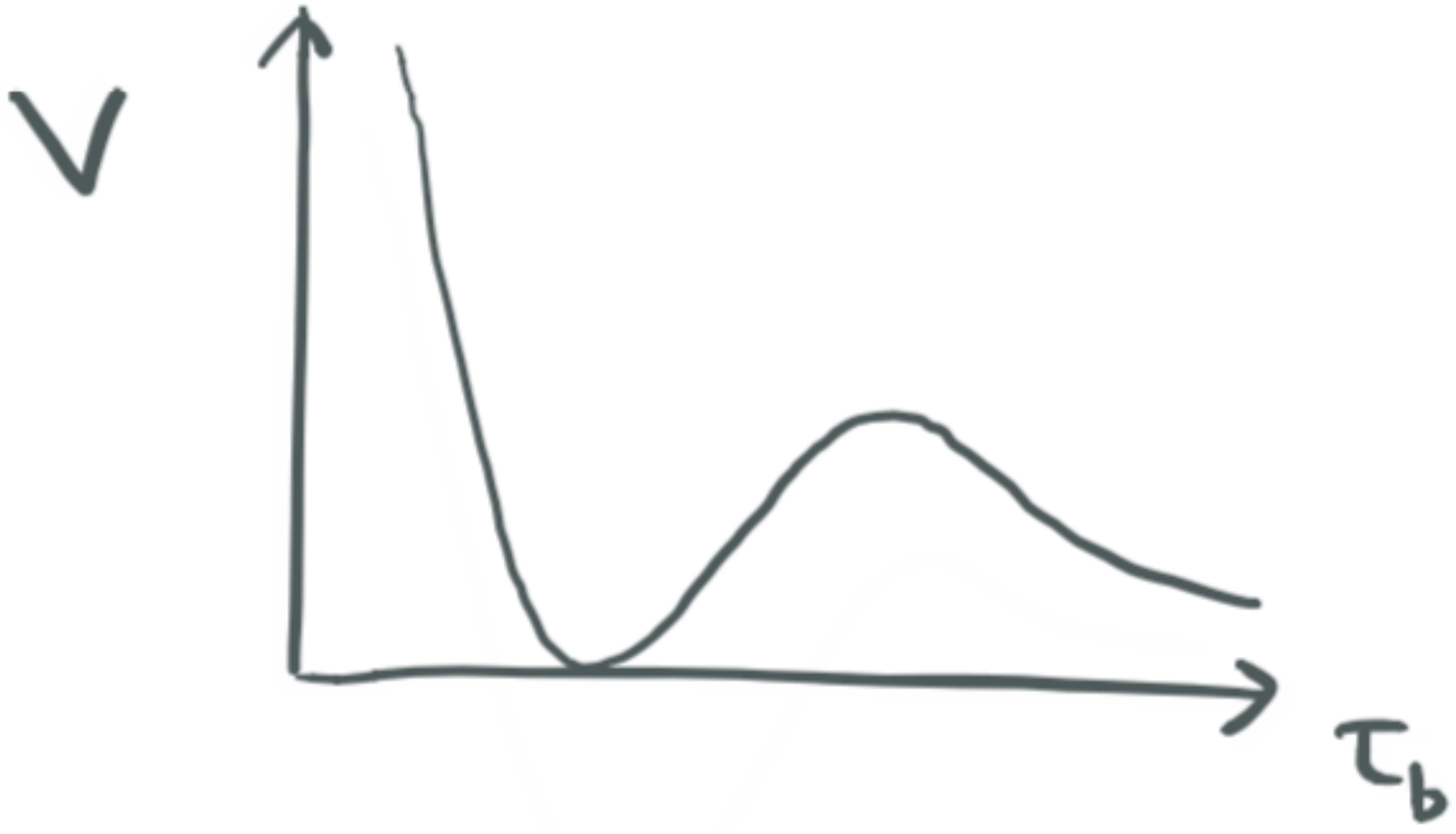

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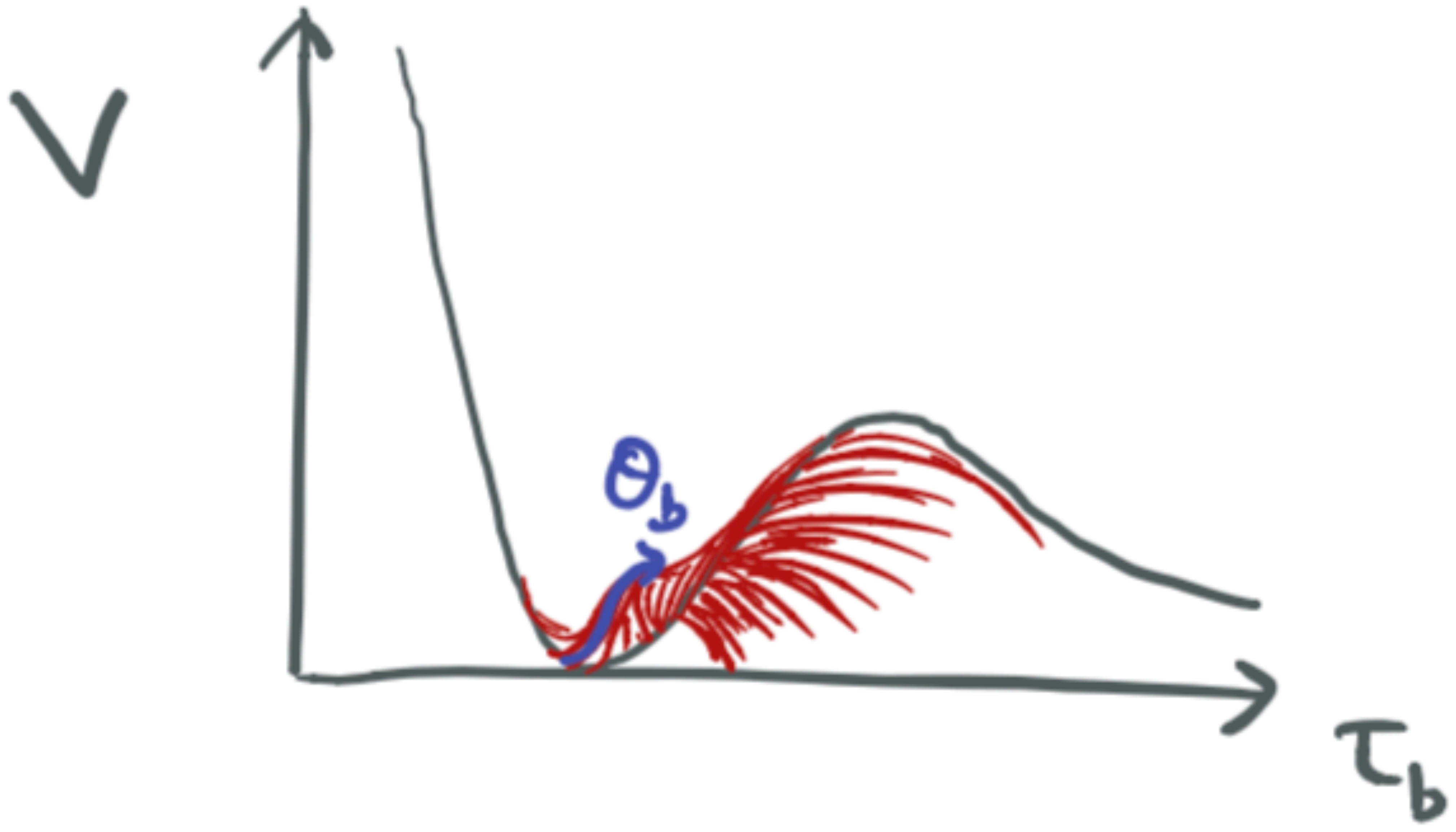
Obtain scalar potential with (non SUSY) AdS minimum, $V_{\text{AdS}} \sim -\frac{\xi |W_0|^2}{a_s \langle \tau_s \rangle \mathscr{V}^3}$

Add an uplift $V_{\text{up}} = \frac{\kappa}{\mathscr{V}^\alpha}$ (where $\alpha = 4/3$ for anti D3 branes)

Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021



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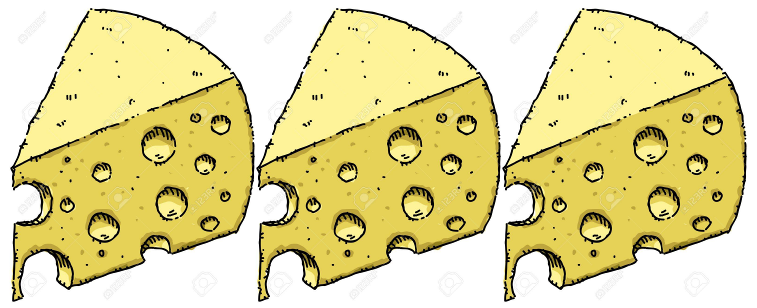

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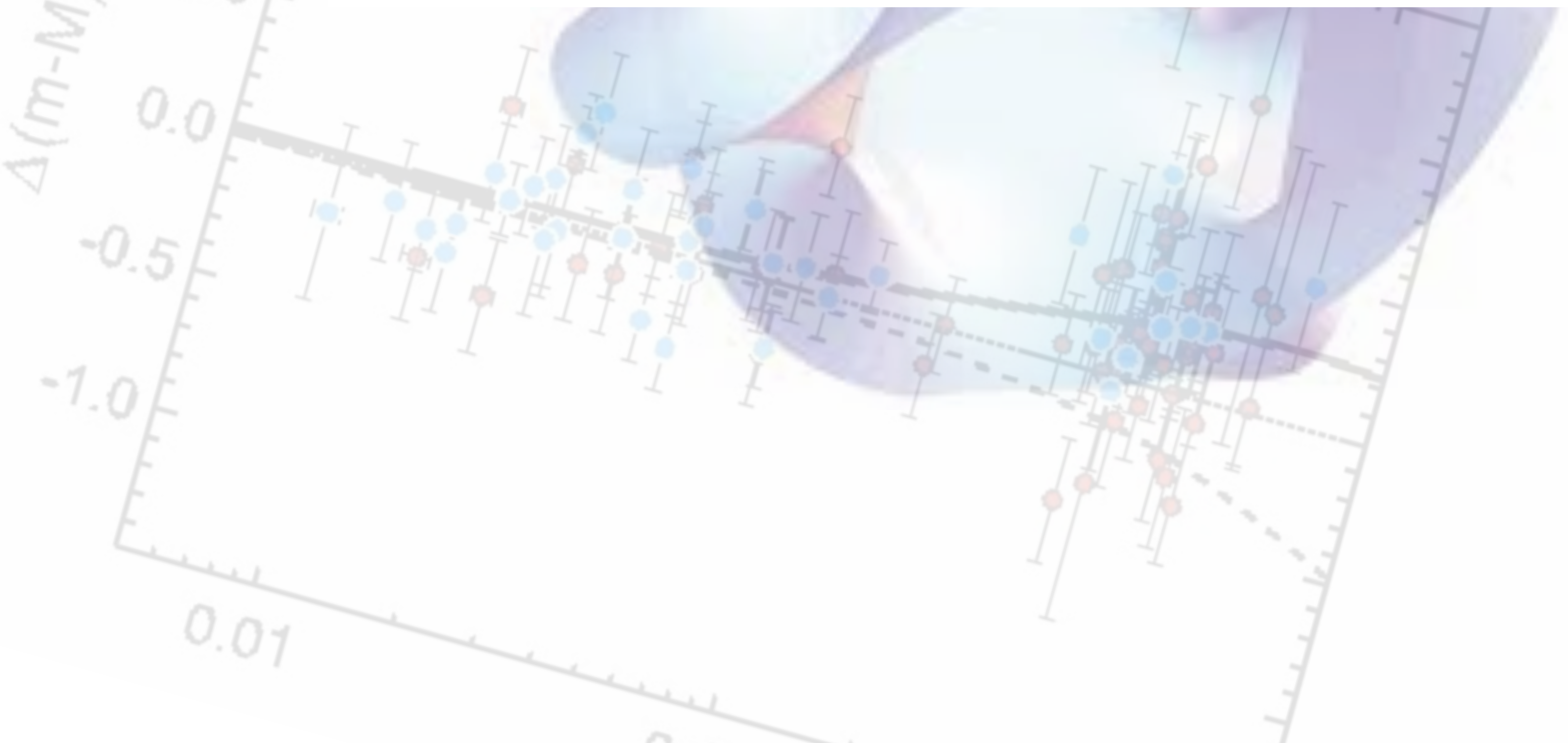
EXCITE THE BIG AXION



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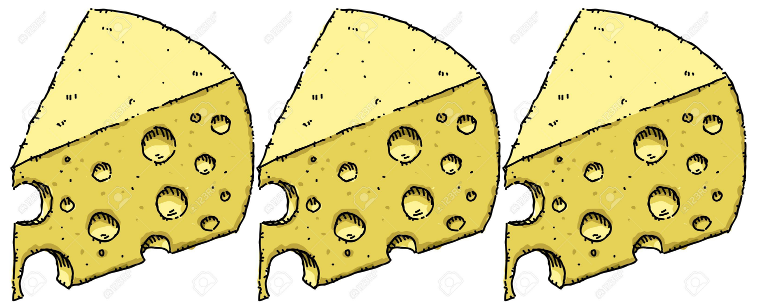

