From Inflation to Quintessence: a complete history of the universe in String Theory

Tony Padilla

Based on 2407.0340 [hep-th]. See also 2112.10783 [hep-th] and 2112.10779 [hep-th]

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

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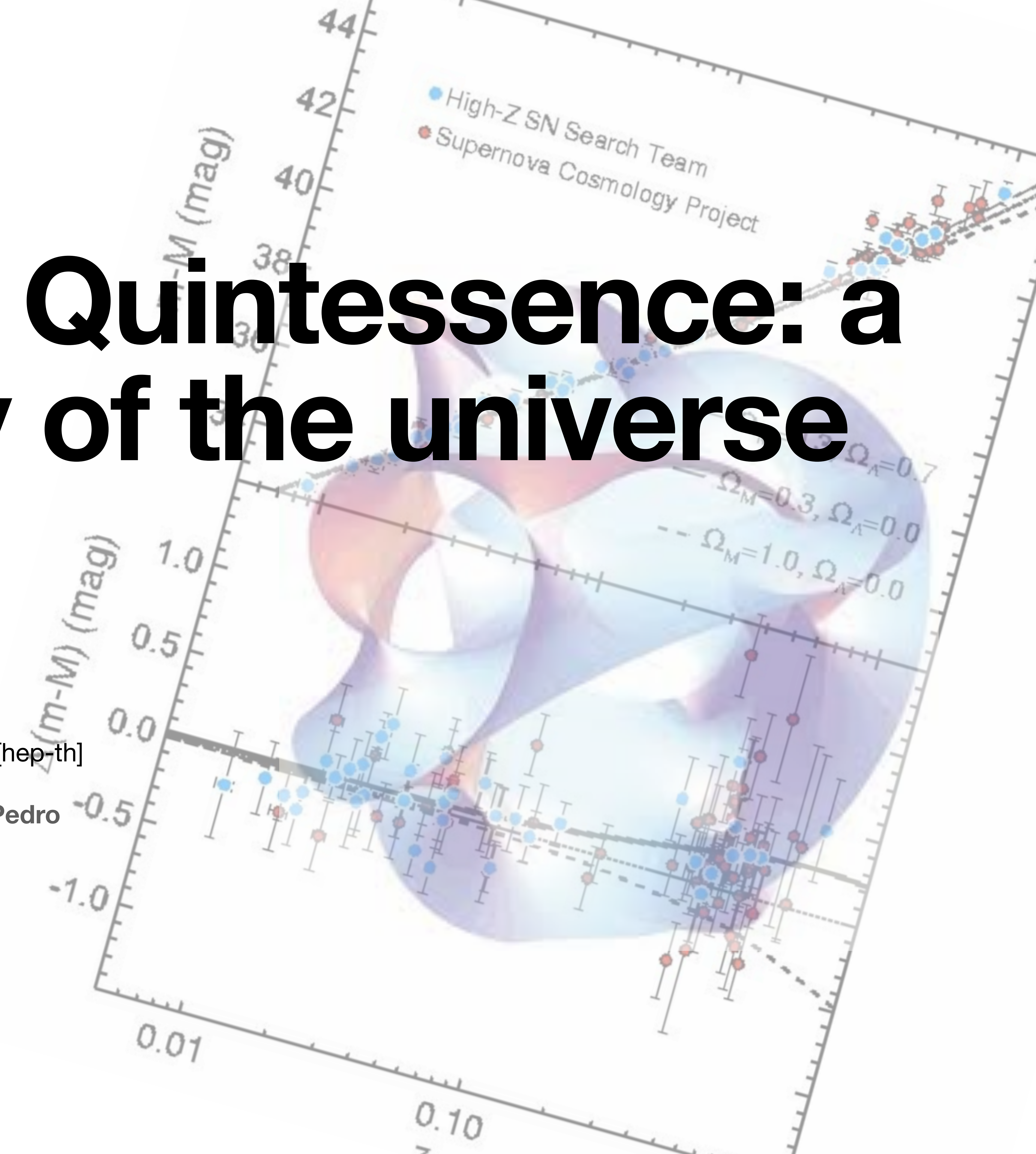
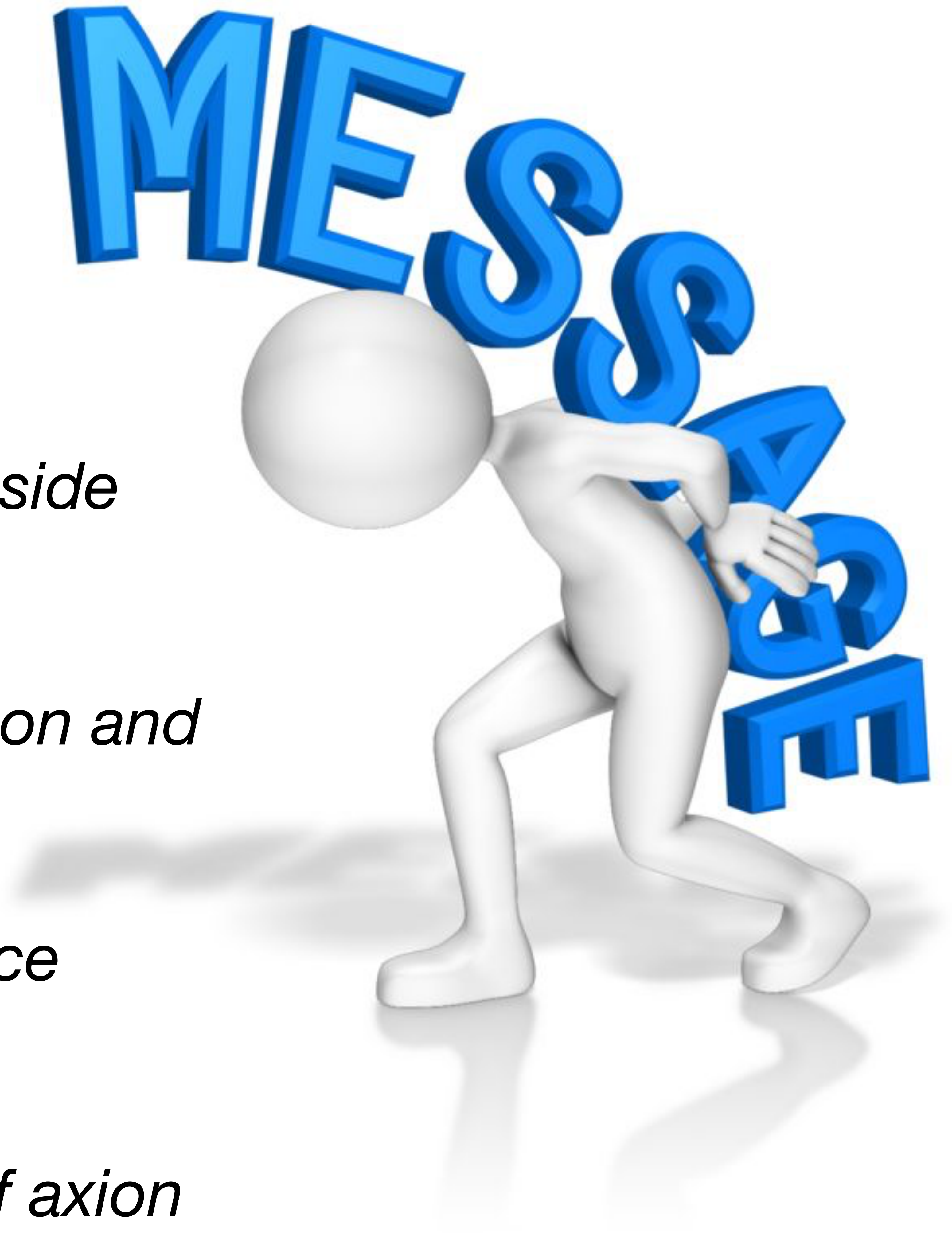


Take Home Message

Cicoli, Cunillera, Padilla, Pedro 2024



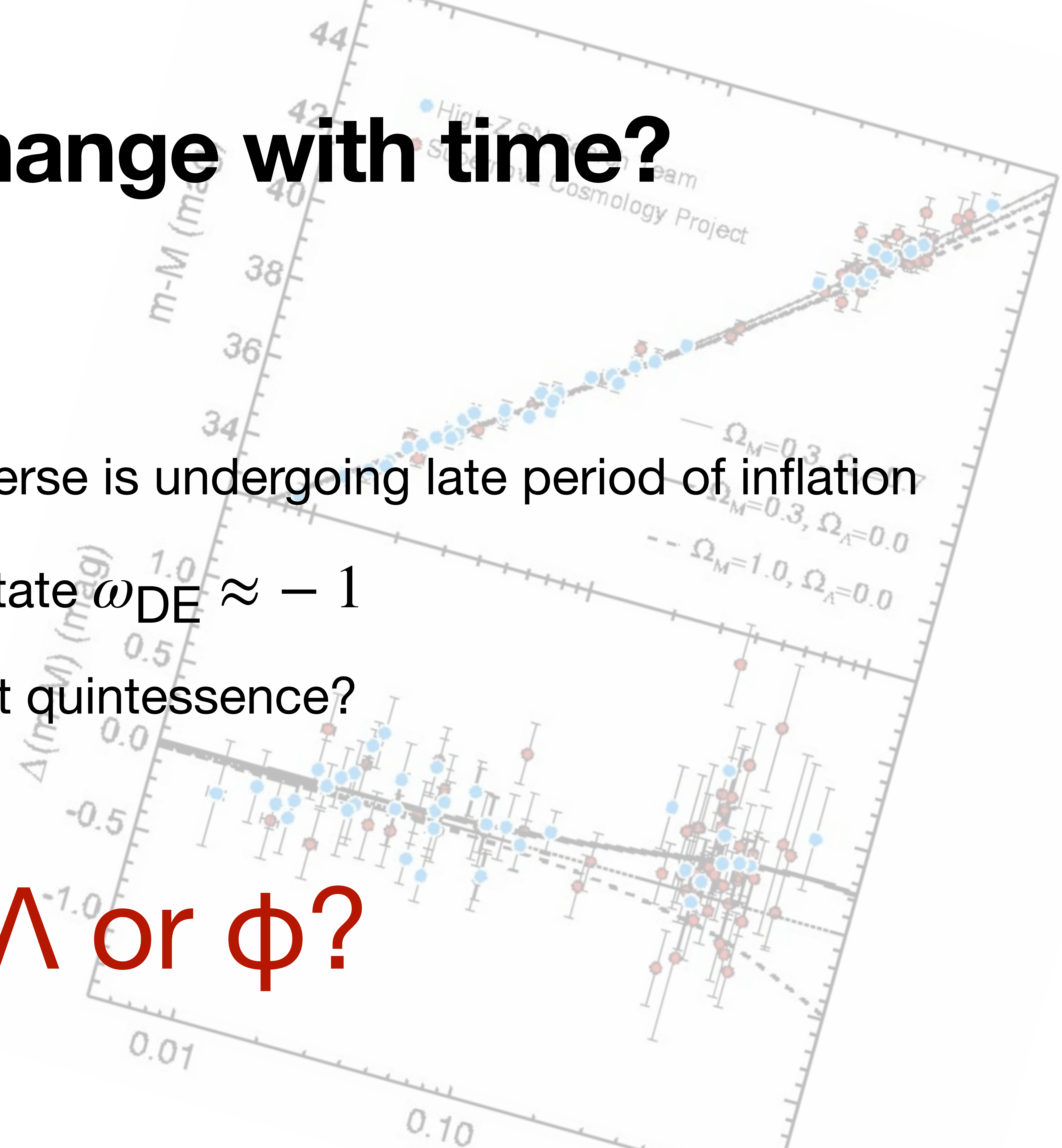
Building quintessence into string theory is hard. Building it alongside inflation is hard^2

We identified a blueprint for building a consistent model of inflation and quintessence in perturbative string theory.

A concrete model combines fibre inflation with axion quintessence generated by poly-instanton corrections to the super potential

This yields predictions for inflationary observables, abundance of axion DM, and quintessence.

Does dark energy change with time?