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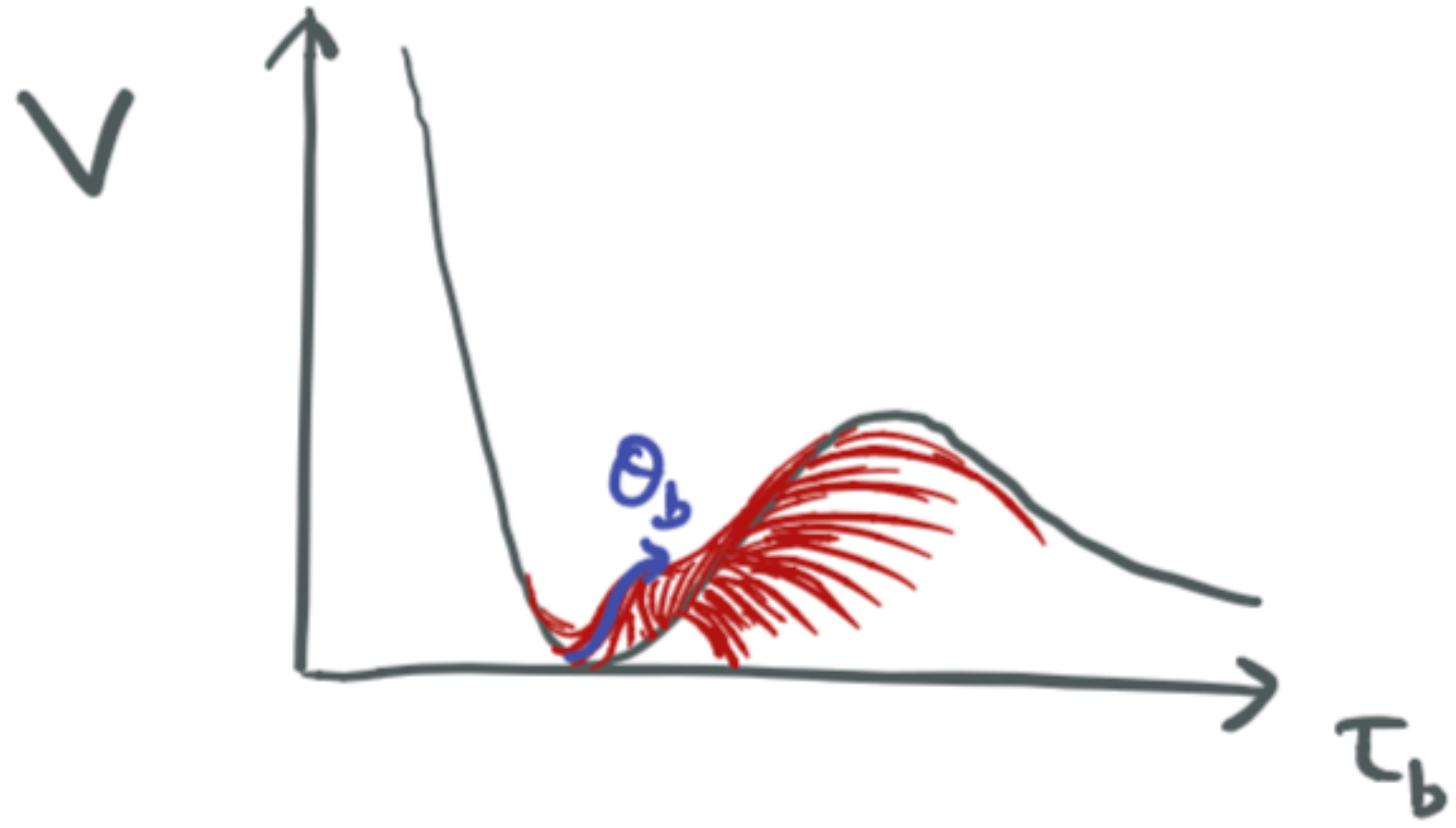
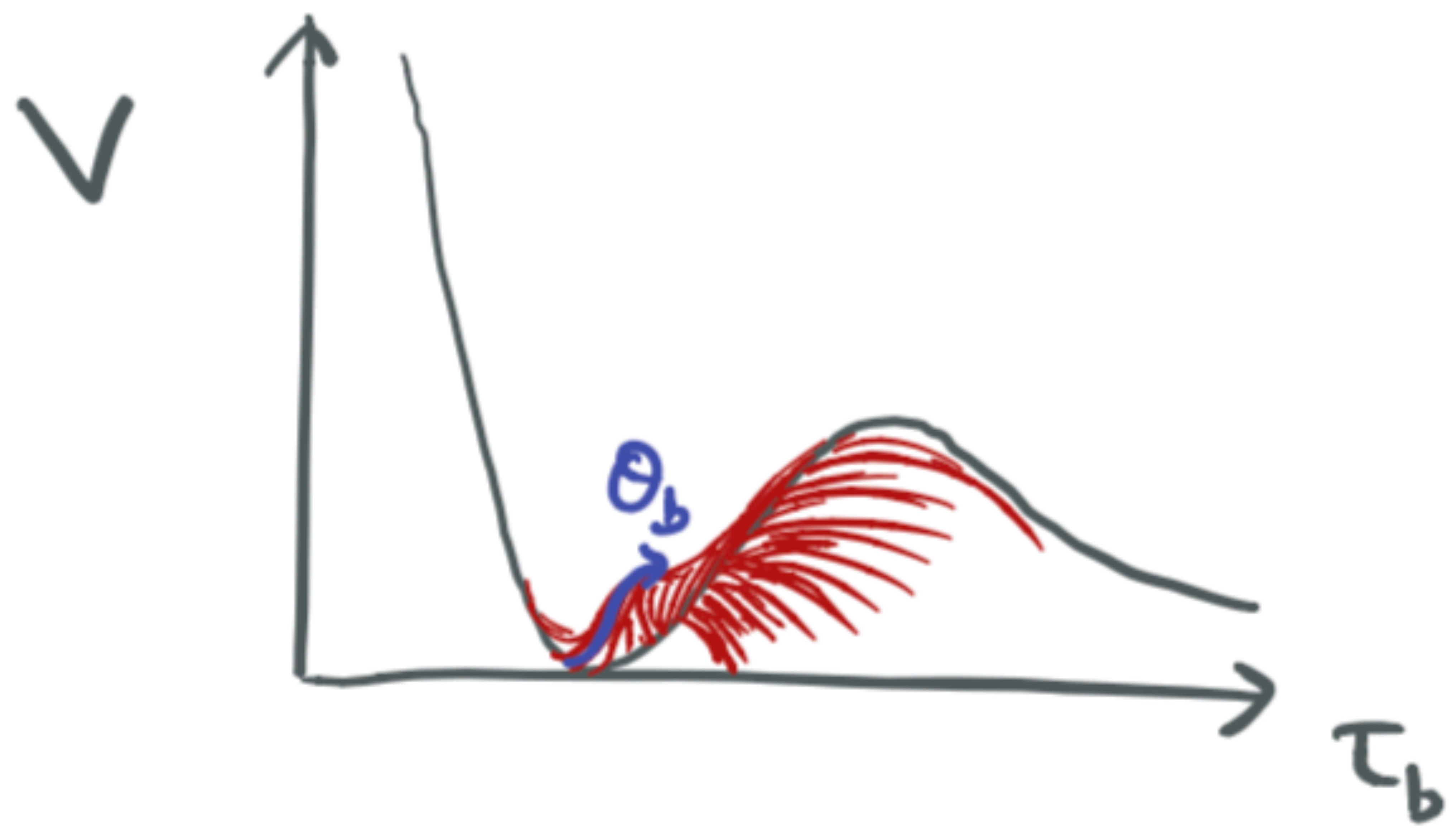


EXCITE THE BIG AXION

$$V_{\rm DE} = V_0(1 - \cos(a_b\theta_b)) \text{ where } V_0 \sim \frac{A_b a_b}{\langle\tau_b\rangle^2} |W_0| e^{-a_b\langle\tau_b\rangle}$$

Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021



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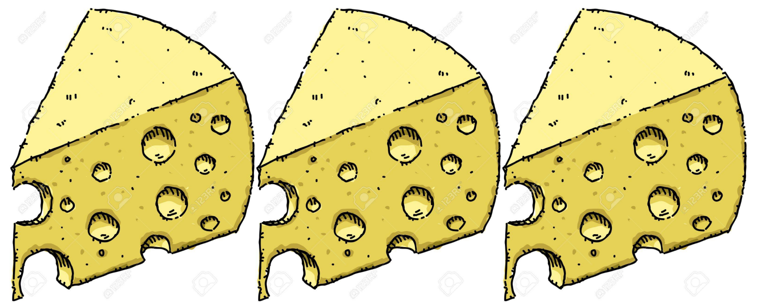

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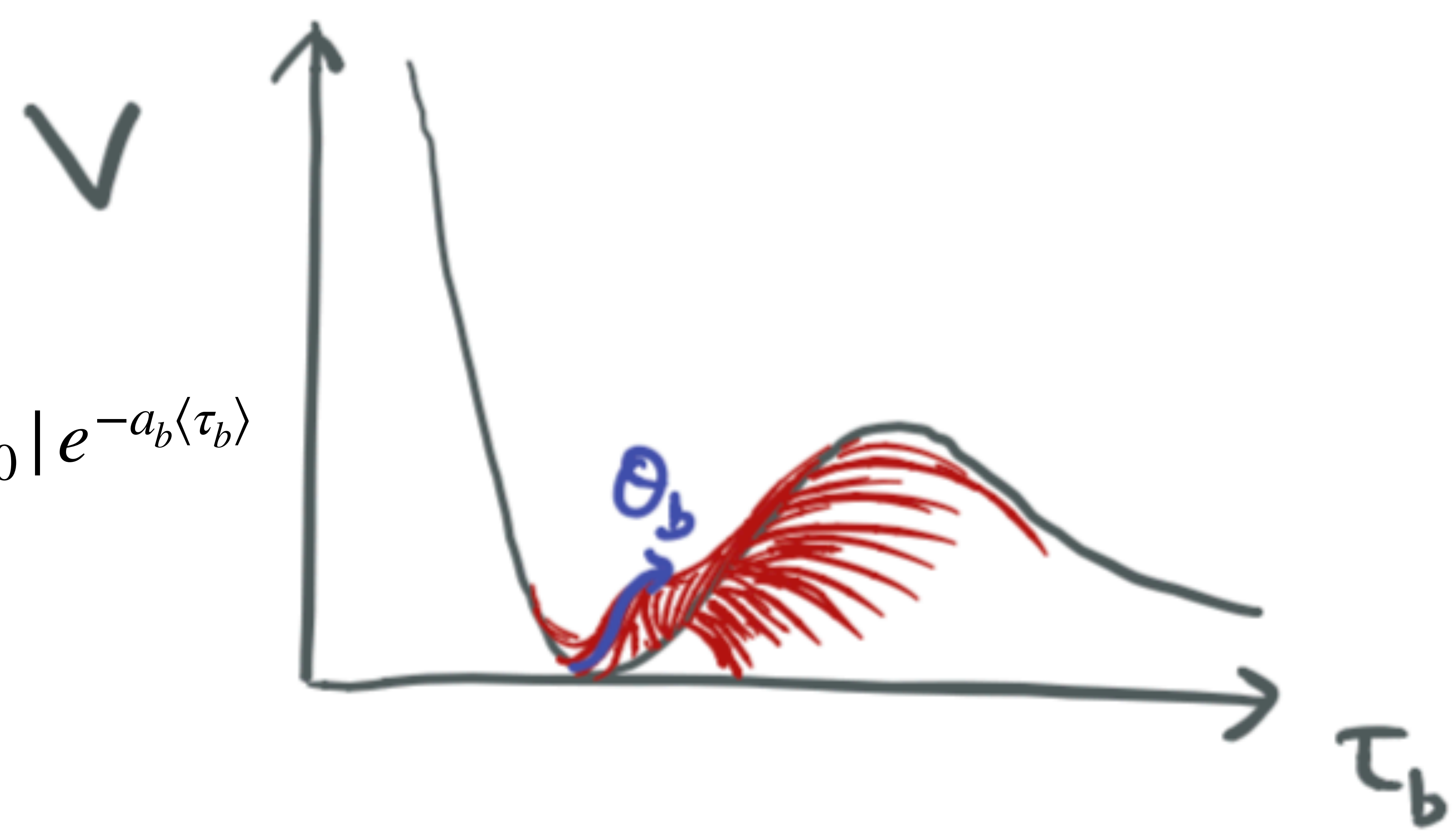
Go to canonical field

$$V_{\rm DE} = V_0(1 - \cos(\phi/f)) \text{ where } f = \sqrt{\frac{3}{2}}\frac{M_{pl}}{a_b\langle\tau_b\rangle}$$

Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

$$V_{\rm DE} = V_0(1 - \cos(\phi/f)) \;\; \text{where} \;\; f = \sqrt{\frac{3}{2}}\frac{M_{pl}}{a_b\langle\tau_b\rangle}, \;\text{and}\;\; V_0 \sim \frac{A_b a_b}{\langle\tau_b\rangle^2}|W_0|\,e^{-a_b\langle\tau_b\rangle}$$



How flat is the hilltop?

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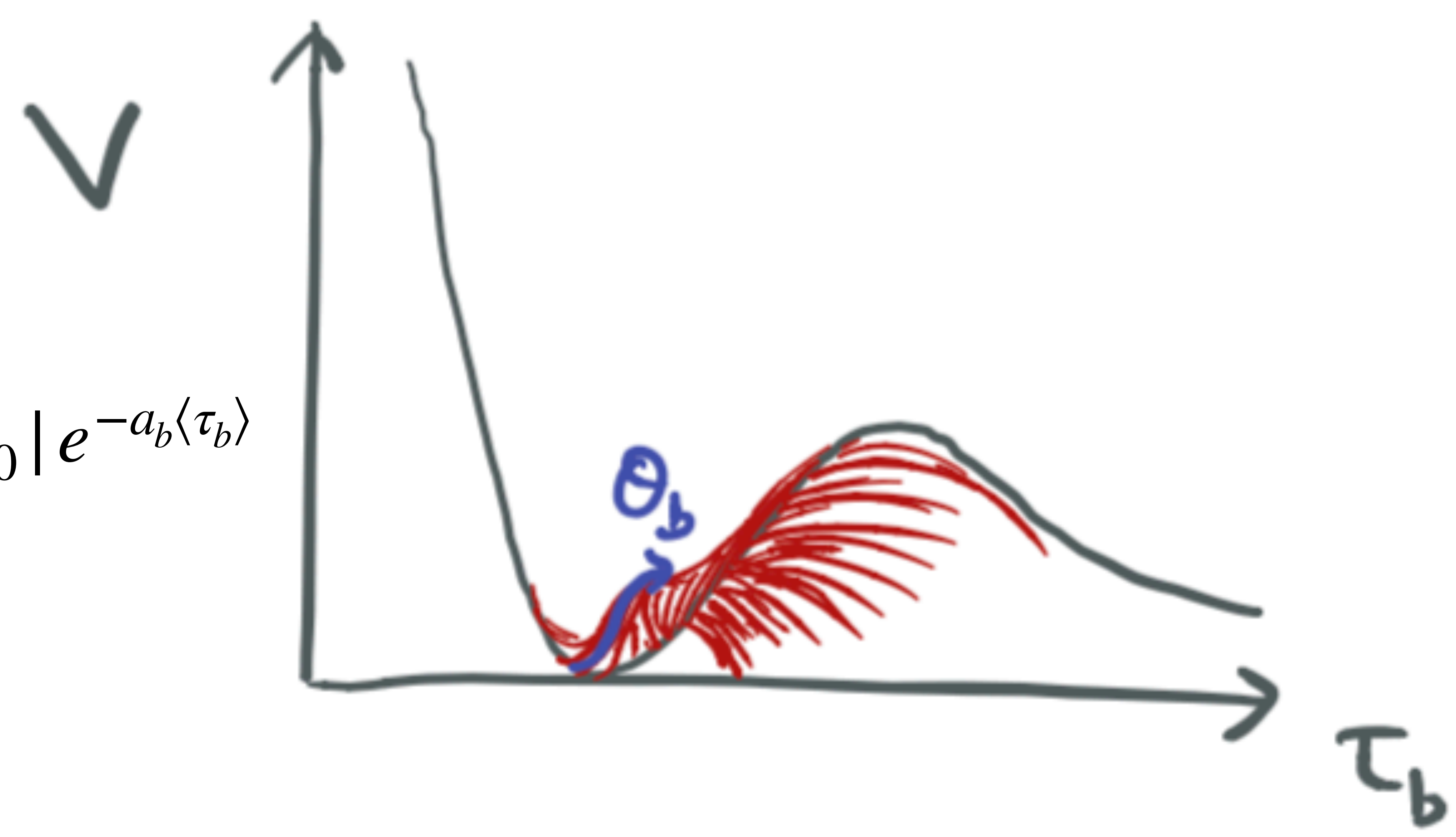

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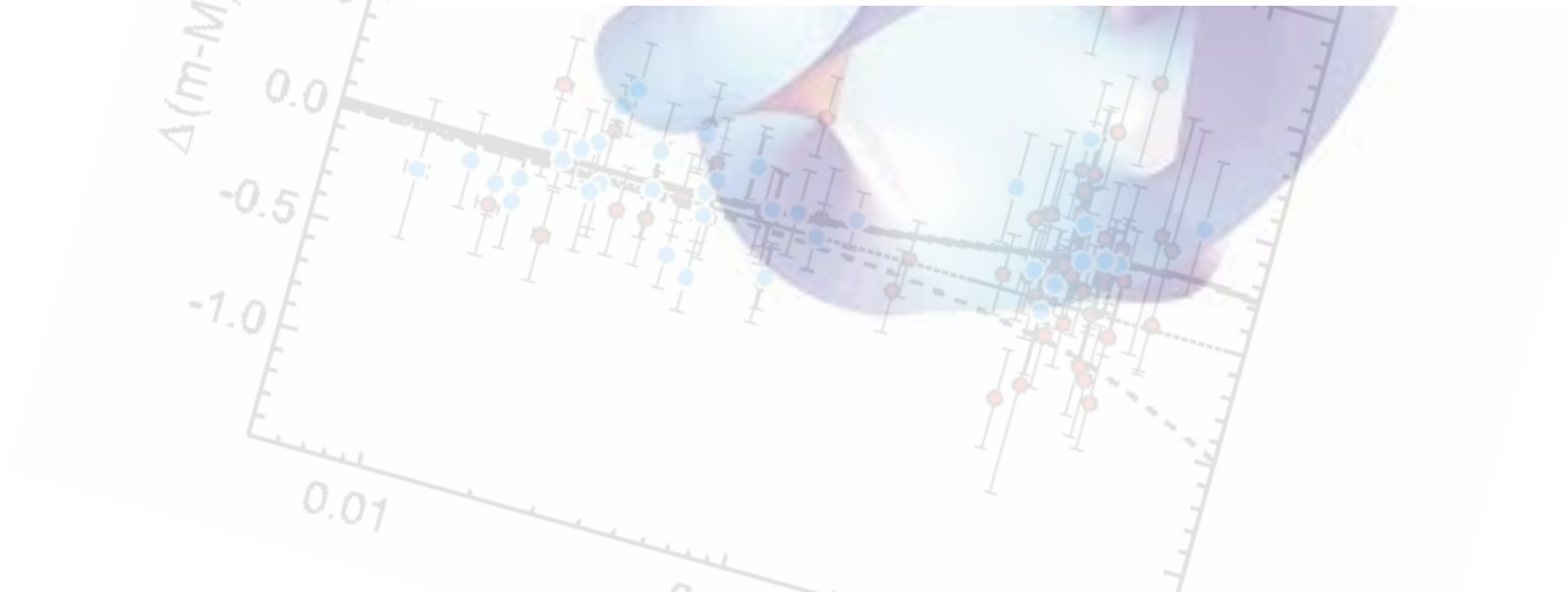

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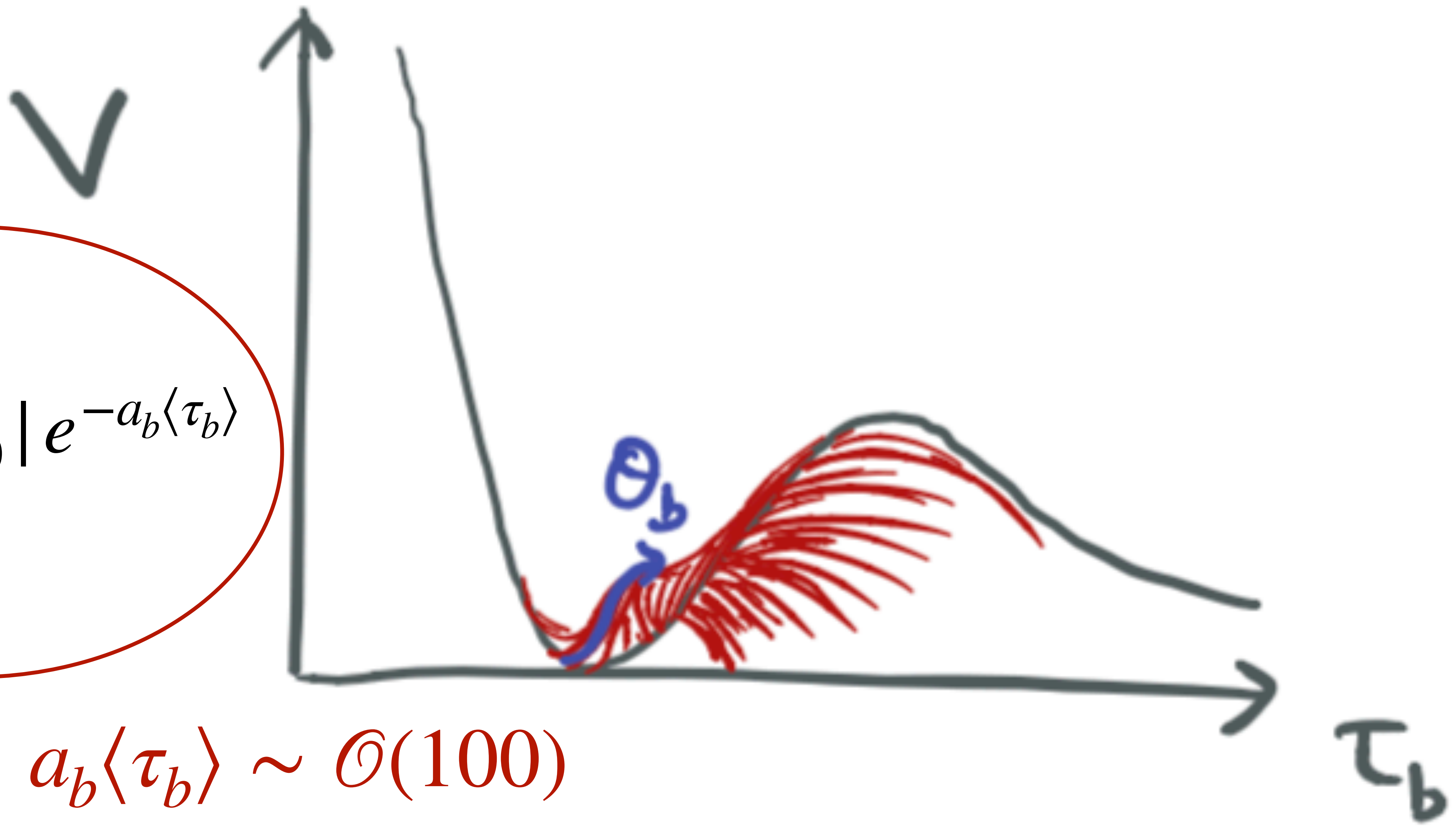

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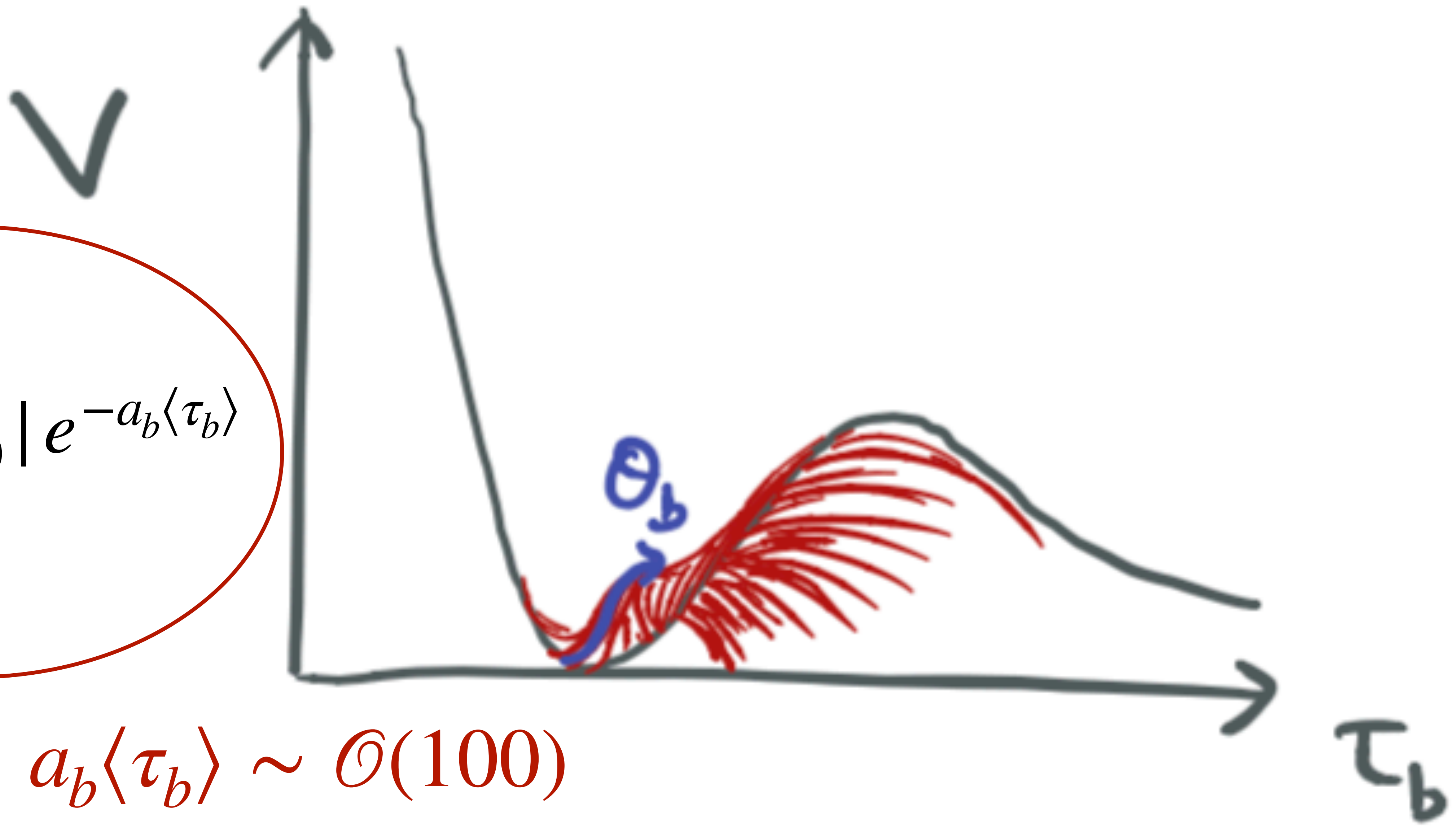

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$\eta_{\text{hilltop}} \sim -\mathcal{O}(3000)$

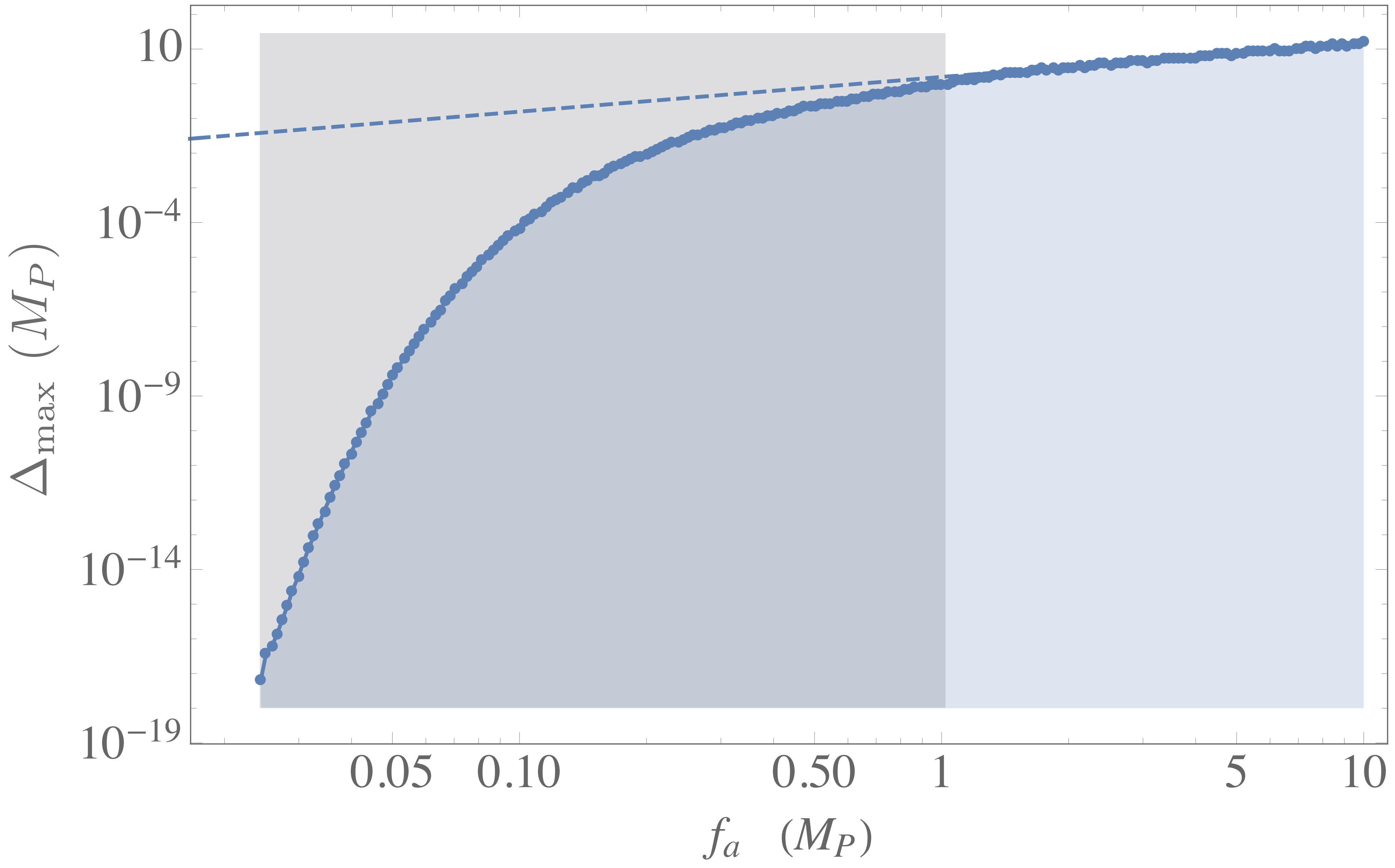
NEED TO BE EXTREMELY CLOSE TO THE HILLTOP!

Problems with hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

To ensure late time acceleration, axion must stay within a distance Δ_{max} of the maximum.