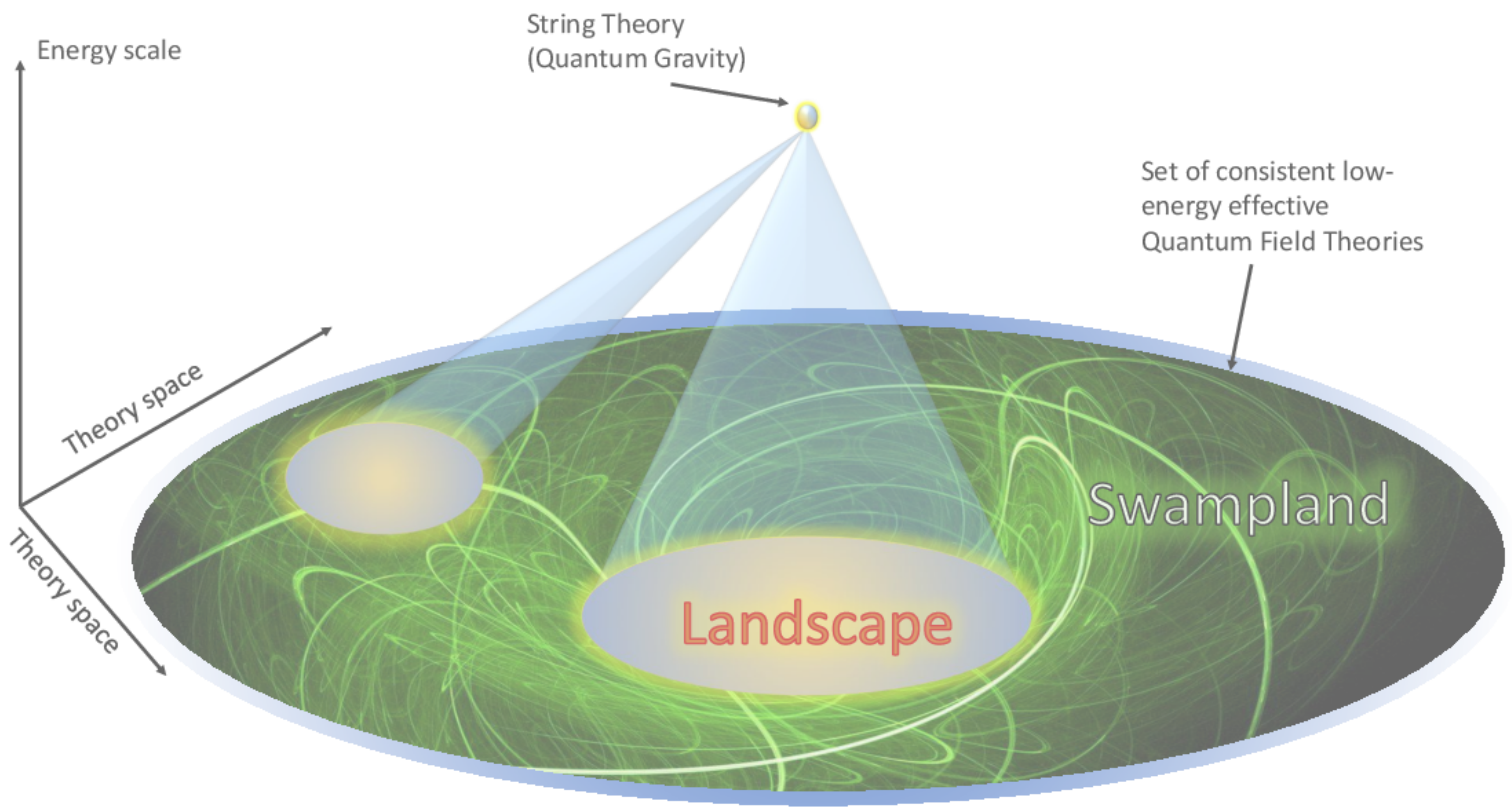


- data (eg CMB, SNe) indicates universe is undergoing late period of inflation
- driven by a fluid with equation of state $\omega_{\text{DE}} \approx -1$
- is it a cosmological constant or is it quintessence?

Is it Λ or ϕ?

What if dark energy is constant?

- empirically simple
- the observational value of the cosmological constant is 120 orders of magnitude smaller than expected by naturalness
- constructing de Sitter vacua in ST is challenging, largely because SUSY must be broken
- should dS be in the ST swampland?



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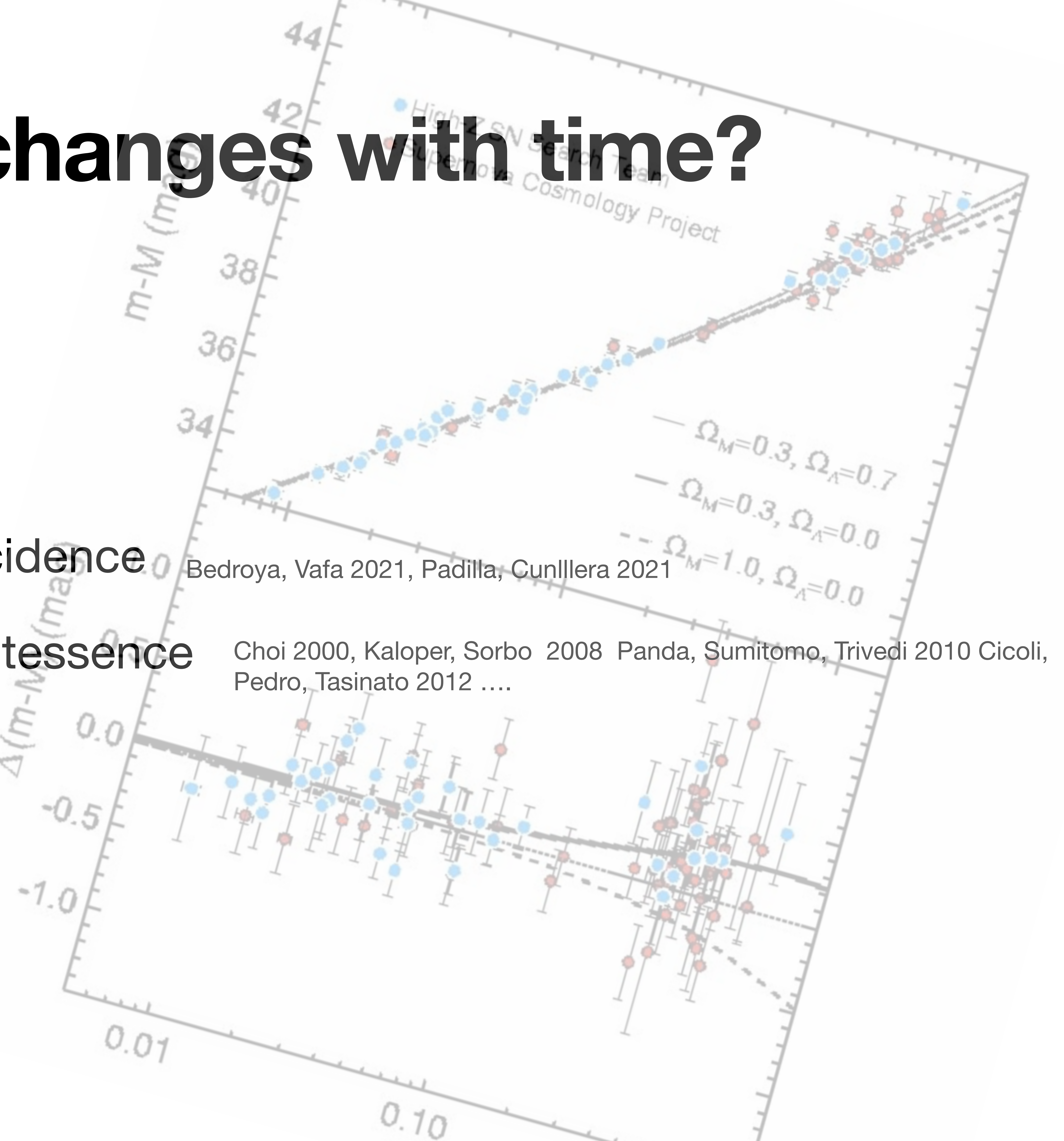


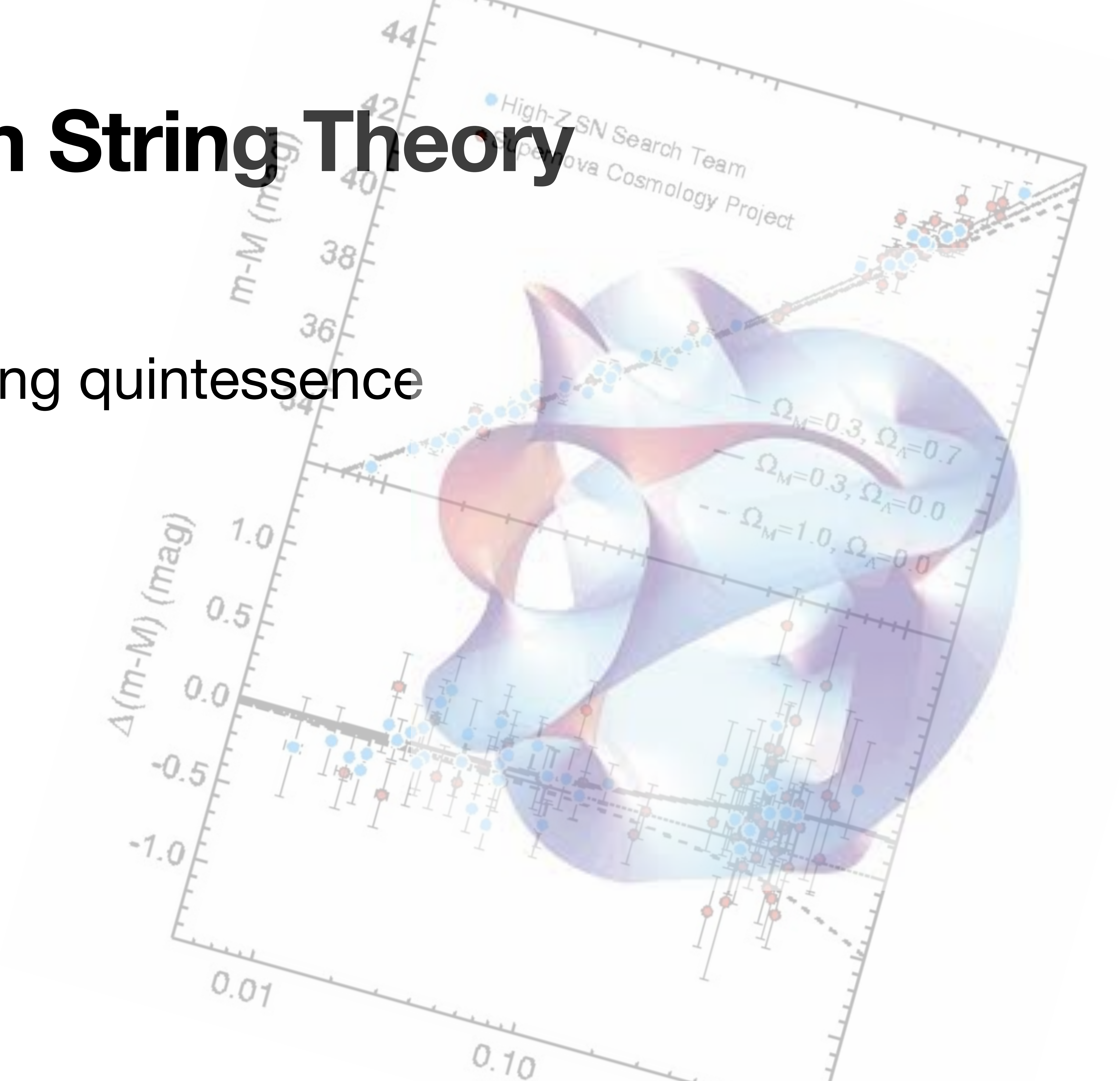
- richer phenomenology
- maybe it could help with cosmic coincidence Bedroya, Vafa 2021, Padilla, Cunlllera 2021
- several old challenges to building quintessence Choi 2000, Kaloper, Sorbo 2008 Panda, Sumitomo, Trivedi 2010 Cicoli, Pedro, Tasinato 2012 ….
- and some new… Cicoli, Cunillera, Padilla, Pedro 2021