This varies with f



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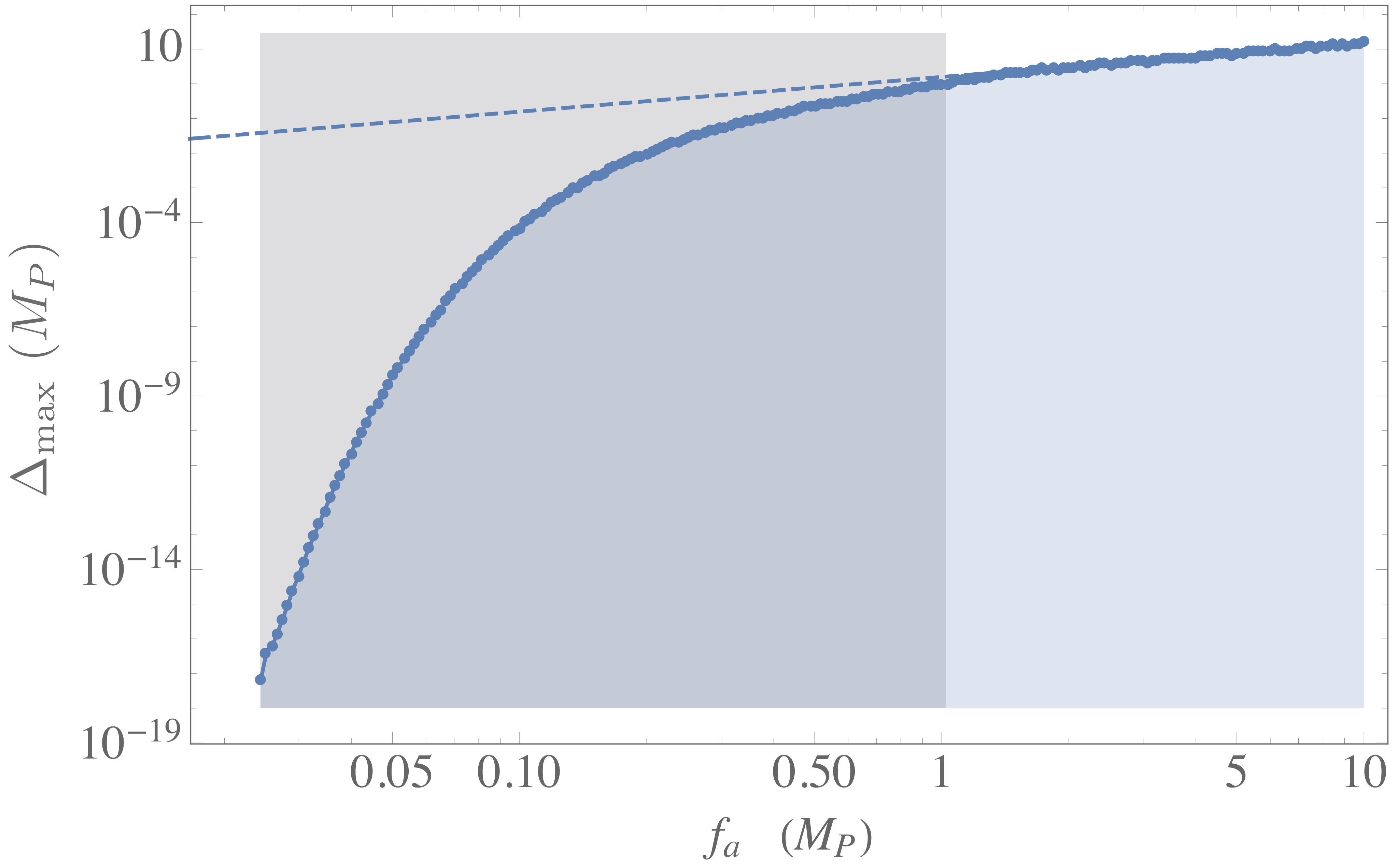
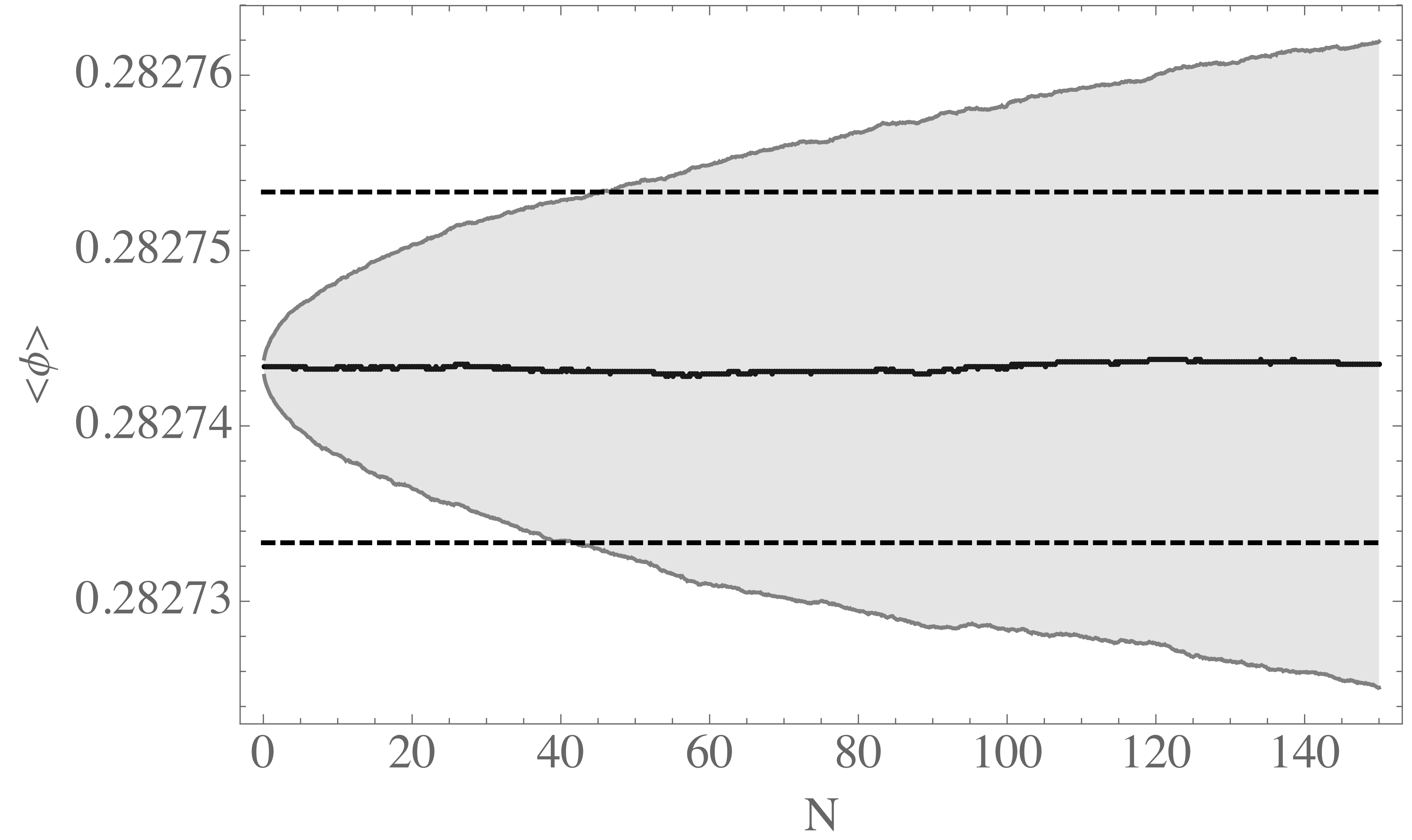


Quantum diffusion will push axion away from its maximum during inflation



Problematic if $H_{inf} \gtrsim \Delta_{max}$

Quintessence in String Theory: a blueprint

Cicoli, Cunillera, Padilla, Pedro in progress

- Stabilisation of volume must see the high inflationary scale to avoid KL problem.

- Vacuum should admit a flat direction (axions) at leading order
- Vacuum should be near Minkowski so that subleading effects can lift to positive energy
- Vacuum should break SUSY so that gravitino mass is decoupled from DE scale

LVS with fibre $\mathcal{V} = \sqrt{\tau_1}\tau_2 - t_s^{3/2}$, loop corrections and uplift correction

Volume stabilised at leading order. Orthogonal mode gives inflation

- Dynamics of low scale DE must be generated separately to decouple it

Non-perturbative corrections yield DE and fraction of DM

Conclusions

Cicoli, Cunillera, Padilla, Pedro 2021

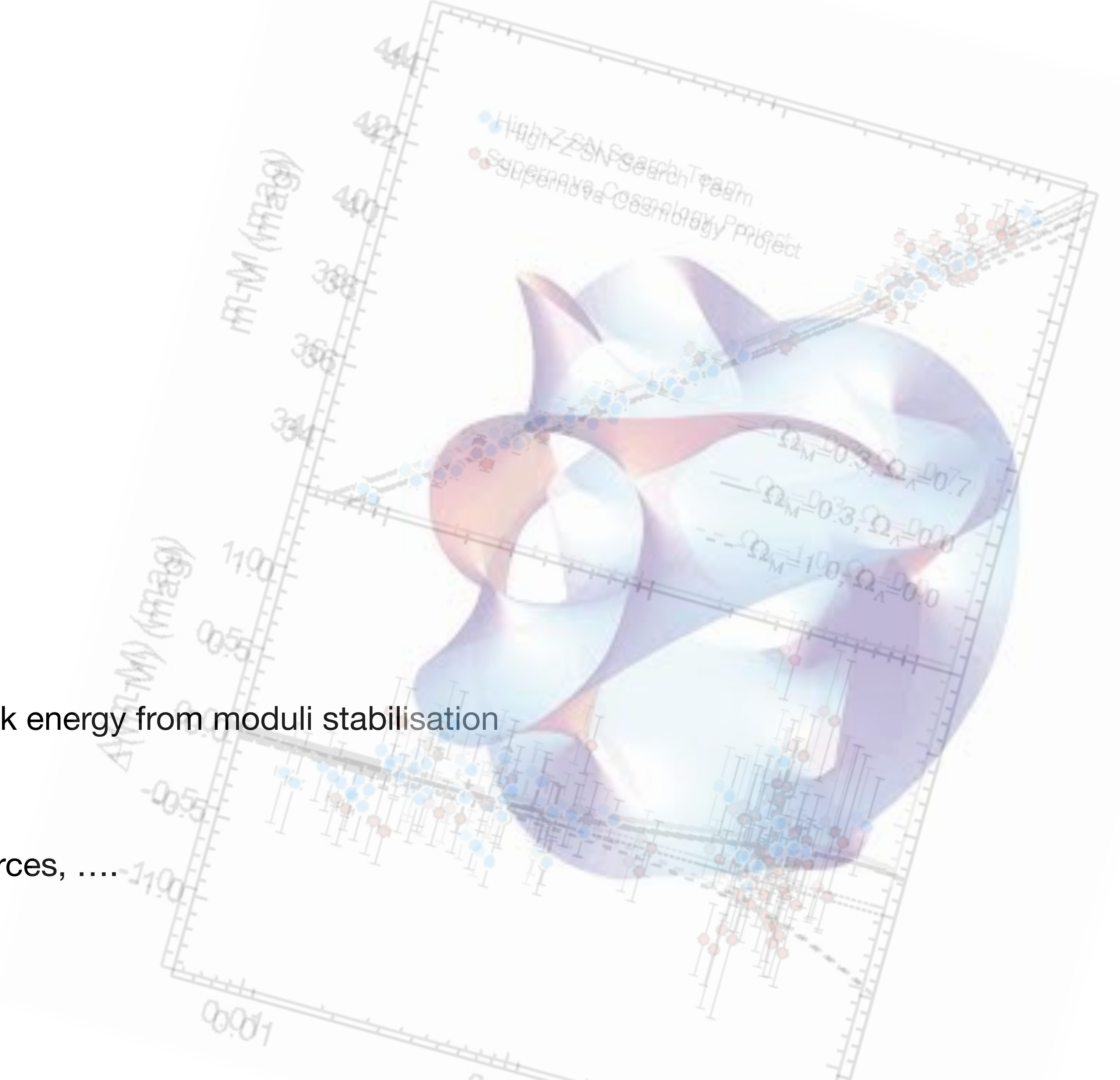
Quintessence or CC?

Like the CC viable quintessence in ST

- requires uplifted non SUSY vacuum
- requires fine tuning of dark energy scale

Unlike CC, quintessence in ST

- requires careful decoupling of dynamical dark energy from moduli stabilisation
- requires finely tuned initial conditions
- has plenty of other old challenges like fifth forces, ….



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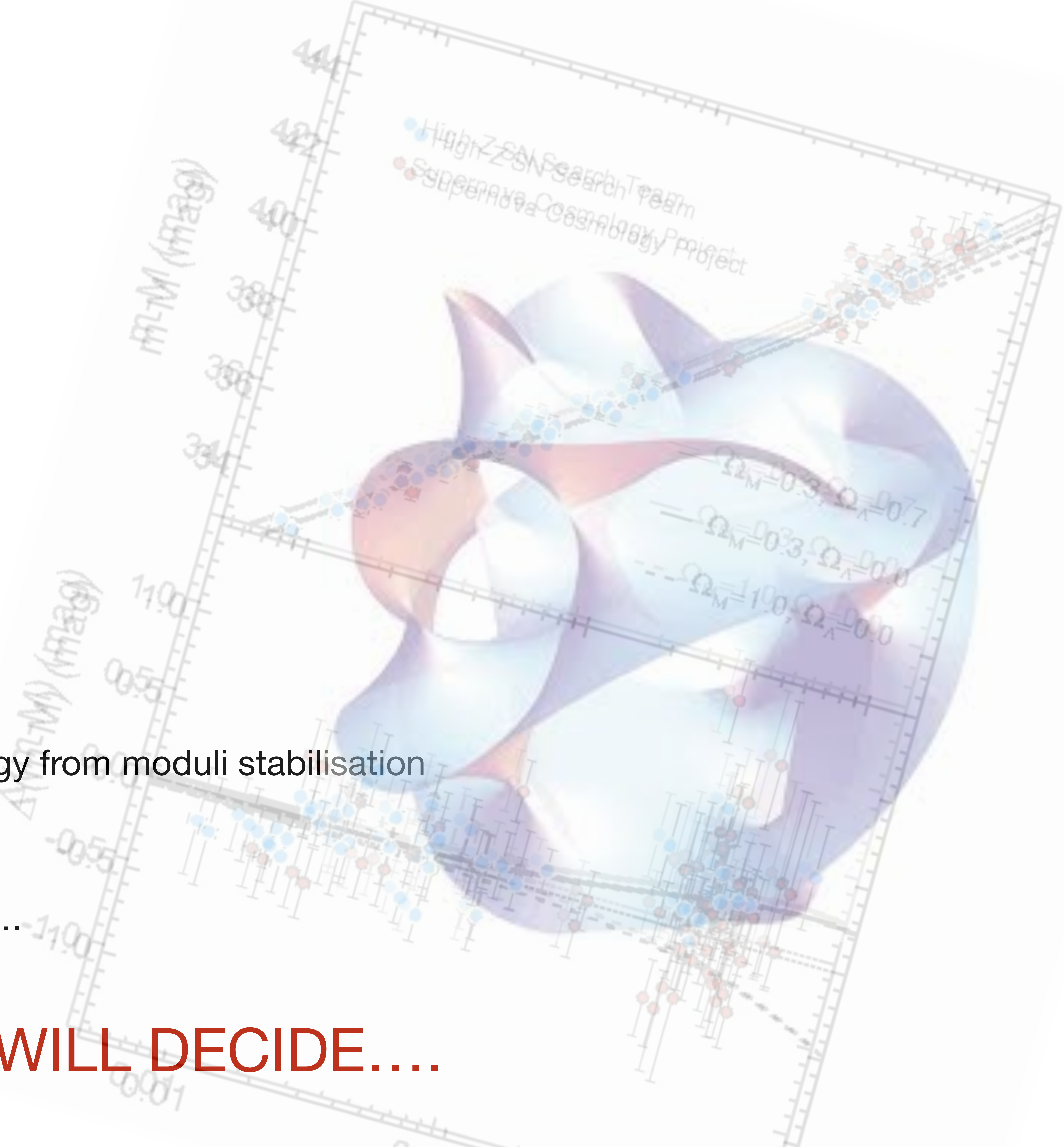
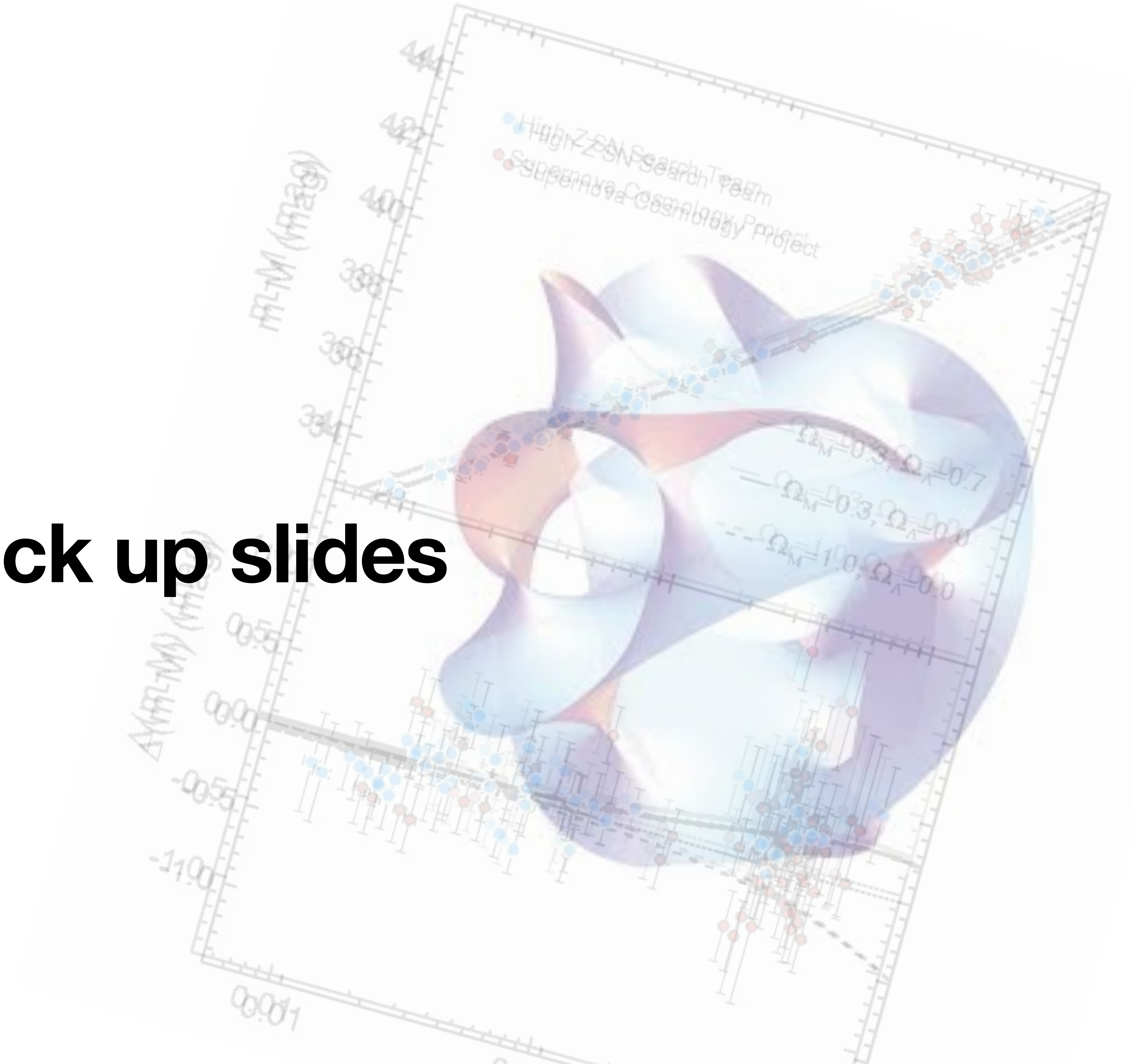


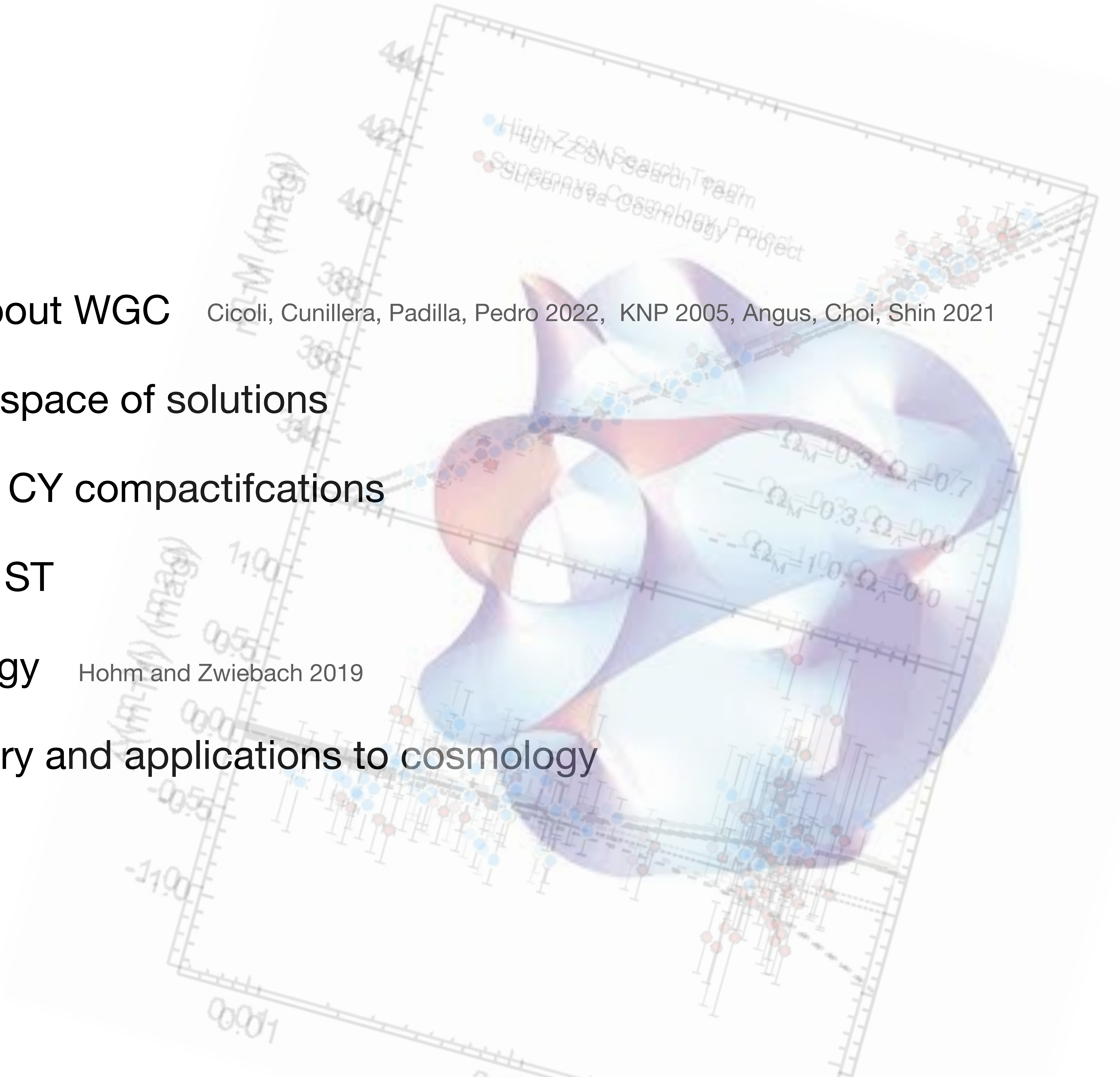
NATURE WILL DECIDE….

Back up slides



What next?

- Revisit axion alignment. Concerns about WGC   Cicoli, Cunillera, Padilla, Pedro 2022, KNP 2005, Angus, Choi, Shin 2021
- Use of AI to better survey parameter space of solutions
- Investigate classical dS vacua in non CY compactifcations
- Develop non-perturbative aspects of ST
    - alpha prime complete cosmology   Hohm and Zwiebach 2019
    - fundamental aspects of M theory and applications to cosmology
    - holography



Cosmology from String Theory

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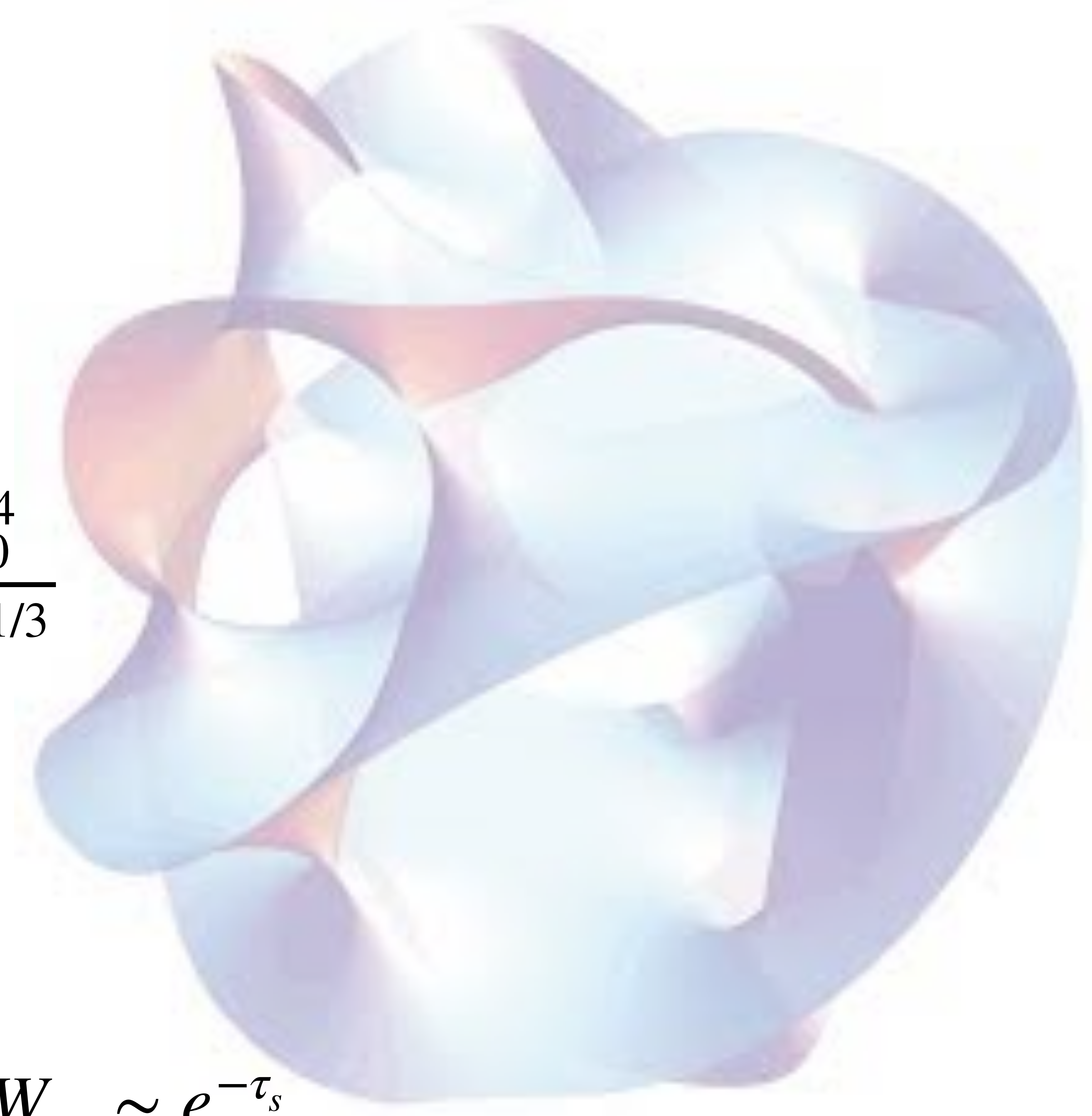
In LVS we include

- Anisotropic geometry with a small 4-cycle, dominating non-pert piece $\delta W_{np} \sim e^{-\tau_s}$
- α' corrections.

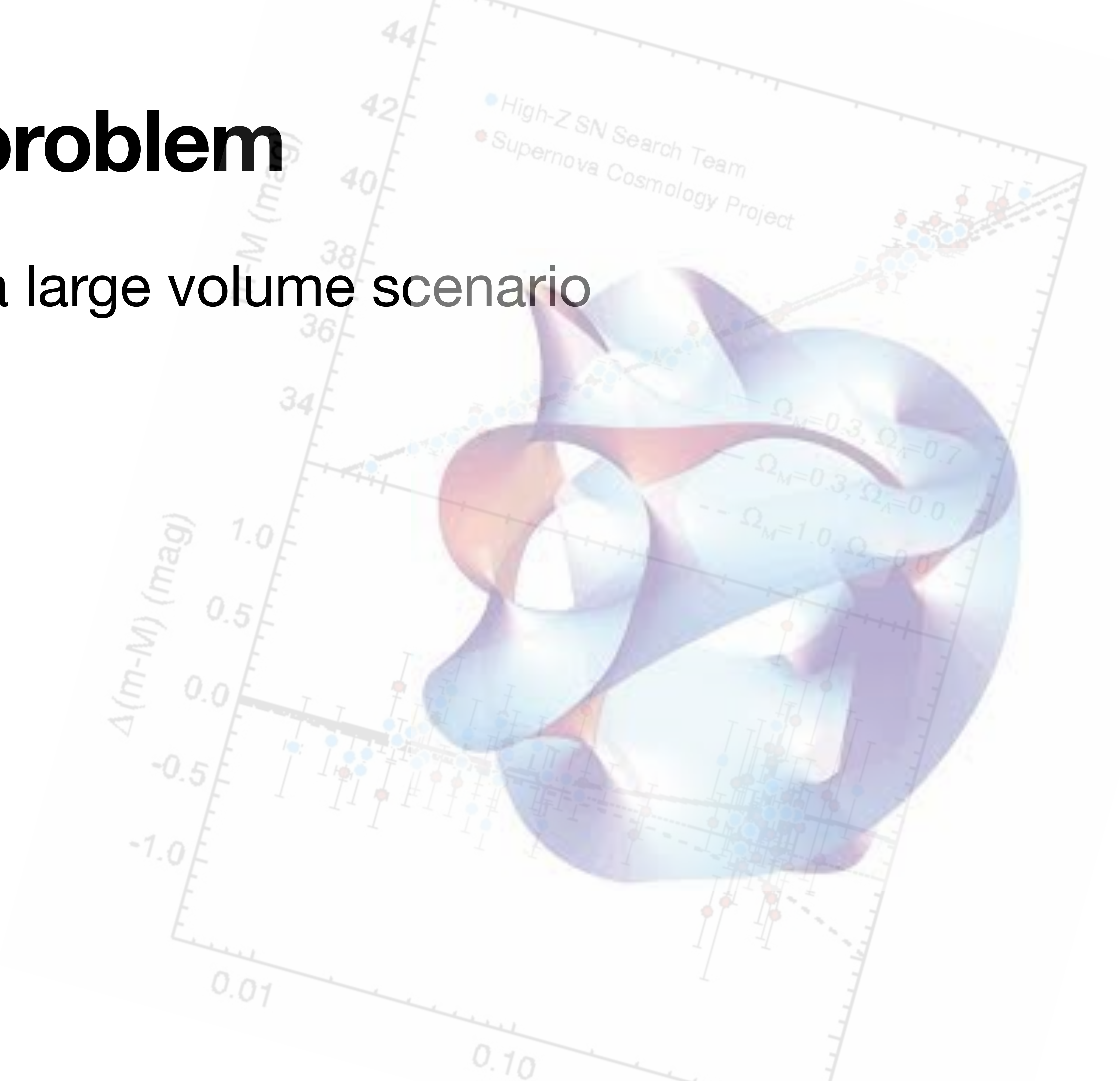
$\delta V \sim e^K (W_0^2 \delta K_p + W_0 \delta W_{np})$ and balance them $W_0^2 \delta K_p \sim W_0 \delta W_{np}$.