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 $m_{\mathscr{V}} \gtrsim 10^{-30} M_{pl}$



Cosmology from String Theory

Reduce down to 4D EFT by compactifying on 6D Calabi Yau

EFT depends on following complex scalar moduli

- axio-dilaton, S
- Kahler moduli, T^i
- complex structure, N^a (which we assume to be fixed)

Lagrangian for scalar moduli given by

$$\mathscr{L} = - K_{I\bar{J}}\partial\Phi^I\partial\Phi^{\bar{J}} - V(\Phi^I)$$

where $K_{I\bar{J}} = \partial_I\partial_{\bar{J}}K$ and $V = e^K(K^{I\bar{J}}D_IWD_{\bar{J}}\bar{W} - 3\,|\,W\,|^2)$

Kahler metric

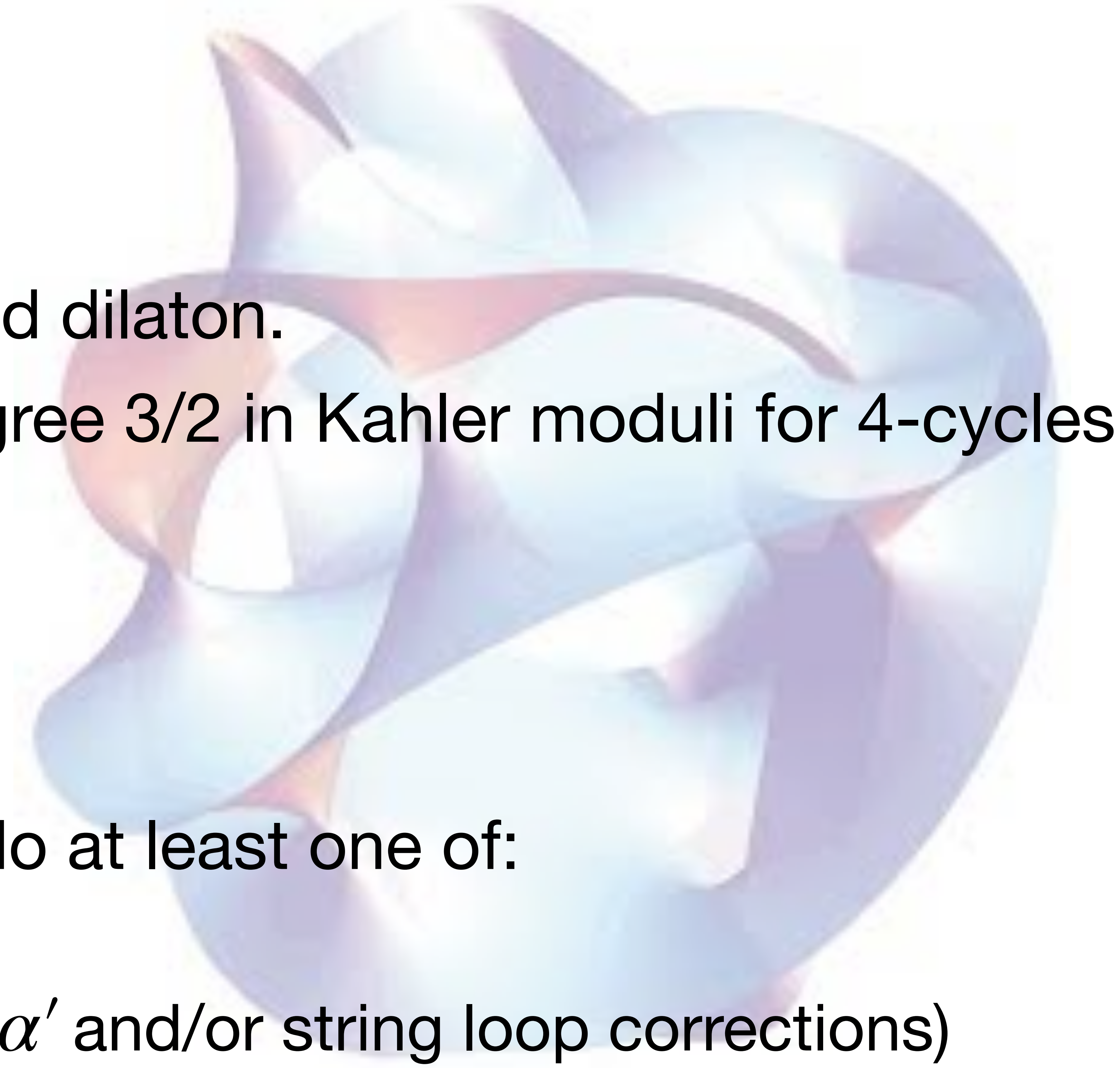
Kahler potential, K

Kahler covariant derivative
$D_IW = (\partial_I + \partial_IK)W$

superpotential, W

Cosmology from String Theory

See eg Cicoli et al 2018



Focus on type IIB strings

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

- K_0, W_0 depend on (already stabilised) complex structure and dilaton.
- $\mathscr{V}$ is the volume of CY and a homogeneous function of degree 3/2 in Kahler moduli for 4-cycles.

V vanishes identically due to famous “no scale structure”

To generate a potential for Kahler moduli $T_i = \tau_i + i\theta_i$ must do at least one of:

- perturbative corrections to Kahler potential $K \rightarrow K + \delta K_p$ (eg α' and/or string loop corrections)
- non-perturbative corrections to superpotential $W \rightarrow W + \delta W_{np}$ (eg instantons, guagino condensates)
- higher derivative corrections to scalar potential $V \rightarrow V + \delta V_{hd}$ (eg Ric^2 G3^2 terms)

Cosmology from String Theory

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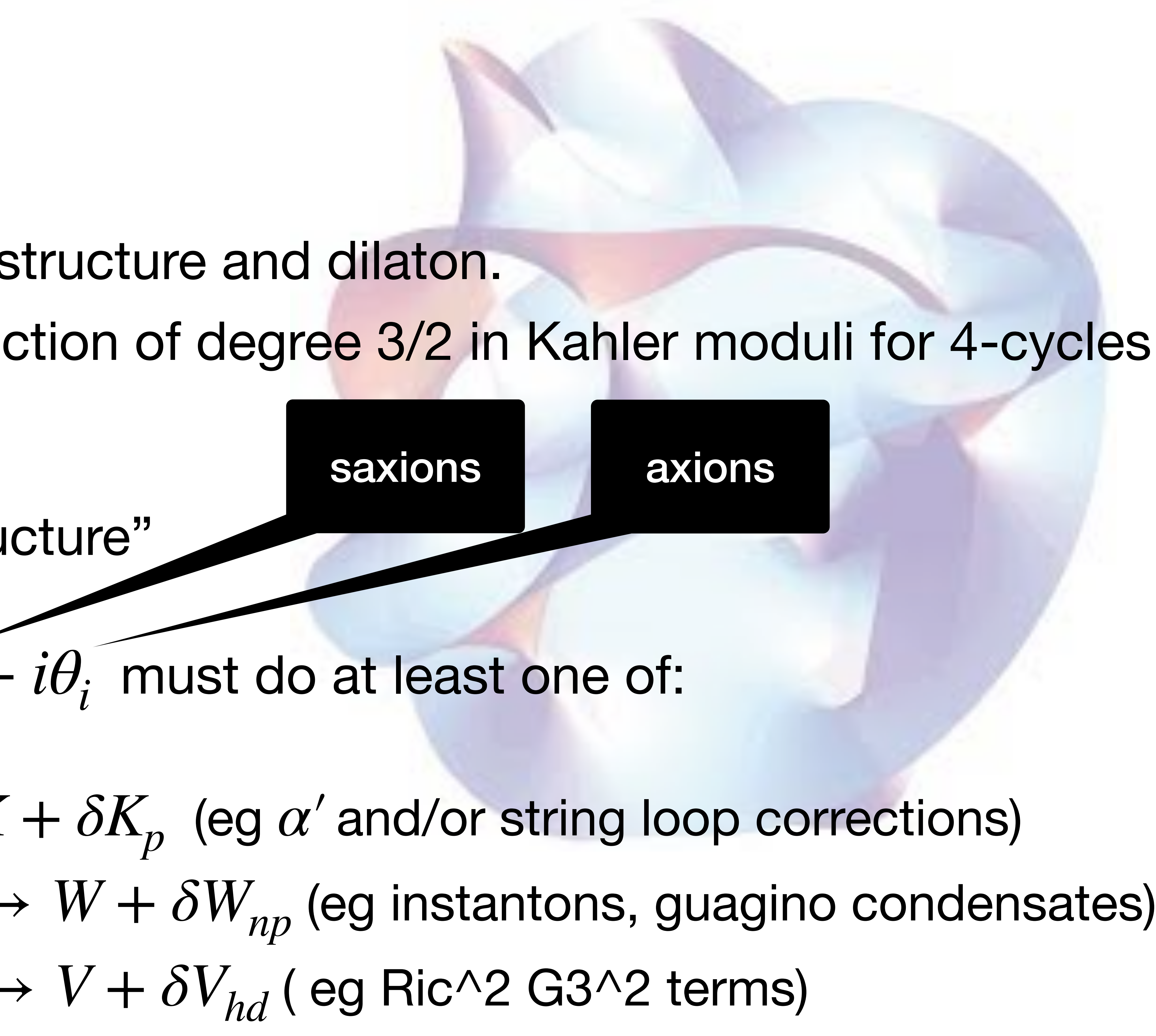

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saxions

axions

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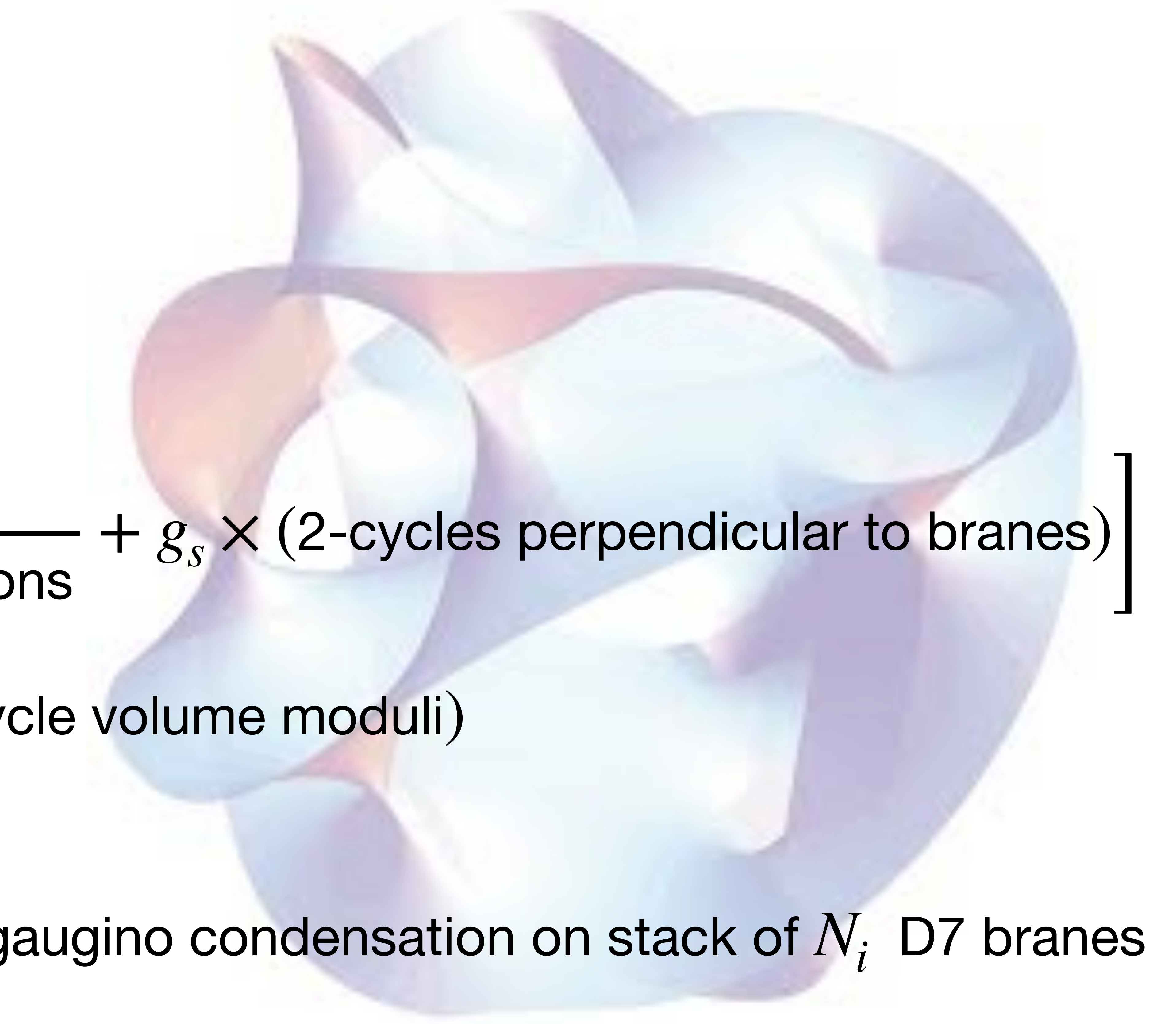


Model building ingredients

- 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
- Higher derivative terms $\delta V_{hd} \sim \frac{1}{g_s^{3/2}\mathscr{V}^4} W_0^4 \times$ (weighted sum over 2-cycle volume moduli)
  Ciupke, Louis, Westphal 2015
- Non-perturbative corrections $\delta W_{np} \sim \sum_i A_i e^{-a_i T^i}$ where $a_i = \frac{2\pi}{N_i}$ for gaugino condensation on stack of N_i D7 branes
  Blumenhagen et al 2009

Inflationary problems for quintessence

Cicoli, Cunillera, Padilla, Pedro 2021

The Kallosh Linde Problem

Kallosh Linde 2004

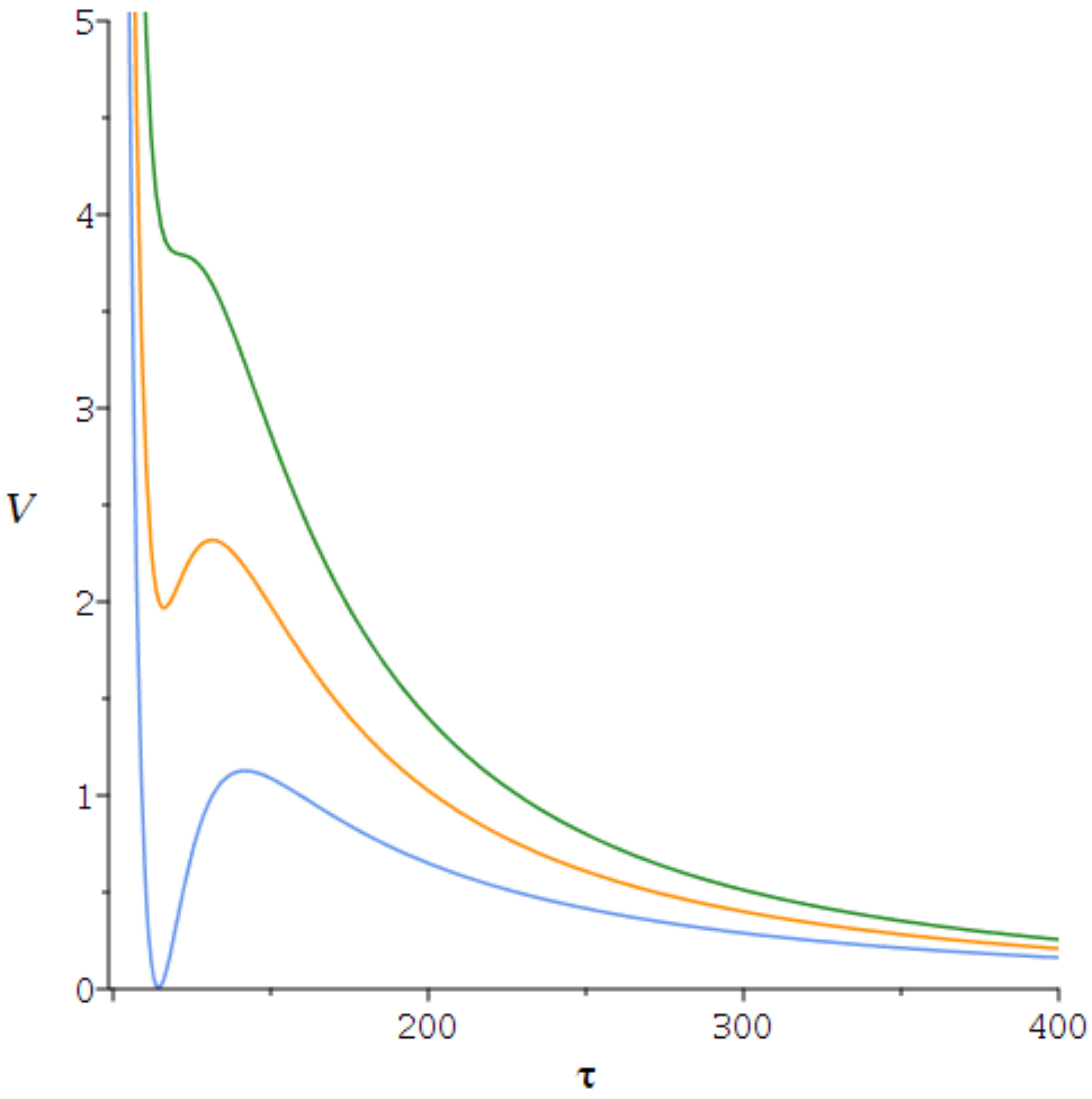
Imagine inflation driven by brane dynamics

$$V \to V_{\text{KKLT}}(\mathscr{V}) + \frac{U(\sigma)}{\mathscr{V}^{\frac{4}{3}}}$$

To avoid the runaway in volume requires

$$H^2_{\text{inf}} \lesssim V_{\text{barrier}} \sim m^2_{3/2}$$

Sets very high scale of SUSY breaking



Inflationary problems for quintessence

Cicoli, Cunillera, Padilla, Pedro 2021

The KL Problem for Quintessence

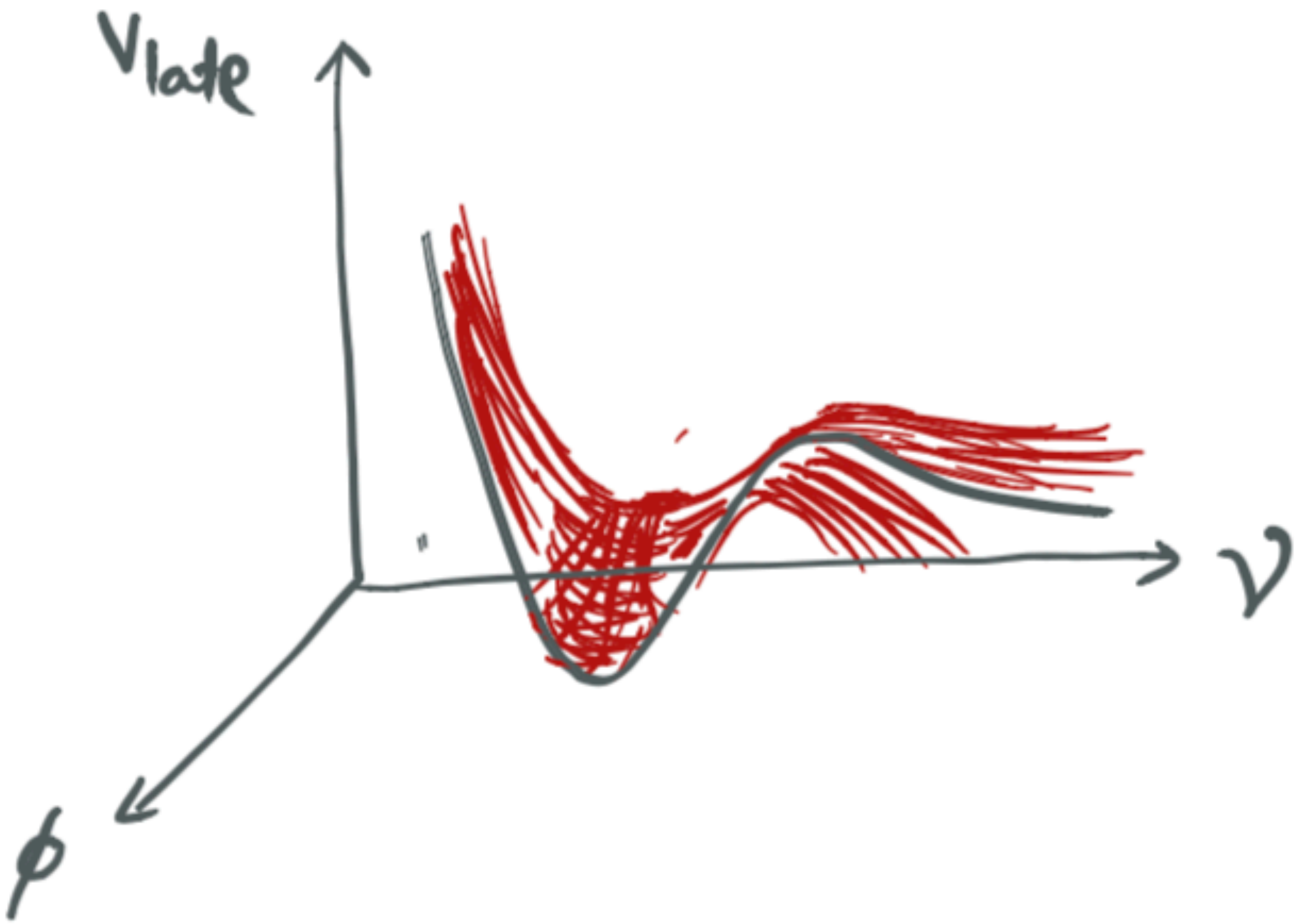
$$V = V_{\text{vol}}(\mathscr{V}) + V_{\text{inf}}(\sigma, \mathscr{V}) + V_{\text{DE}}(\phi, \mathscr{V})$$

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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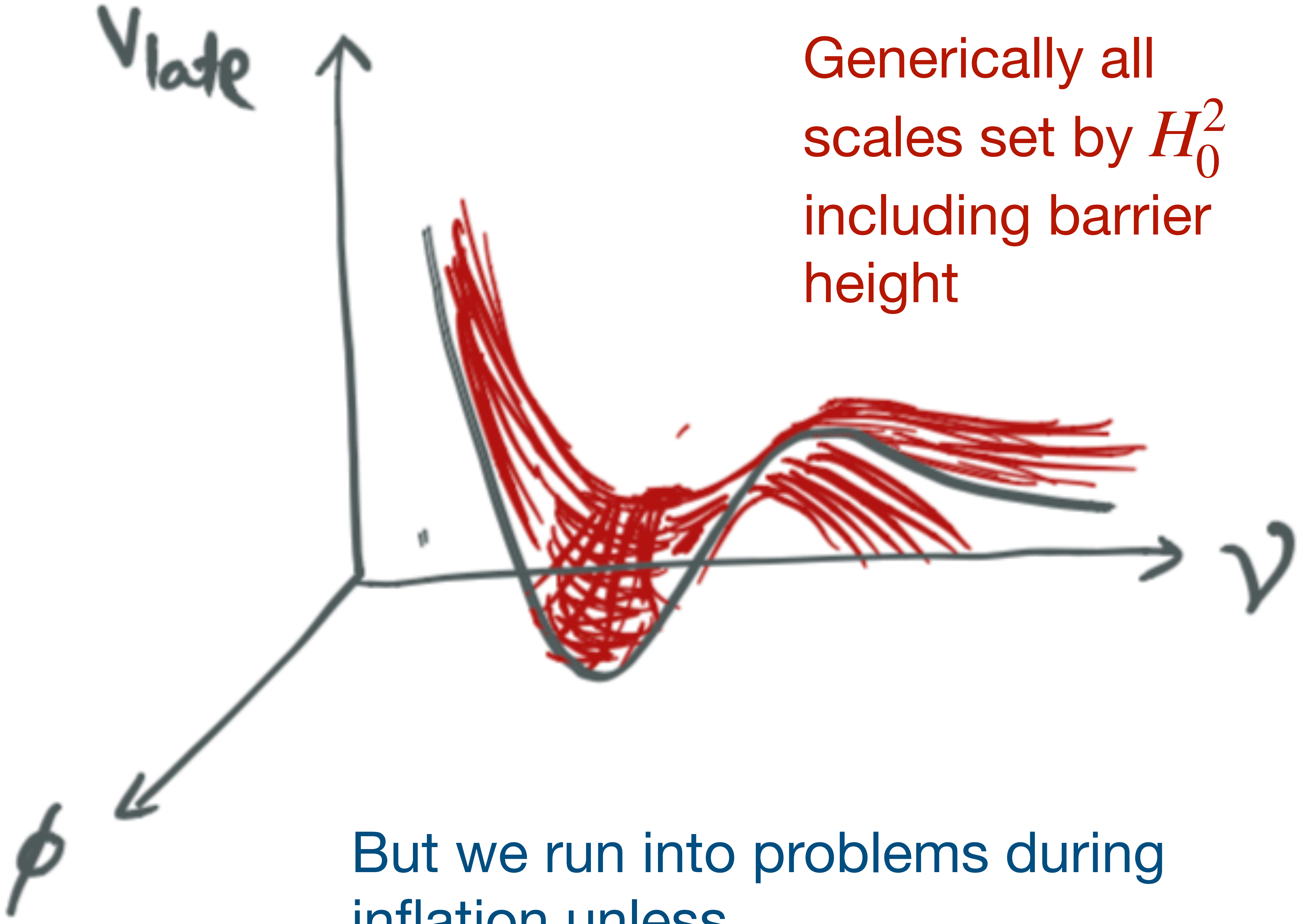


Generically all scales set by H_0^2 including barrier height

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!