The light volume problem

Hebecker 2019

Example: quintessence in a large volume scenario



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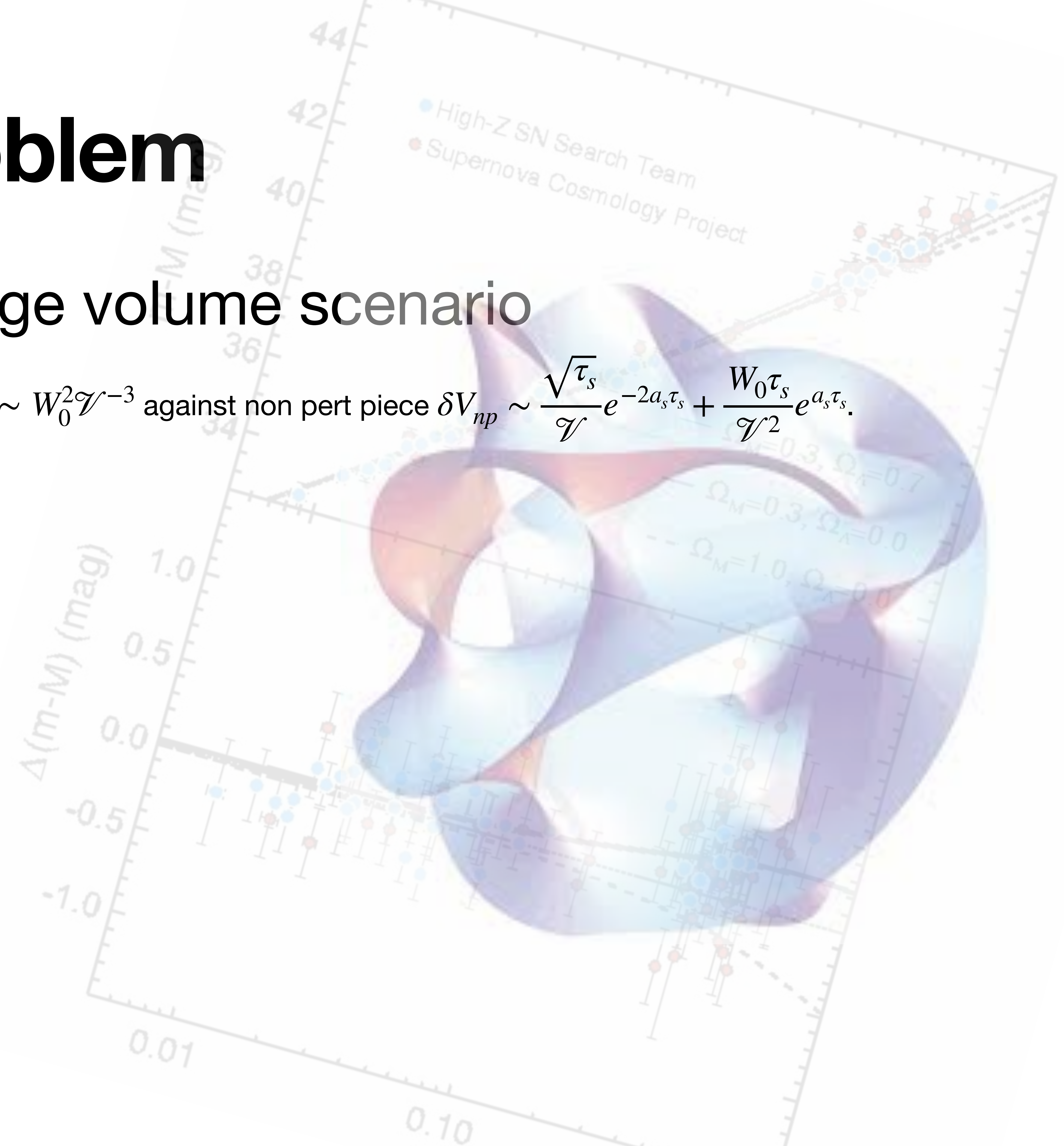

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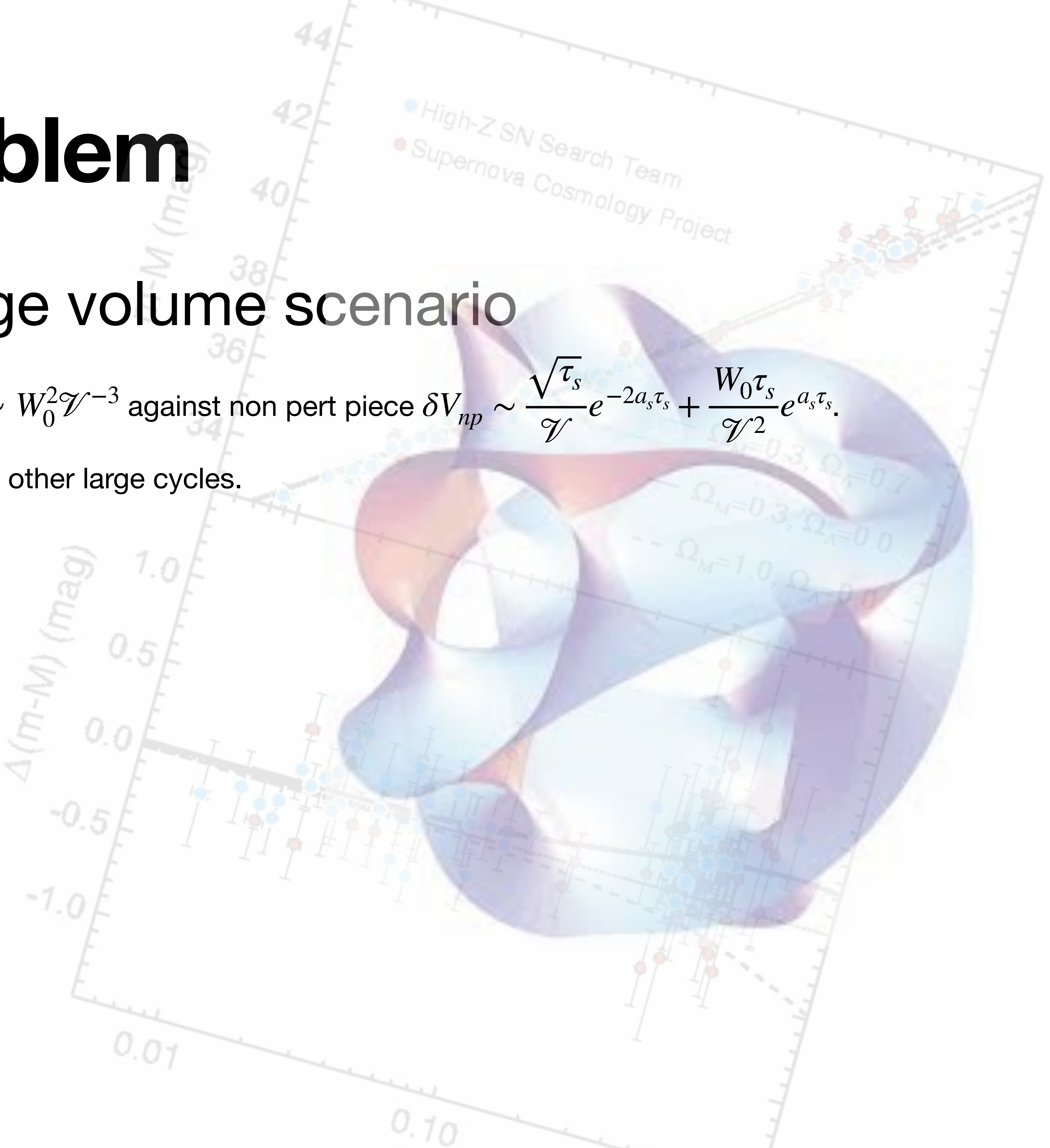

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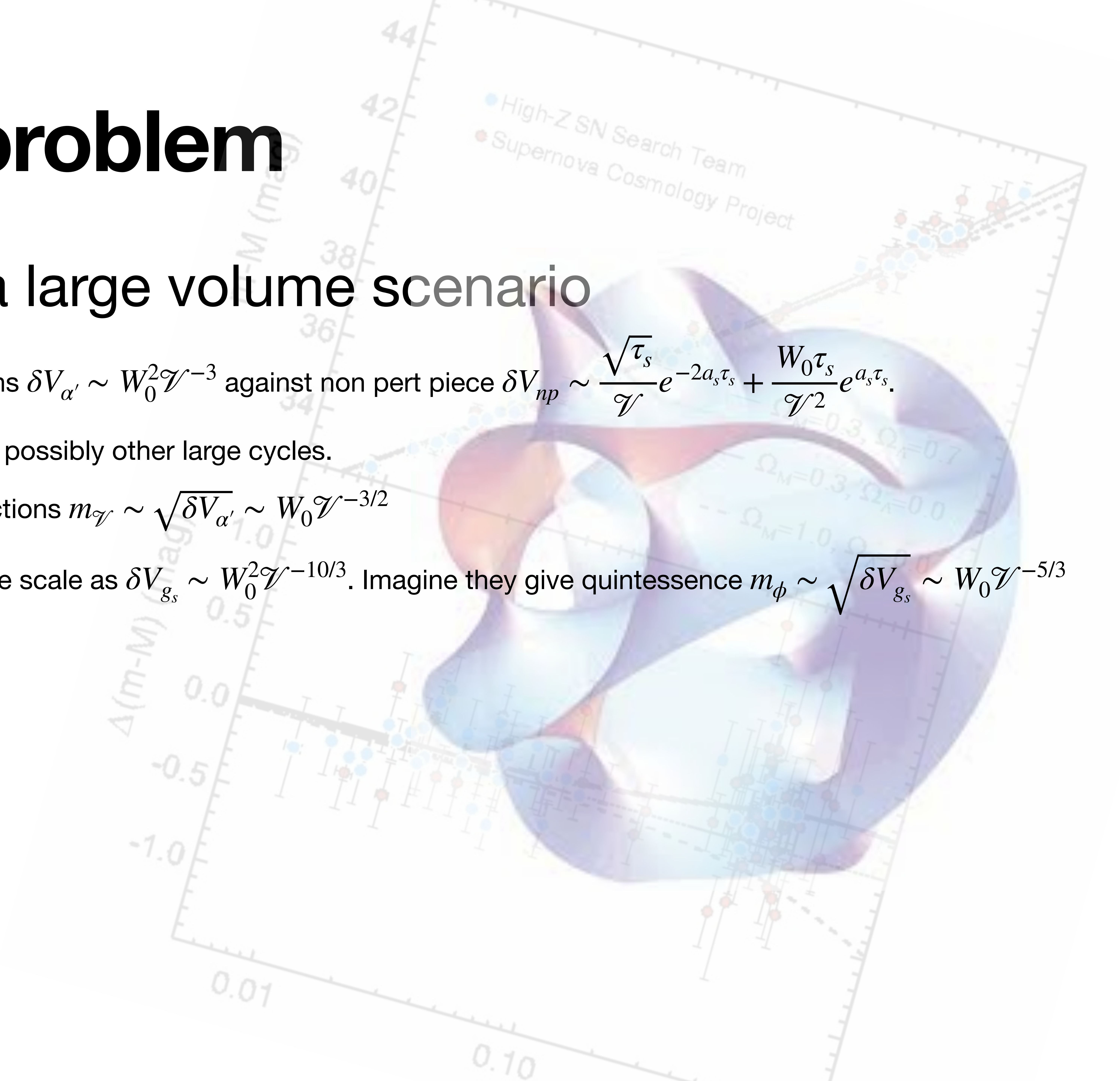

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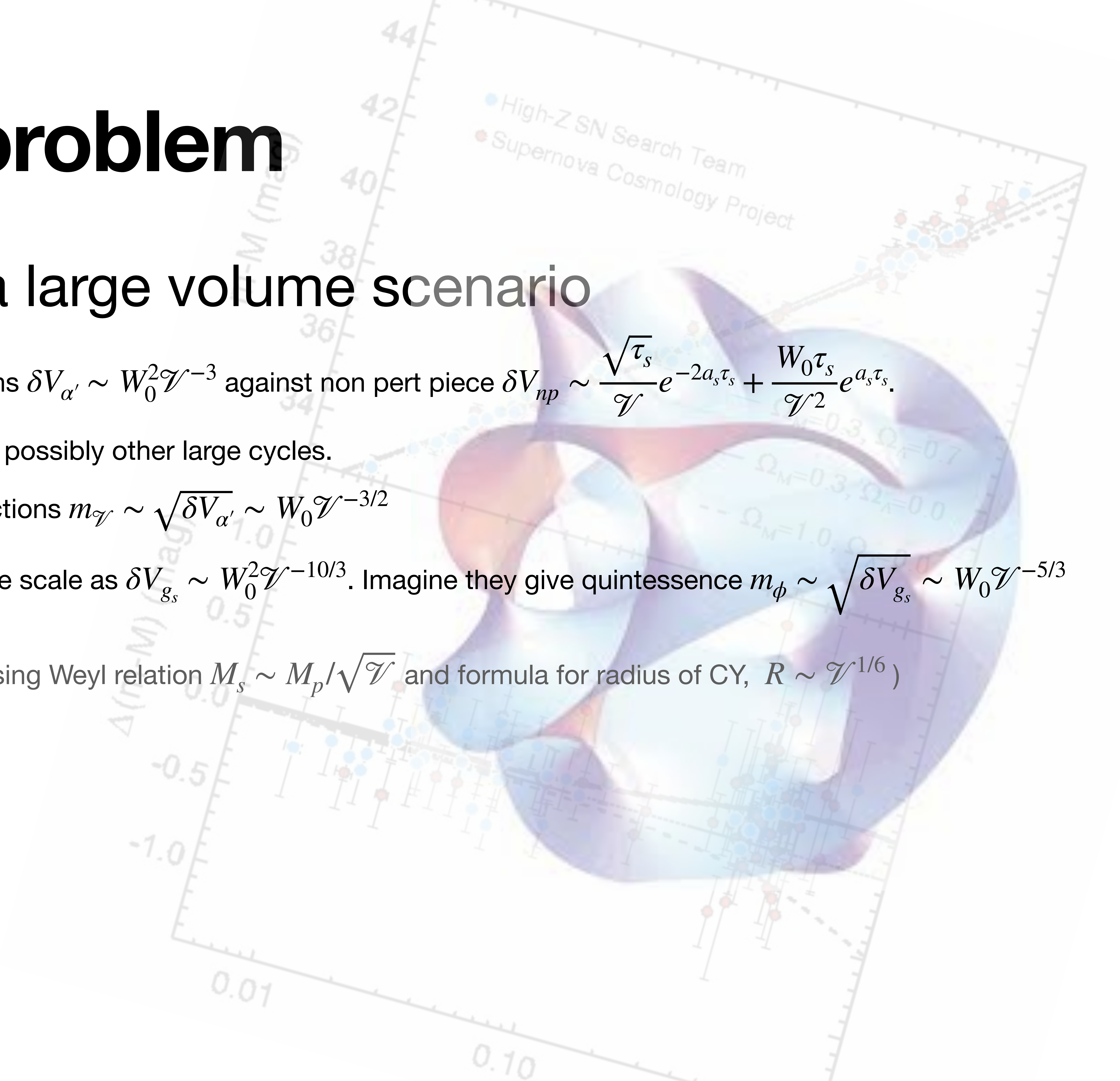

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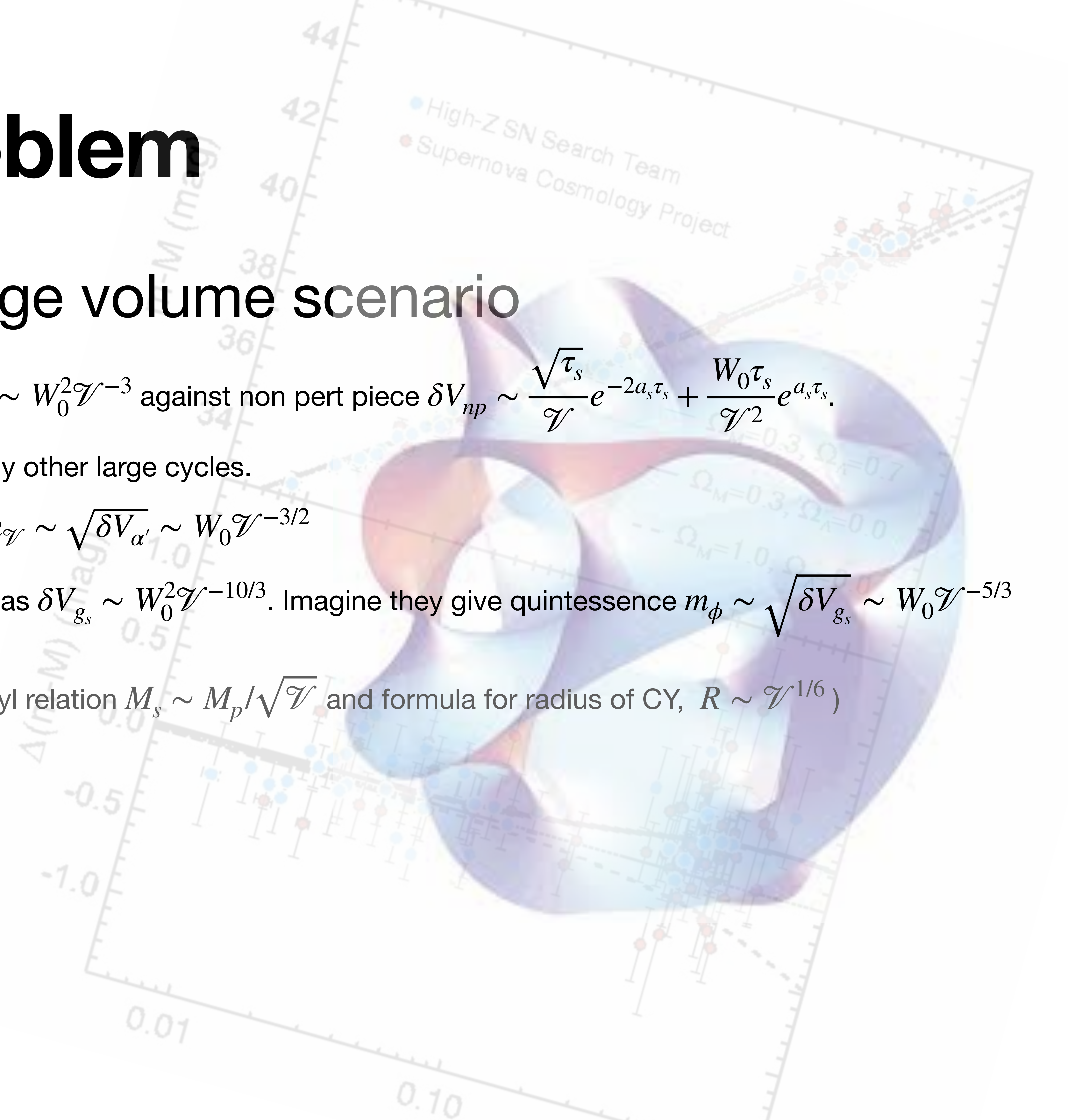

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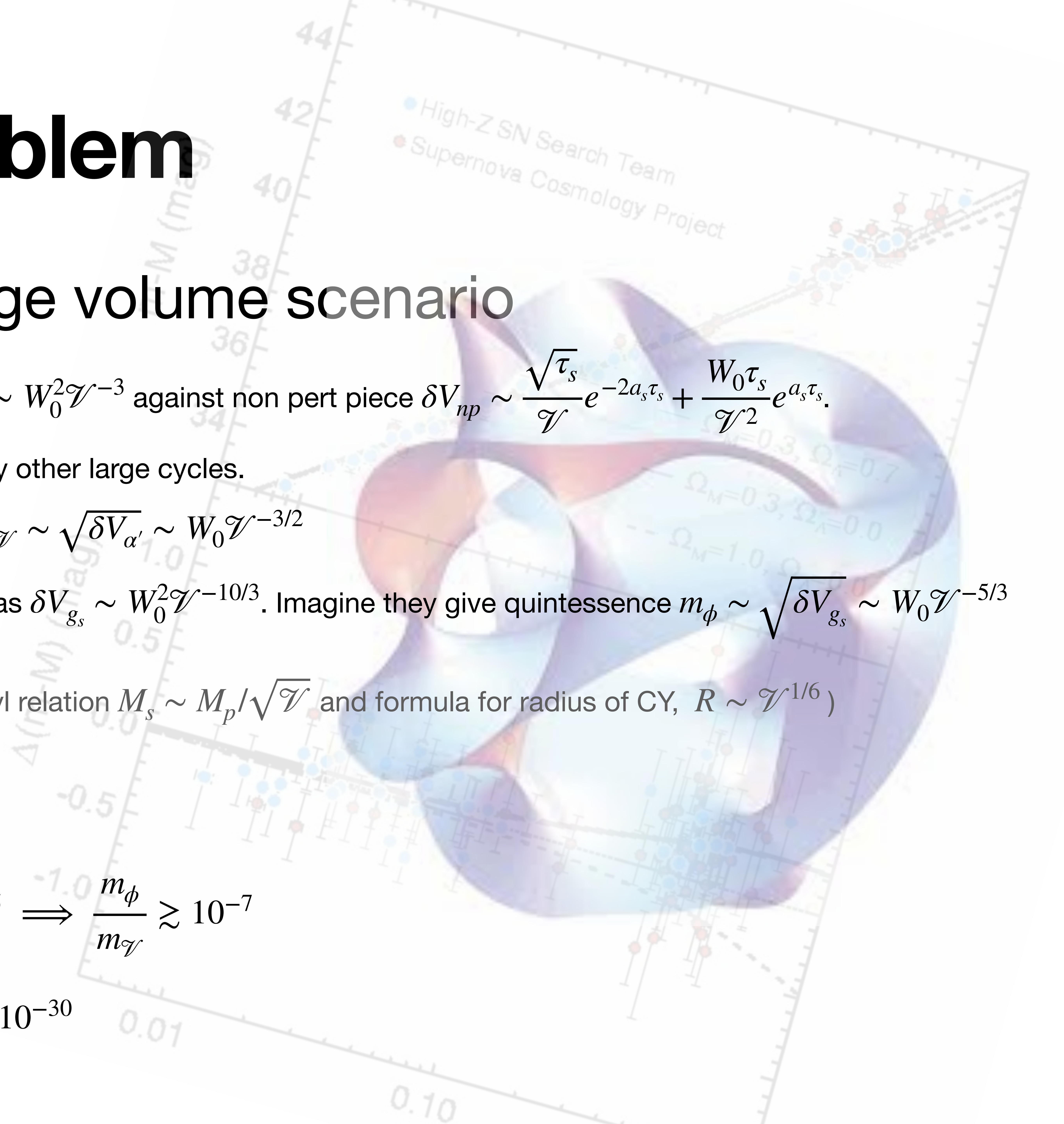

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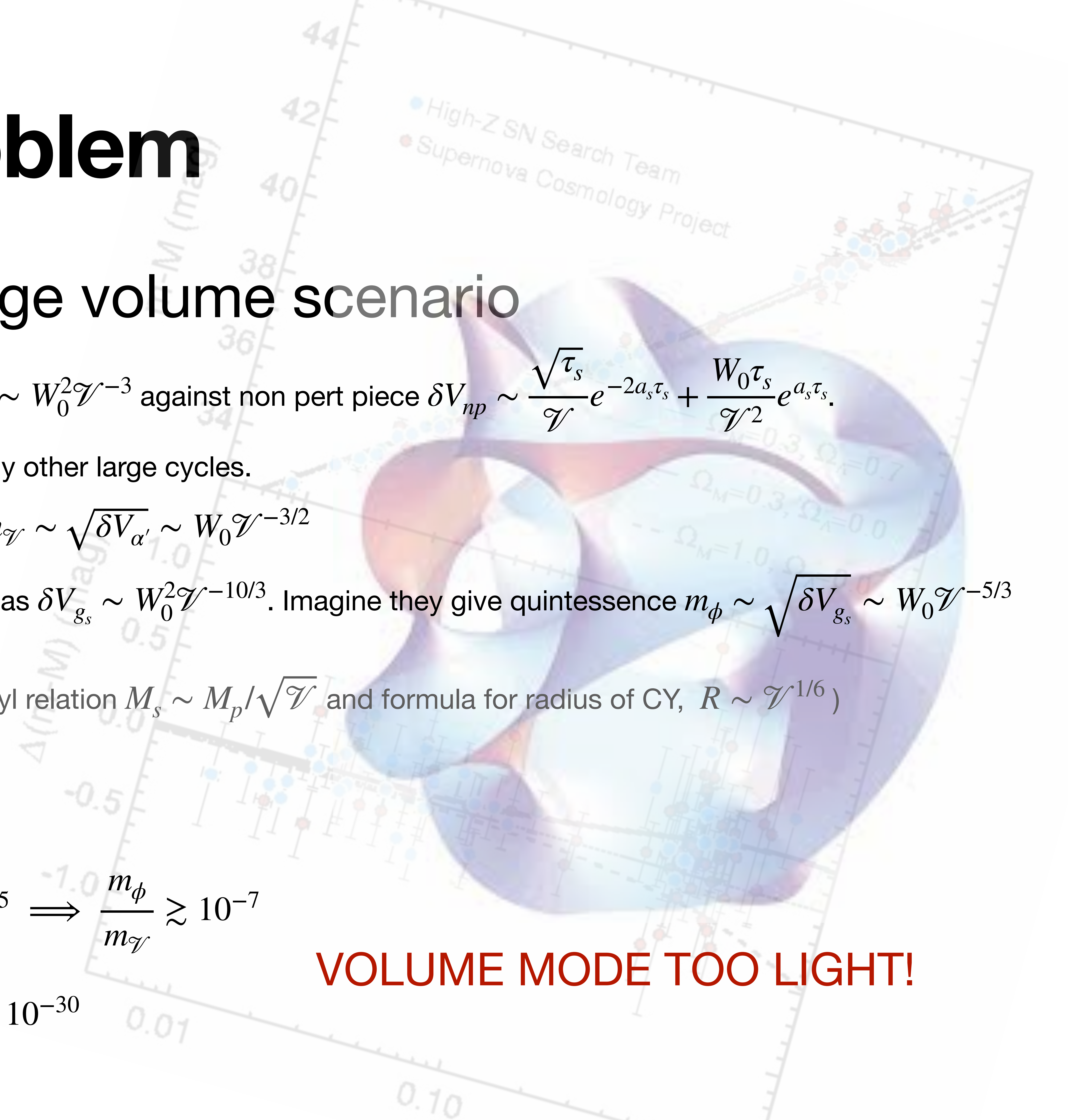
VOLUME MODE TOO LIGHT!



Parametric vs Numerical control

Cicoli, Cunillera, Padilla, Pedro 2021

Parametric control

Arbitrarily small couplings $(g_s, \alpha' \rightarrow 0)$. All corrections can be neglected. SUSY is retained

Reduces to tree-level supergravity. Calculations can be made exact.

Numerical control

Small but finite couplings $(g_s, \alpha' \ll 1)$. Corrections can become important, SUSY can be explicitly/softly broken. Rich phenomenology but requires caution. Limited (non-)perturbative knowledge.

Parametrically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

Type IIB at the boundary

Complex structure stabilised

Kahler moduli $T^i = \tau^i + i\theta^i$, axio-dilaton $S = s + i\alpha$

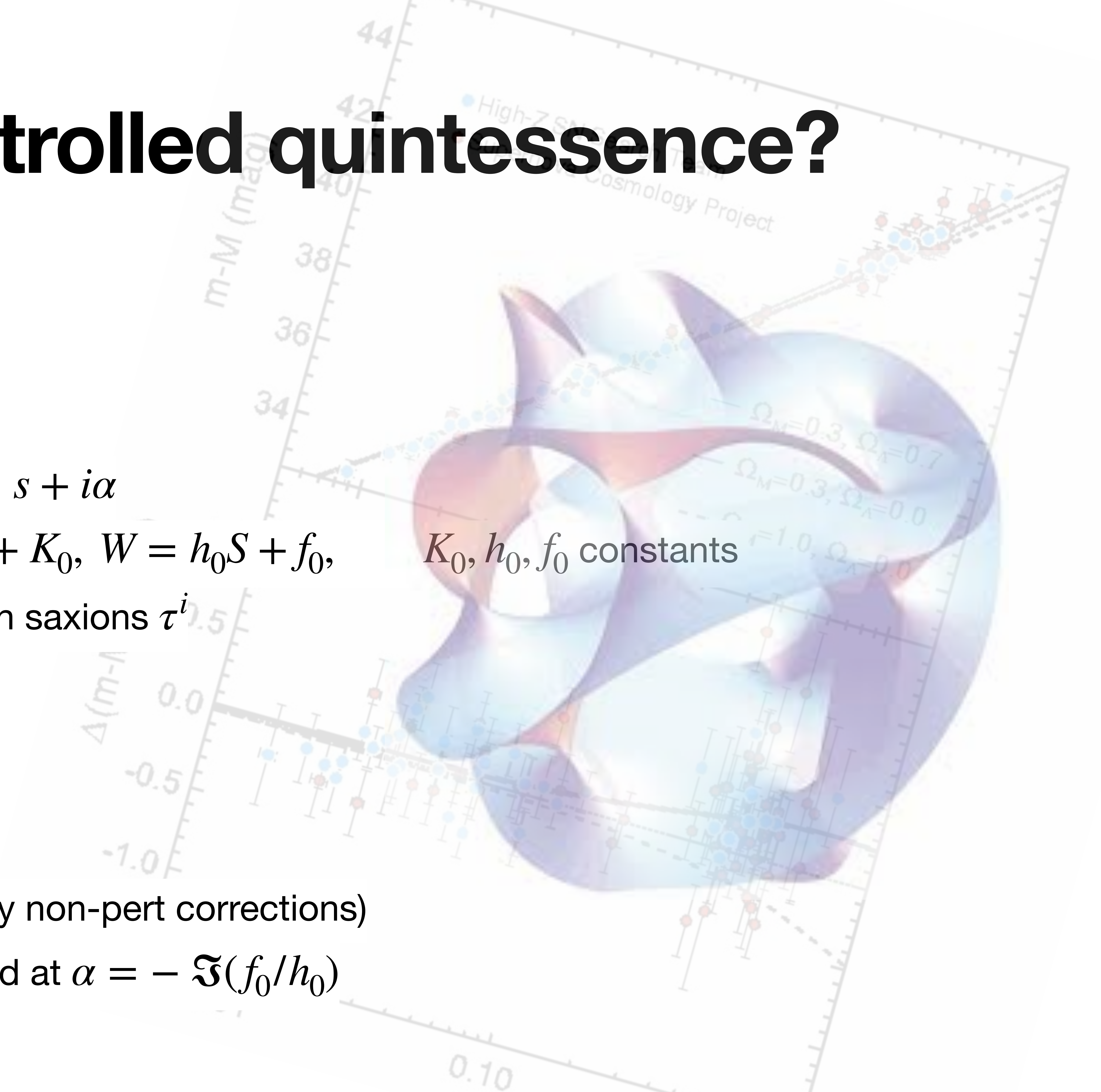
At the boundary, $K = -2\ln\mathcal{V} - \ln(S+\bar{S}) + K_0,\ W = h_0 S + f_0,$ $\qquad K_0, h_0, f_0$ constants