Quintessence in String Theory: a blueprint

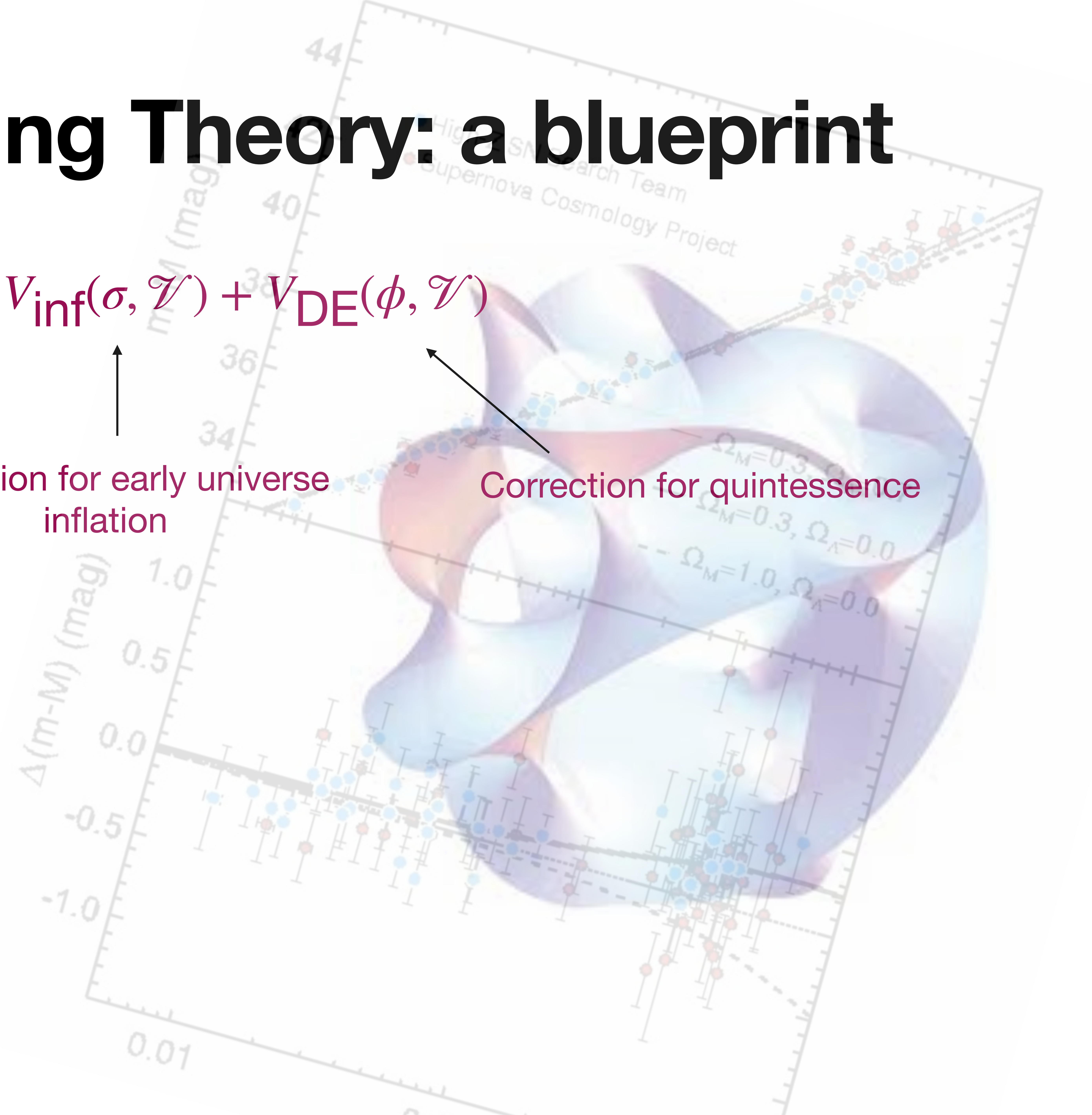
Cicoli, Cunillera, Padilla, Pedro 2021

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

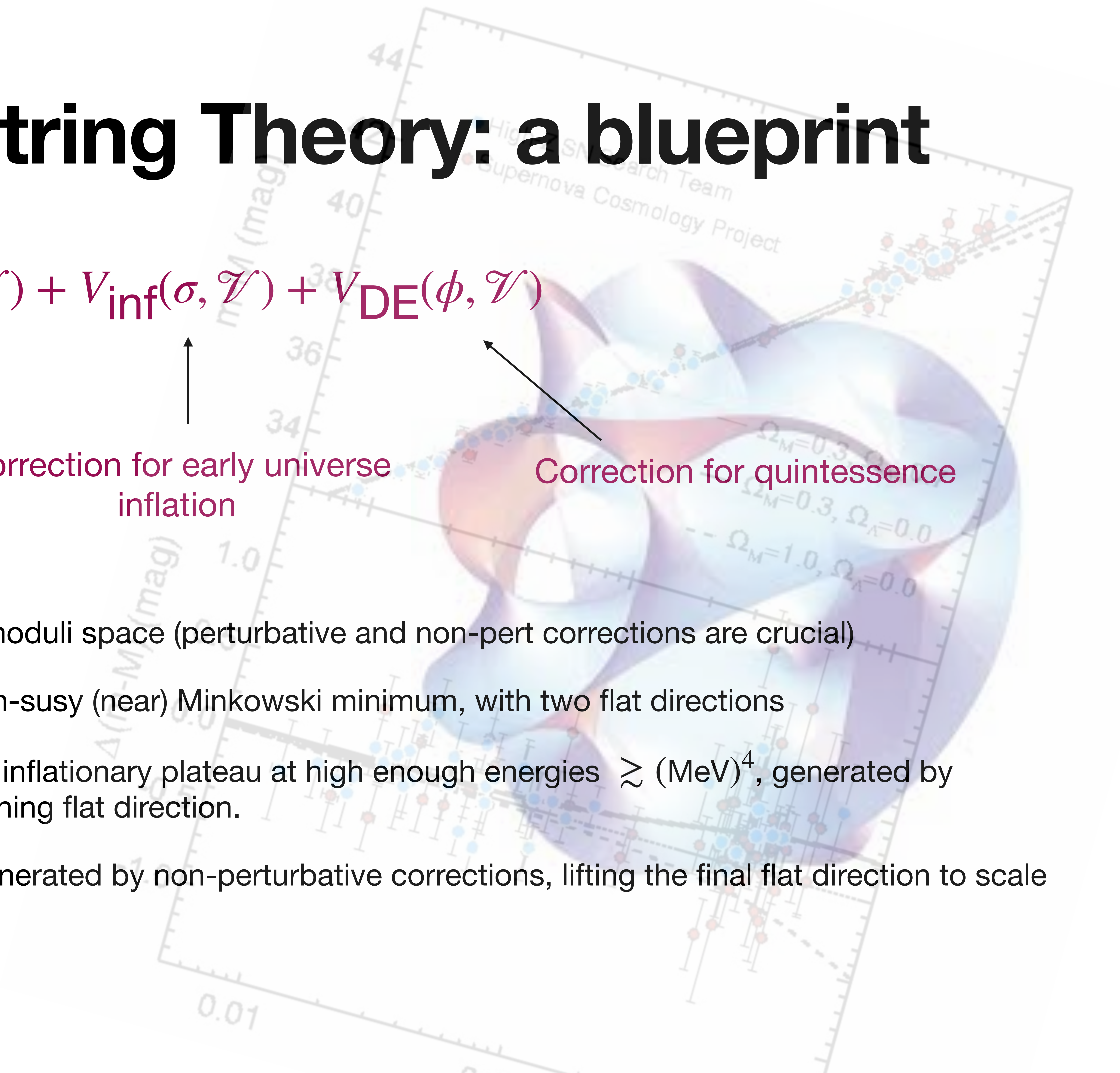
Correction for early universe inflation

Correction for quintessence



Quintessence in String Theory: a blueprint

Cicoli, Cunillera, Padilla, Pedro 2021



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Leading order potential for volume mode

Correction for early universe inflation

Correction for quintessence

- quintessence cannot occur at boundary of moduli space (perturbative and non-pert corrections are crucial)
- at leading order $V_{\text{vol}}(\mathscr{V})$ should admit a non-susy (near) Minkowski minimum, with two flat directions
- at sub-leading order V_{inf} should contain an inflationary plateau at high enough energies $\gtrsim$ (MeV)^4, generated by perturbative corrections. There is one remaining flat direction.
- at sub-sub-leading order V_{DE} should be generated by non-perturbative corrections, lifting the final flat direction to scale as (meV)^4

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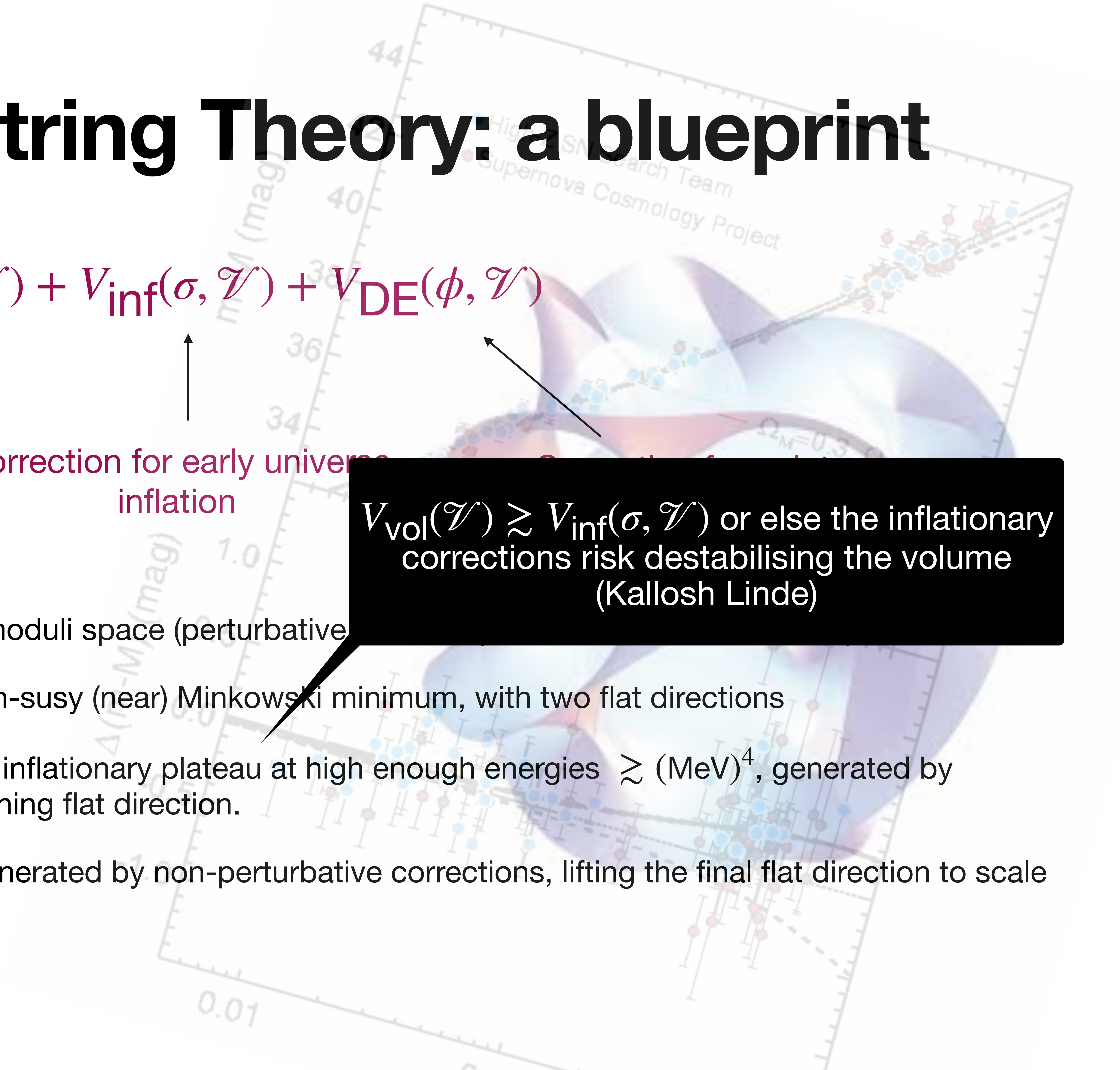

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Correction for early univers inflation

$V_{\text{vol}}(\mathscr{V}) \gtrsim V_{\text{inf}}(\sigma, \mathscr{V})$ or else the inflationary corrections risk destabilising the volume (Kallosh Linde)

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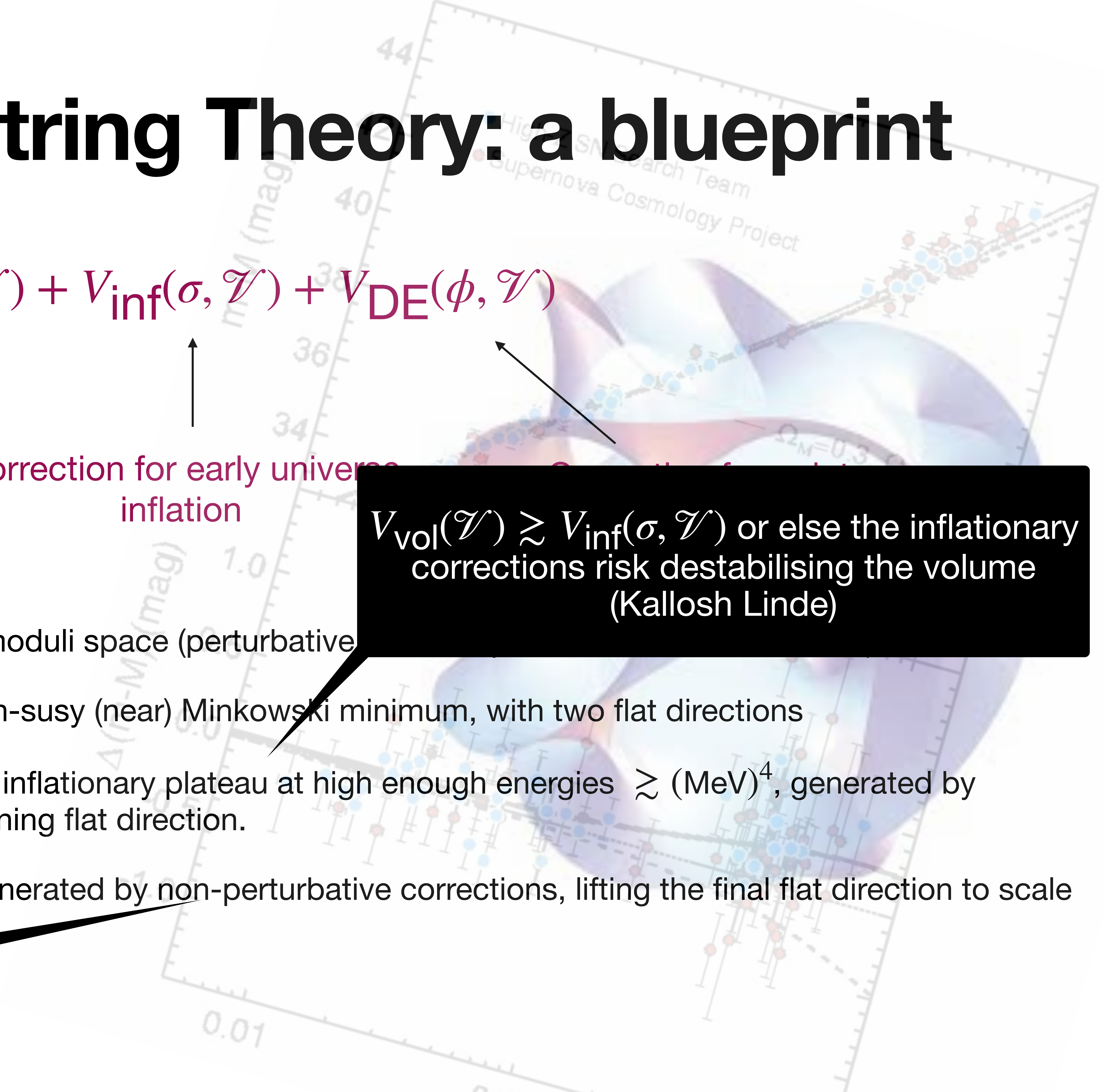

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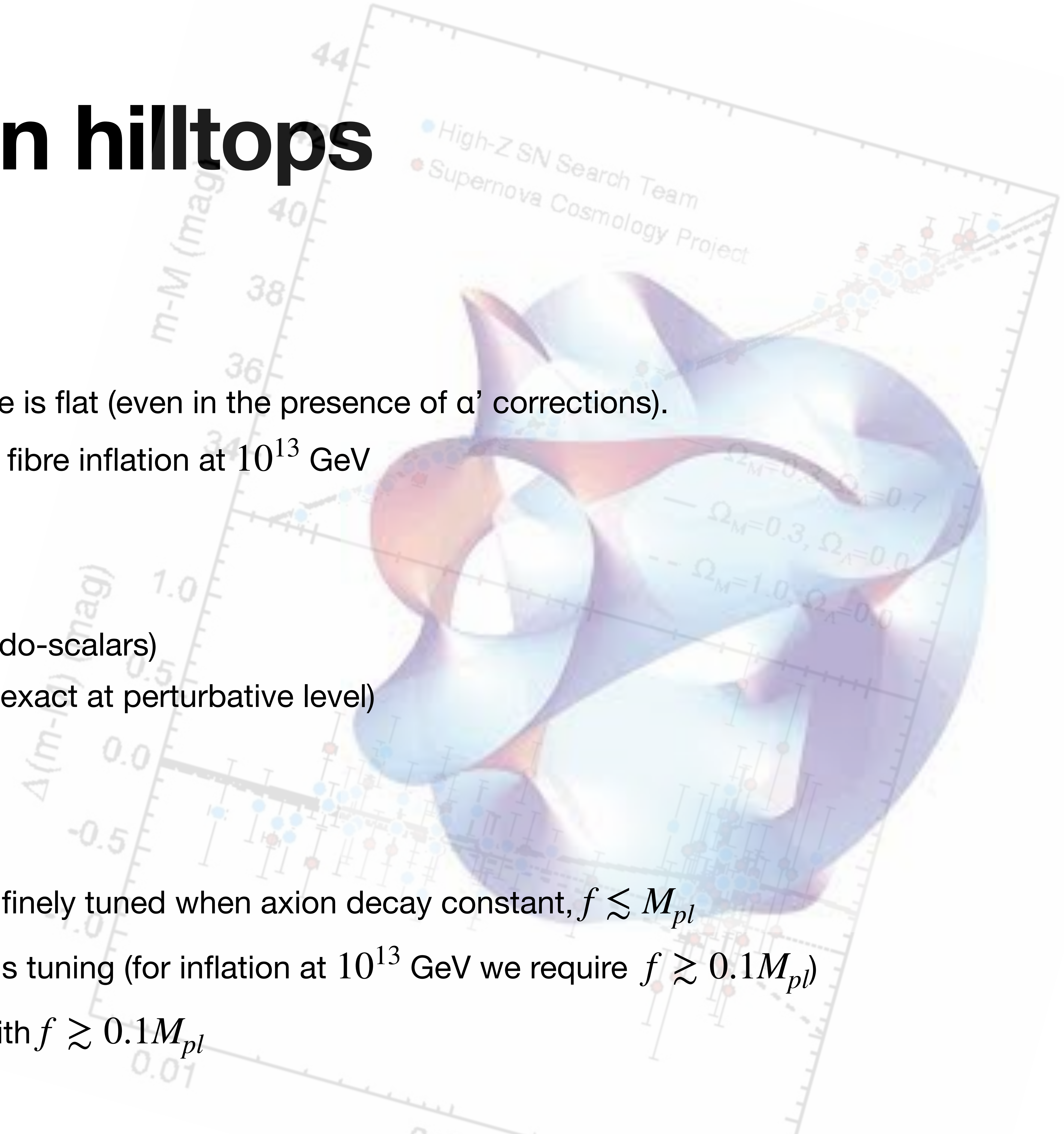
Required to generate the required hierarchy between inflation and DE

Fibre inflation & axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021, 2024



FIBRE INFLATION

- Two large Kahler moduli. Mode orthogonal to the volume is flat (even in the presence of α' corrections).
- Orthogonal mode is lifted by loop corrections and gives fibre inflation at 10^{13} GeV

AXIONS HILLTOPS

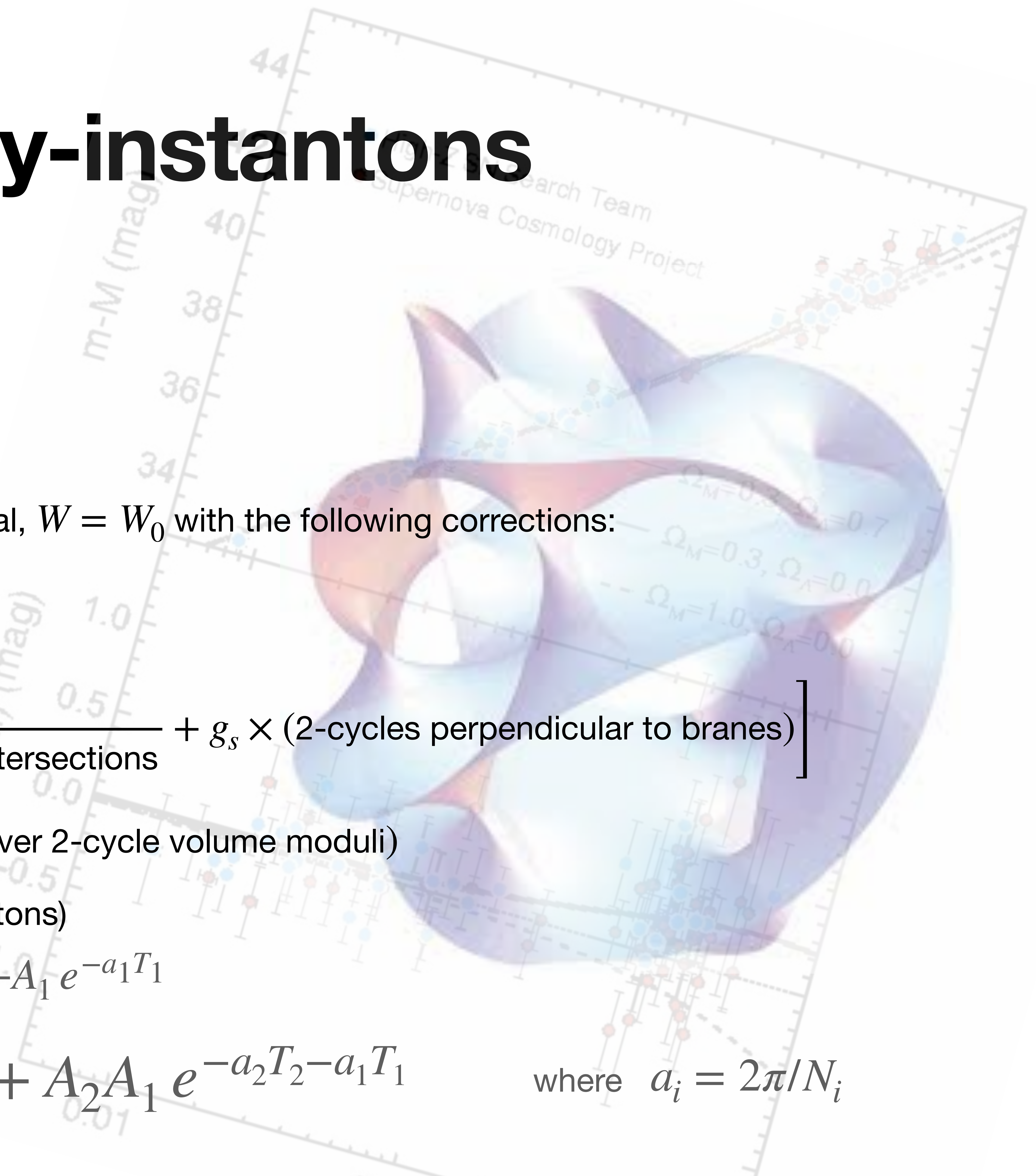
- axions avoid 5th force problems (since they are pseudo-scalars)
- axions are radiatively stabile (since shift symmetry is exact at perturbative level)