$\mathcal{V}$ is a homogeneous function of degree 3/2 in saxions τ^i

$$V = \frac{e^{K_0}}{2s\mathcal{V}^2}\,|\,h_s\bar{S} - f_0\,|^2$$

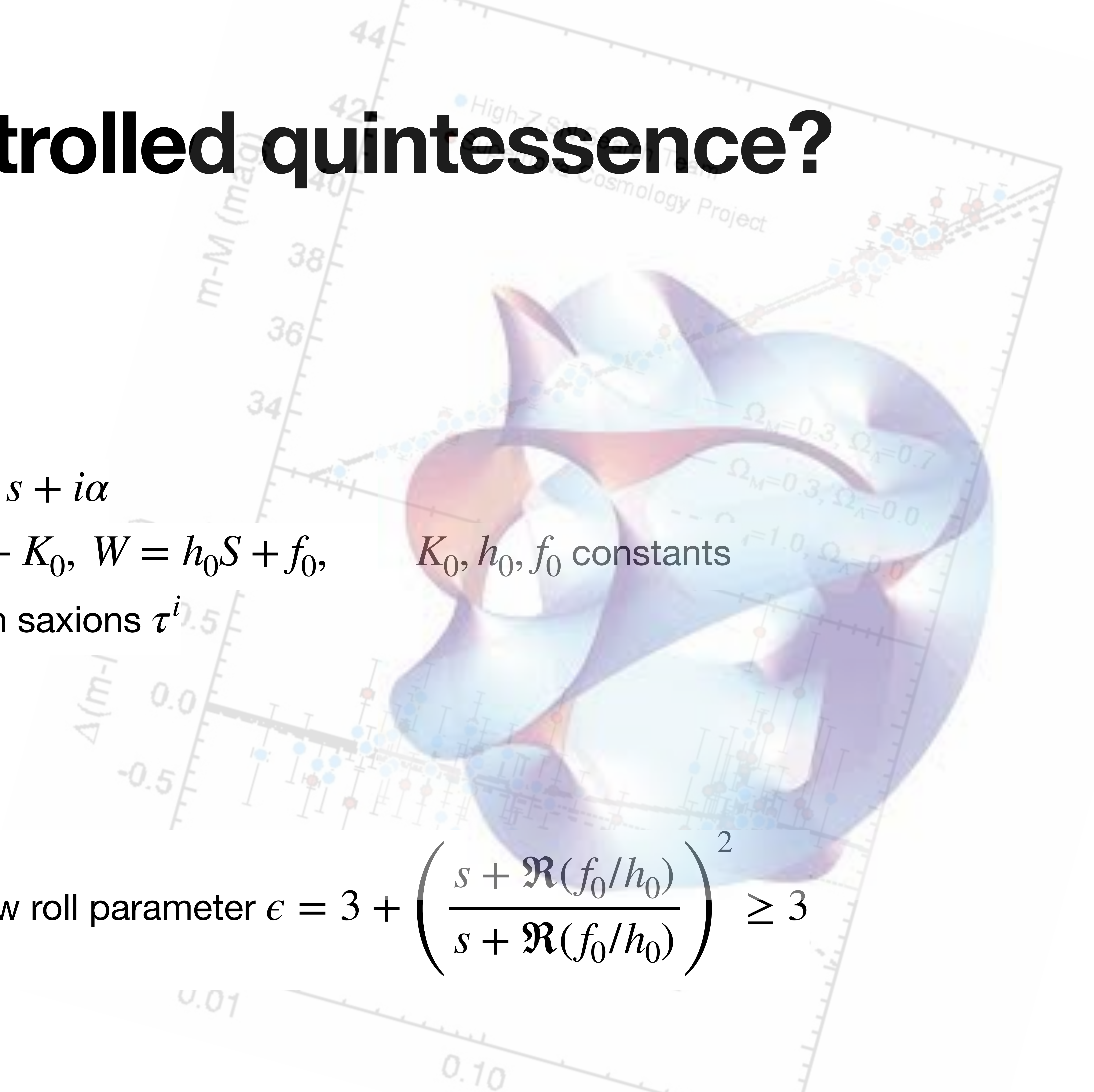
Axion directions θ^i are flat (need to be lifted by non-pert corrections)

Imaginary part of axio-dilaton can be stabilised at $\alpha = -\,\mathfrak{I}(f_0/h_0)$



Parametrically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021



Type IIB at the boundary

Complex structure stabilised

Kahler moduli $T^i = \tau^i + i\theta^i$, axio-dilaton $S = s + i\alpha$

At the boundary, $K = -2\ln\mathscr{V} - \ln(S+\bar{S}) + K_0,\ W = h_0 S + f_0,$ K_0, h_0, f_0 constants

$\mathscr{V}$ is a homogeneous function of degree 3/2 in saxions τ^i

Aftering integrating out α,

$V = \frac{e^{K_0}}{2s\mathscr{V}^2}|h_0|^2\left[s - \Re(f_0/h_0)\right]^2$ giving slow roll parameter $\epsilon = 3 + \left(\frac{s+\Re(f_0/h_0)}{s+\Re(f_0/h_0)}\right)^2 \geq 3$

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Stabilise dilaton at SUSY min so leading order V vanishes. Add some perturbative and non perturbative corrections

$$\delta V \sim \frac{\mathscr{A}}{\mathscr{V}^{2+p}} + \frac{\mathscr{B} e^{-f}}{\mathscr{V}^{2+q}} + \frac{\mathscr{C}}{\mathscr{V}^{2+r} g^{n}},$$

f, g are homogeneous functions of degree one in τ^i

Still get $\epsilon \geq 3$

Breaking SUSY doesn't help

No slow roll for IIA or heterotic either, at least in parametrically controlled regime

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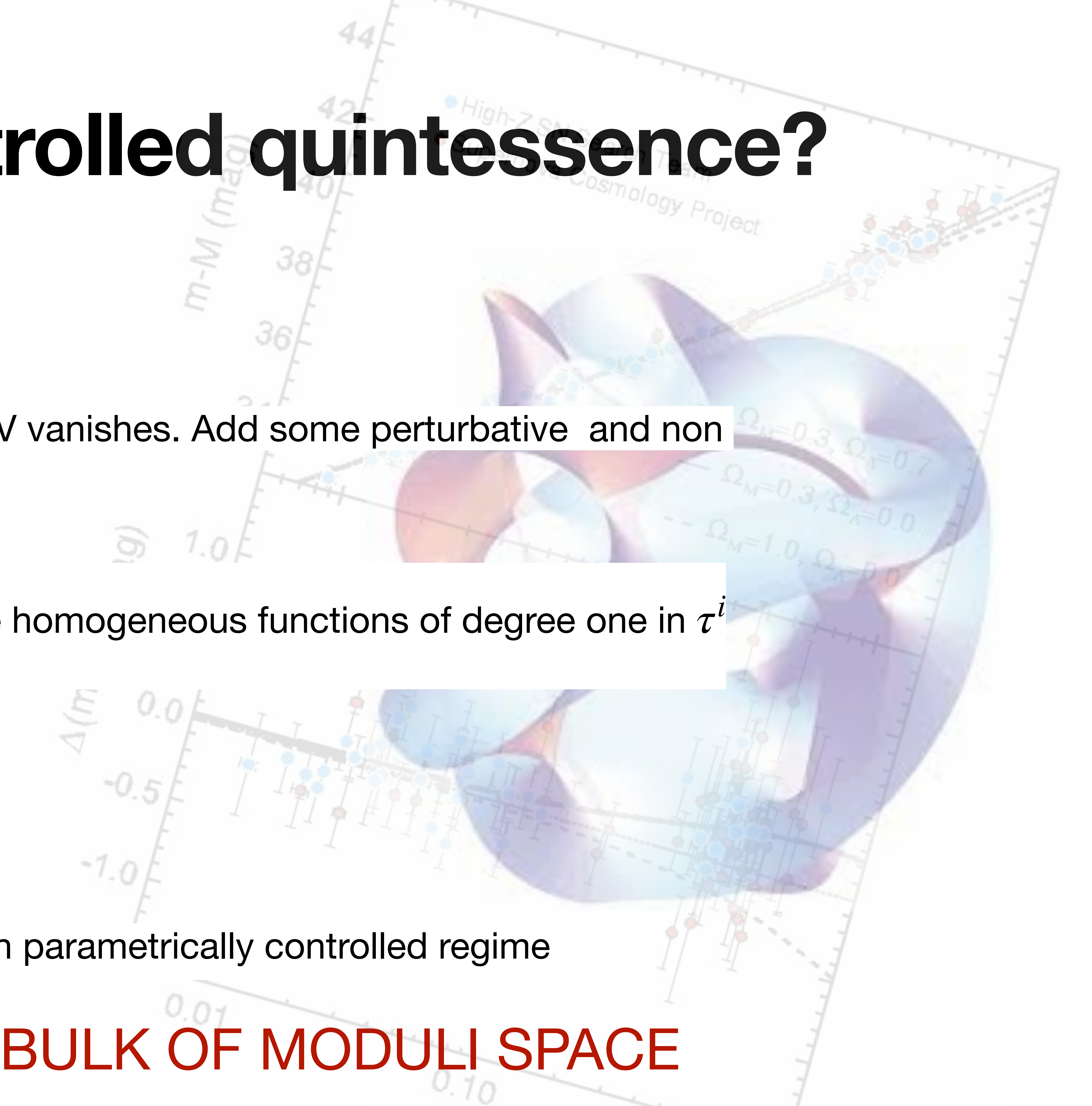
NEED TO GO INTO BULK OF MODULI SPACE



Problems with hilltops

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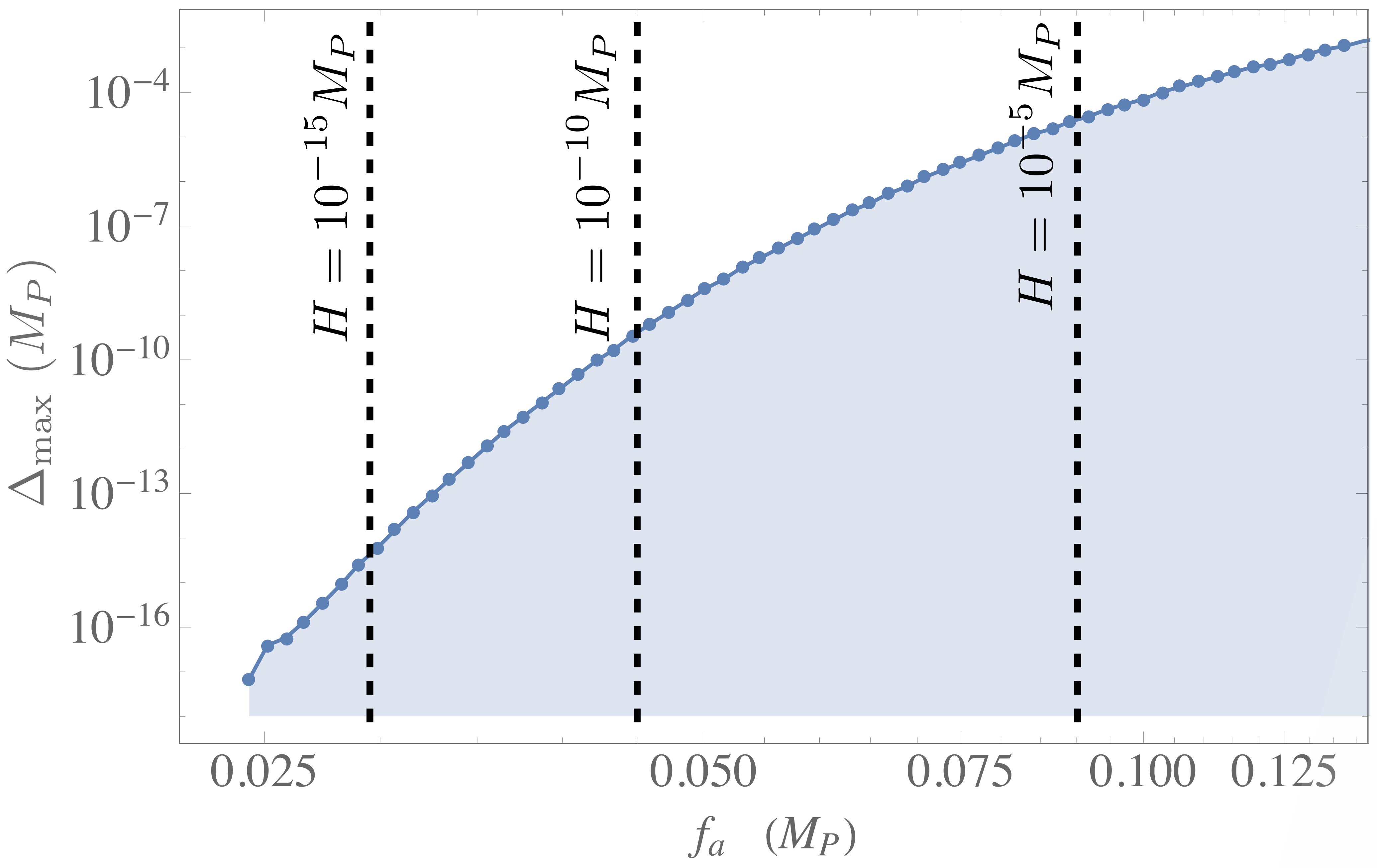
Zooming in ….



Typically we have $f \lesssim 0.02 M_{pl}$ (as in our LVS model)

This sets $\Delta_{\text{max}} \lesssim 10^{-20} M_{pl}$

Problems with quantum diffusion only avoided if

$H_{\text{inf}} \lesssim 10^{-20} M_{pl} \sim 10$ MeV

Too contrived?

Problems with hilltops

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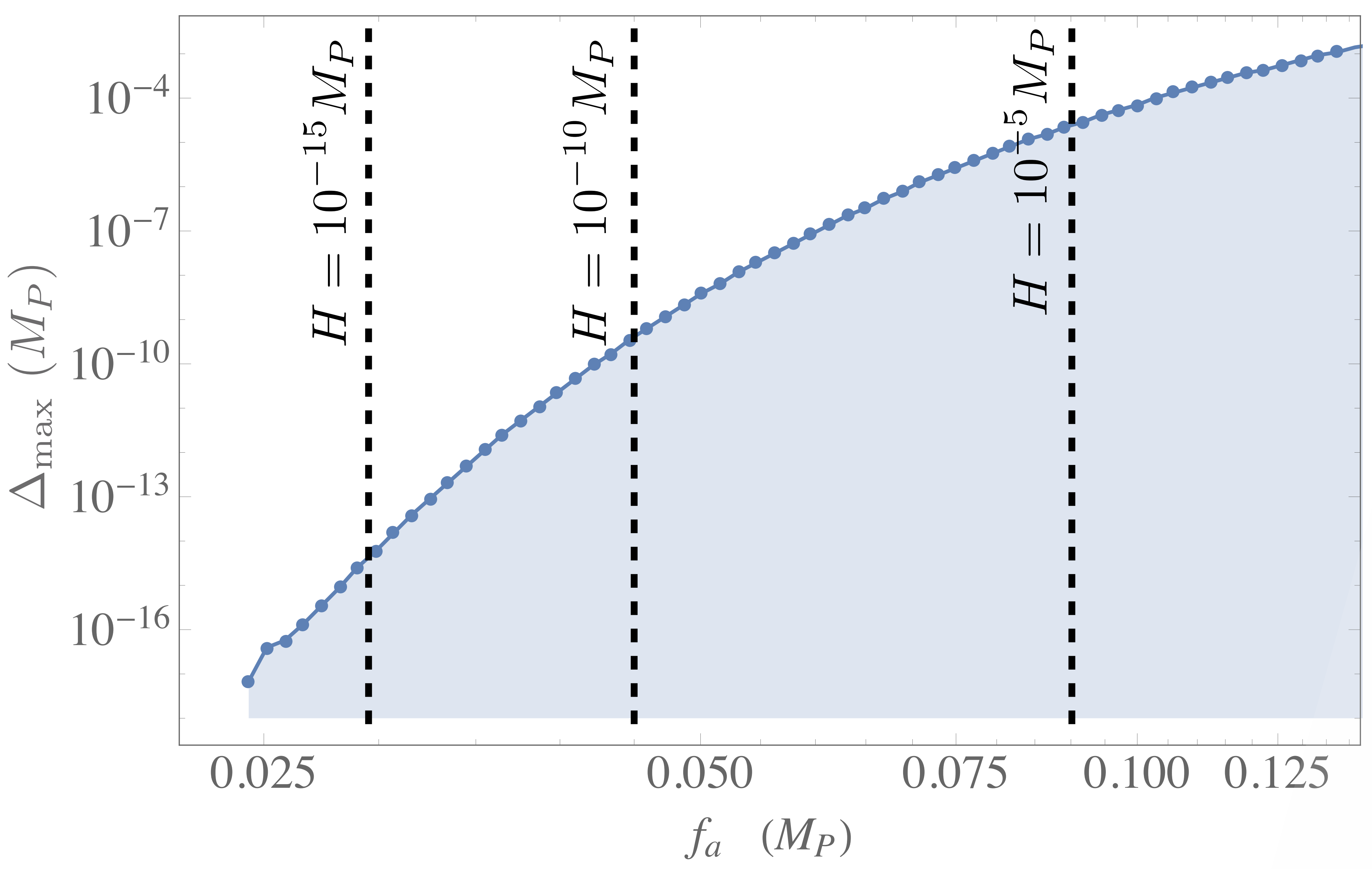

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Too contrived? AXION ALIGNMENT?