But……

- initial conditions for hilltop quintessence must be very finely tuned when axion decay constant, $f \lesssim M_{pl}$
- quantum diffusion during inflation generically spoils this tuning (for inflation at 10^{13} GeV we require $f \gtrsim 0.1M_{pl}$)
- as per the WGC, hard to get the correct scale of DE with $f \gtrsim 0.1M_{pl}$

Fibre inflation with poly-instantons

Cicoli, Cunillera, Padilla, Pedro 2024



LVS on a fibred Calabi Yau $\mathcal{V} = \frac{1}{\sqrt{2k}} \sqrt{\tau_1}\tau_2 - \frac{1}{3}\sqrt{\frac{2}{\hat{k}}}\, \tau_s^{3/2}$

A tree level Kahler potential $K = K_0 - 2\ln \mathcal{V}$ and super potential, $W = W_0$ with the following corrections:

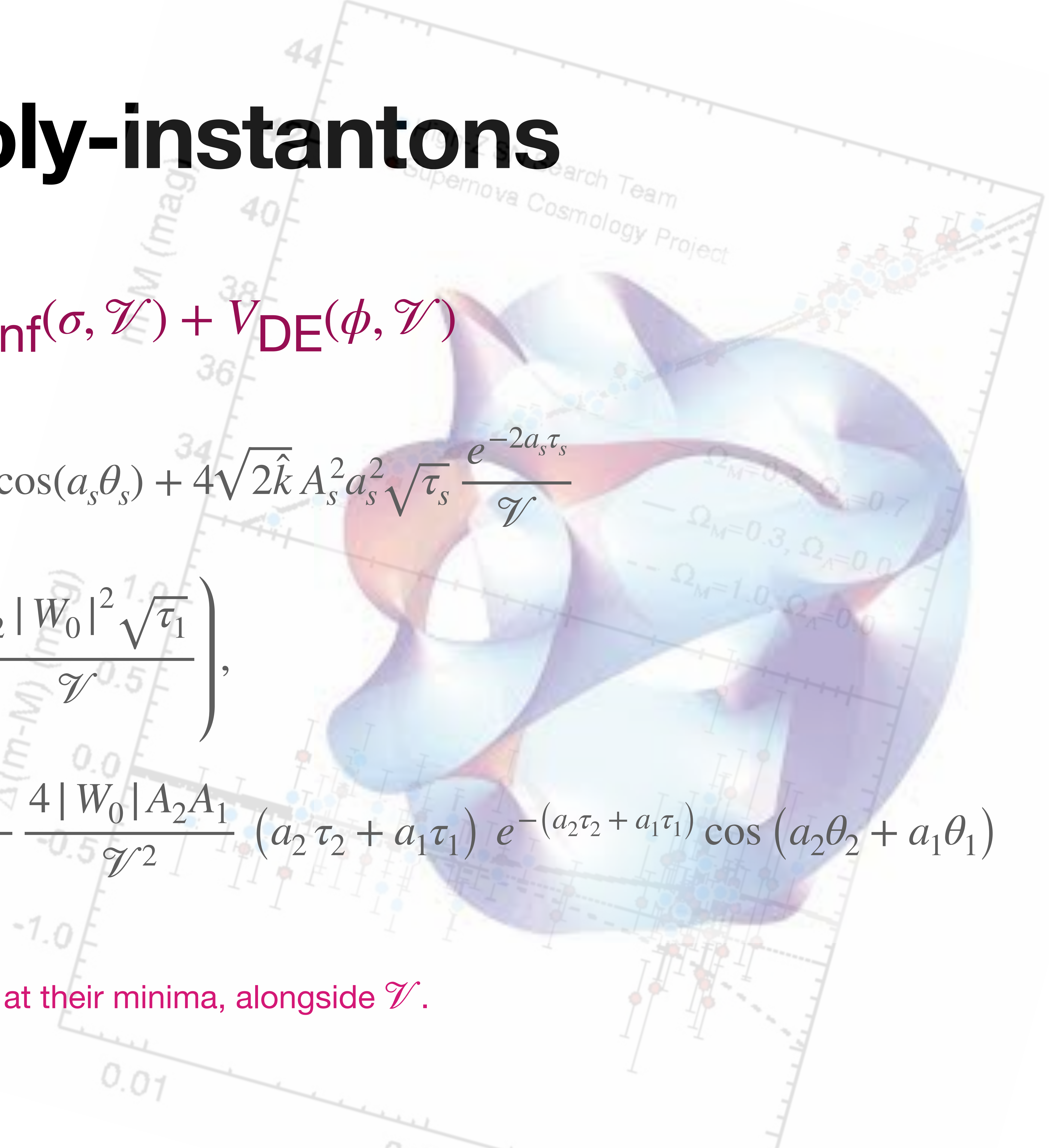
- $\alpha^{'3}$ corrections $\delta K_{\alpha'} \sim \frac{1}{g_s^{3/2}\mathcal{V}}$
- Loop corrections $\delta K_{g_s} \sim \frac{1}{\mathcal{V}} \sum_{\text{2-cycles}} \left[\frac{1}{\text{2-cycles along brane intersections}} + g_s \times (\text{2-cycles perpendicular to branes})\right]$
- Higher derivative terms $\delta V_{hd} \sim \frac{1}{g_s^{3/2}\mathcal{V}^4} W_0^4 \times (\text{weighted sum over 2-cycle volume moduli})$
- Non-perturbative corrections to the super potential (poly instantons)

$$\begin{aligned}\delta W_{np} &= A_s\, e^{-a_s T_s} + A_2\, e^{-a_2 T_2 + A_1\, e^{-a_1 T_1}} \\ &\approx A_s\, e^{-a_s T_s} + A_2\, e^{-a_2 T_2} + A_2 A_1\, e^{-a_2 T_2 - a_1 T_1}\end{aligned}$$

where $a_i = 2\pi / N_i$

Fibre inflation with poly-instantons

Cicoli, Cunillera, Padilla, Pedro 2024



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

$$V_{\mathrm{vol}} = \frac{\kappa}{\mathscr{V}^n} + \frac{3\xi|W_0|^2}{4g_s^{3/2}\mathscr{V}^3} - 4|W_0|A_s a_s\tau_s\frac{e^{-a_s\tau_s}}{\mathscr{V}^2}\cos(a_s\theta_s) + 4\sqrt{2\hat{k}}\,A_s^2a_s^2\sqrt{\tau_s}\,\frac{e^{-2a_s\tau_s}}{\mathscr{V}}$$

$$V_{\mathrm{inf}} = \frac{|W_0|^2}{\mathscr{V}^3}\left(\frac{B_1|W_0|^2}{\tau_1} - \frac{\sqrt{2k}\,\tilde{C}}{\sqrt{\tau_1}} + \sqrt{\frac{2}{k}}\frac{B_2|W_0|^2\sqrt{\tau_1}}{\mathscr{V}}\right),$$

$$V_{\mathrm{DE}} = -\frac{4|W_0|A_2}{\mathscr{V}^2}\left(a_2\tau_2\right)e^{-a_2\tau_2}\cos\left(a_2\theta_2\right) - \frac{4|W_0|A_2A_1}{\mathscr{V}^2}\left(a_2\tau_2 + a_1\tau_1\right)e^{-\left(a_2\tau_2 + a_1\tau_1\right)}\cos\left(a_2\theta_2 + a_1\theta_1\right)$$

A la standard LVS, the small moduli τ_s and θ_s are stabilised at their minima, alongside $\mathscr{V}$.

We tune the uplift κ so that this occurs at $V = 0$

Early universe dynamics

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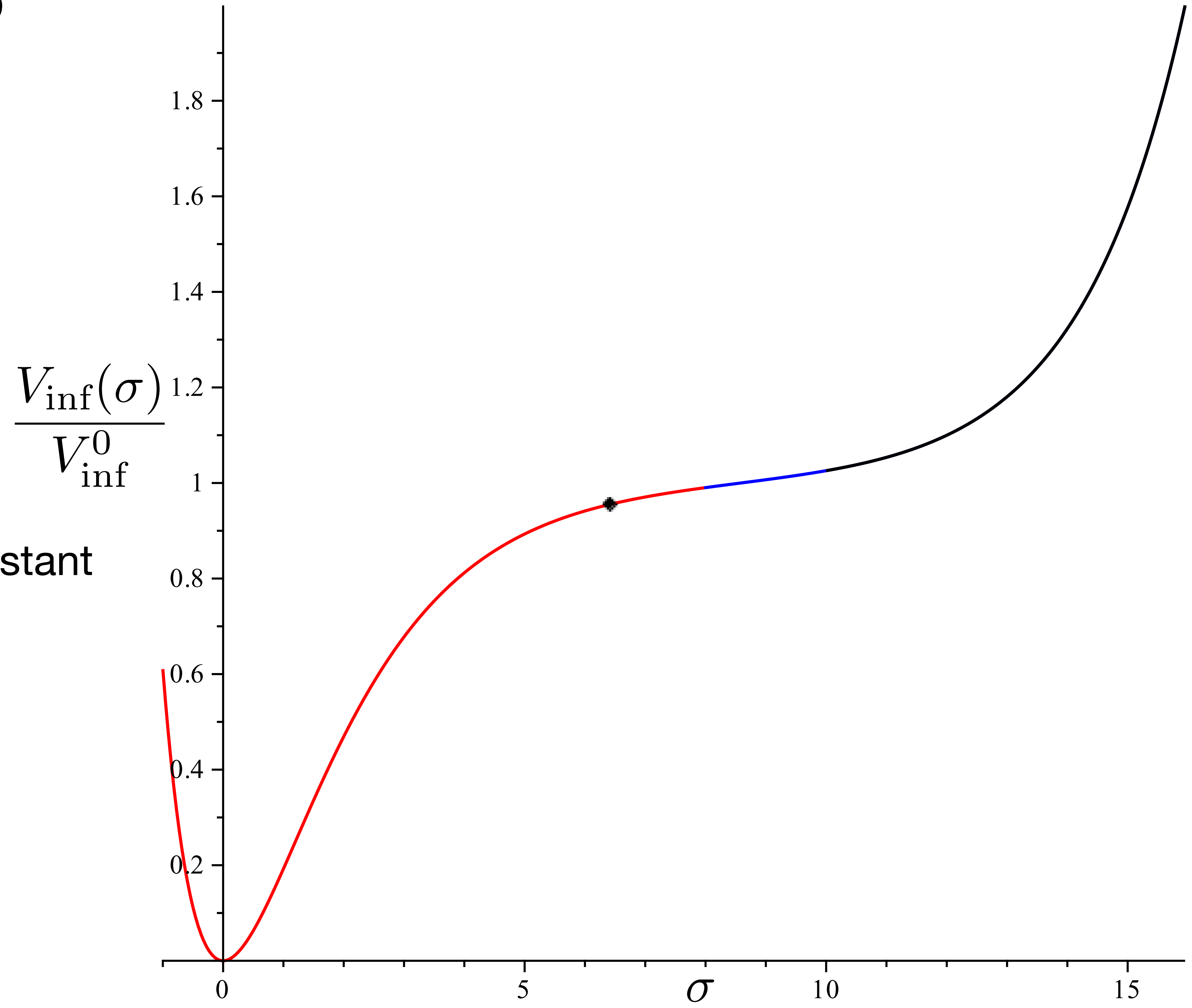
$$V_{\text{early}} = V_{\text{inf}}(\sigma, \mathscr{V})$$

Recall that $\mathscr{V} \approx \frac{1}{\sqrt{2k}} \sqrt{\tau_1} \tau_2$ is stabilised.

For the fibre there exists an orthogonal mode $\sigma = \ln(\tau_1/\tau_2)/\sqrt{3}$ + constant whose potential has the form

$$V_{\text{inf}}(\sigma) = V_0 \left[e^{-\frac{2\sigma}{\sqrt{3}}} - 2\, e^{-\frac{\sigma}{\sqrt{3}}} + 2\mathscr{R} \cosh\left(\frac{\sigma}{\sqrt{3}} \right) \right]$$

Observationally viable inflation occurs when $\mathscr{R} \ll 1$ for $\mathscr{V} \sim 1000$, $\tau_1/\tau_2 \approx 0.001/\Pi_2$ such that $H_{\text{inf}} \sim 10^{13}$ GeV



Late universe dynamics

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$$V_{\text{late}} = V_{\text{DE}}(\phi, \mathscr{V})$$

Recall that all saxions are now stabilised along with θ_s.

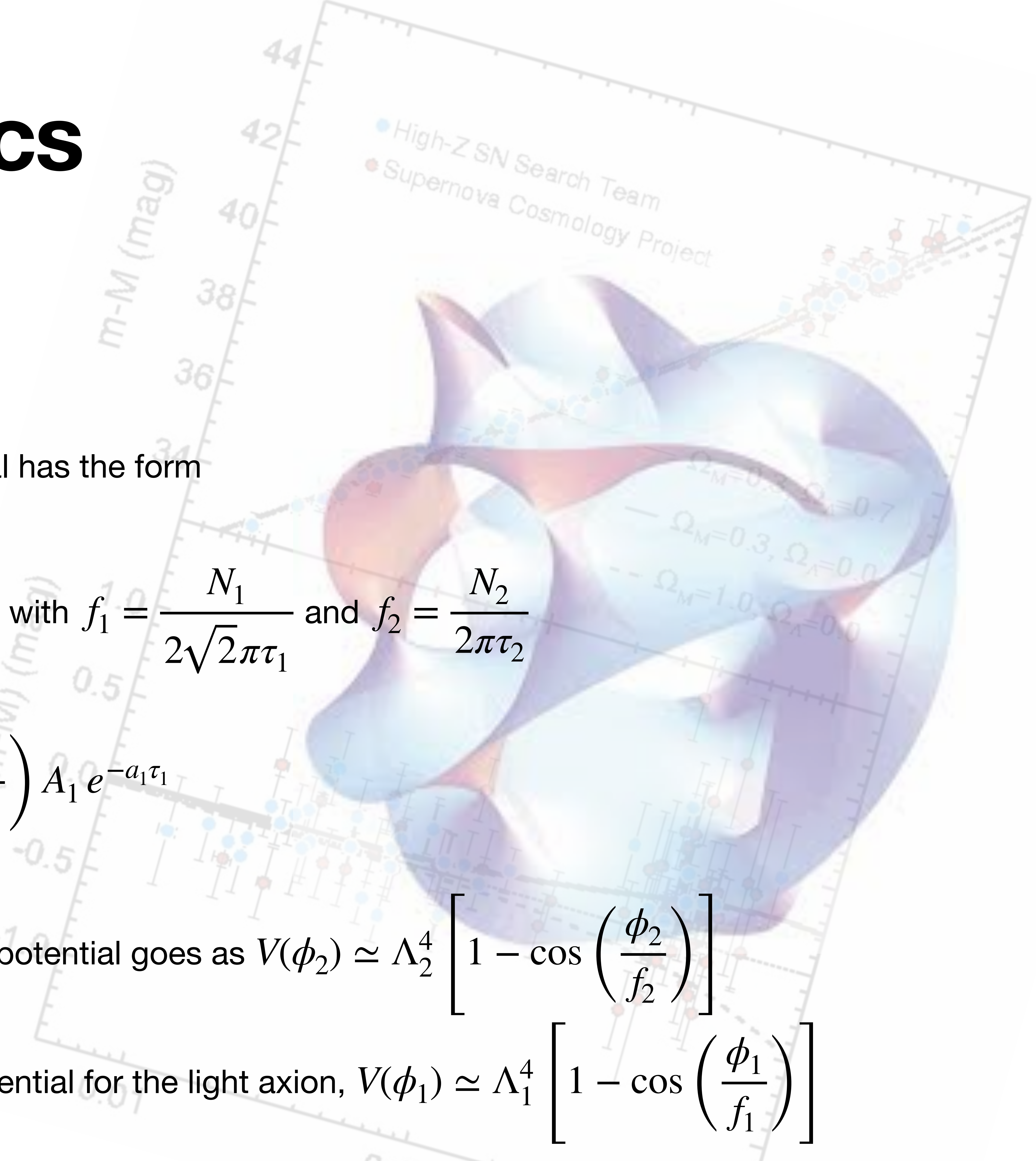
In terms of canonically normalised axions, the late time potential has the form

$$V_{\text{late}} \simeq \Lambda_2^4 \left[1 - \cos\left(\frac{\phi_2}{f_2}\right)\right] + \Lambda_1^4 \left[1 - \cos\left(\frac{\phi_1}{f_1} + \frac{\phi_2}{f_2}\right)\right] \text{ with } f_1 = \frac{N_1}{2\sqrt{2}\pi\tau_1} \text{ and } f_2 = \frac{N_2}{2\pi\tau_2}$$

Crucially $\Lambda_2^4 = \dfrac{4\,|\,W_0\,|\,A_2}{\mathscr{V}^2}\, a_2\tau_2\, e^{-a_2\tau_2} \gg \Lambda_1^4 \equiv \Lambda_2^4 \left(1 + \dfrac{a_1\tau_1}{a_2\langle\tau_2\rangle}\right) A_1\, e^{-a_1\tau_1}$

Due to this hierarchy at leading order, ϕ_1, is a flat direction and potential goes as $V(\phi_2) \simeq \Lambda_2^4 \left[1 - \cos\left(\dfrac{\phi_2}{f_2}\right)\right]$

Heavy axion ϕ_2 is stabilised near zero, leaving the following potential for the light axion, $V(\phi_1) \simeq \Lambda_1^4 \left[1 - \cos\left(\dfrac{\phi_1}{f_1}\right)\right]$



Late universe dynamics

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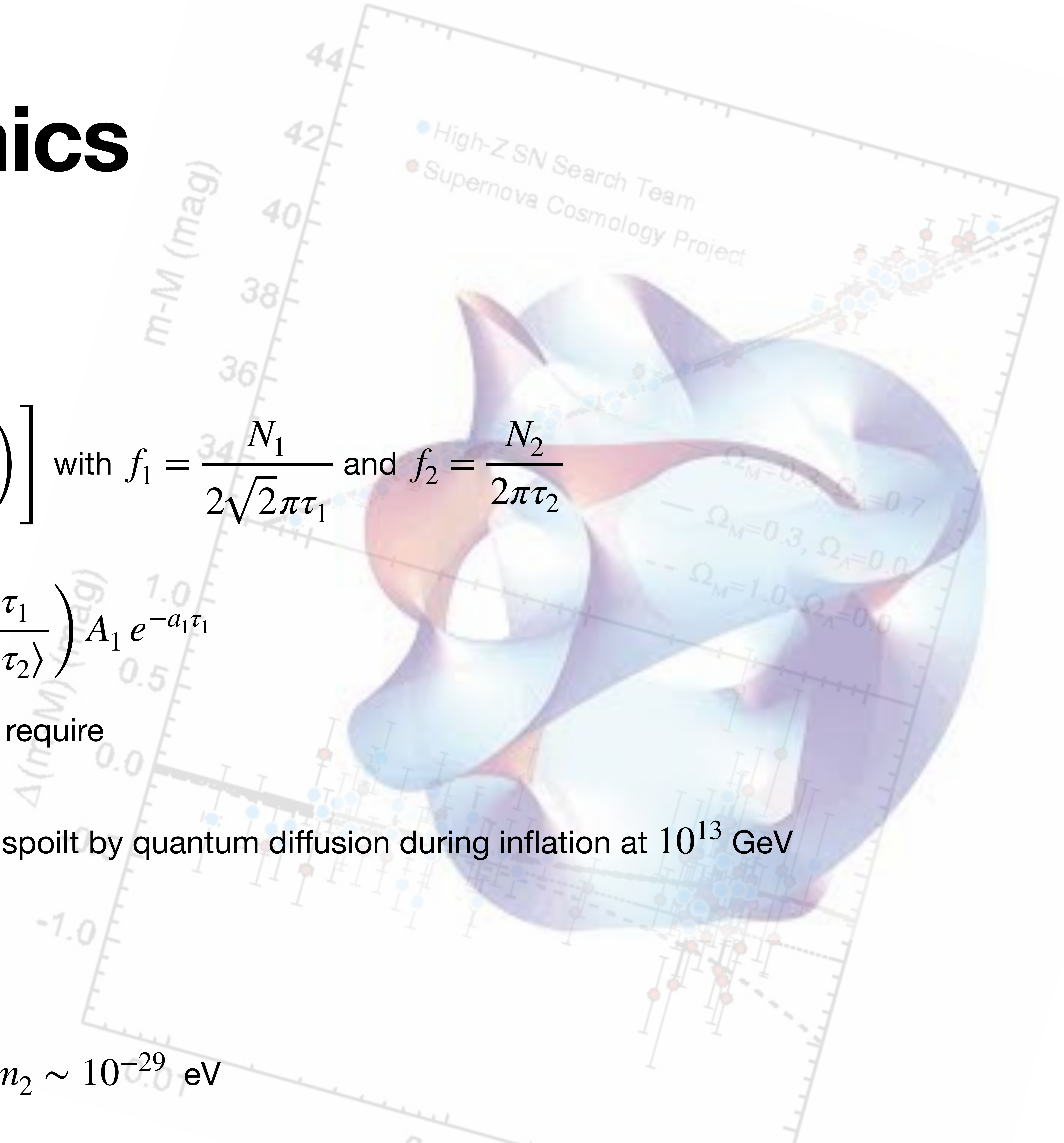

$$V_{\text{late}} = V_{\text{DE}}(\phi, \mathscr{V})$$

$$V_{\text{late}} \simeq \Lambda_2^4 \left[1 - \cos\left(\frac{\phi_2}{f_2}\right)\right] + \Lambda_1^4 \left[1 - \cos\left(\frac{\phi_1}{f_1} + \frac{\phi_2}{f_2}\right)\right] \text{ with } f_1 = \frac{N_1}{2\sqrt{2\pi\tau_1}} \text{ and } f_2 = \frac{N_2}{2\pi\tau_2}$$

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For hilltop quintessence to arise from the light axion, ϕ_1, we require

- $f_1 \gtrsim 0.08 M_{pl}$ in order for initial conditions to avoid being spoilt by quantum diffusion during inflation at 10^{13} GeV

- Λ_1^4 to set the scale of dark energy.

This then sets the axion masses to be $m_1 \sim 10^{-32}$ eV and $m_2 \sim 10^{-29}$ eV

Axion dark matter?

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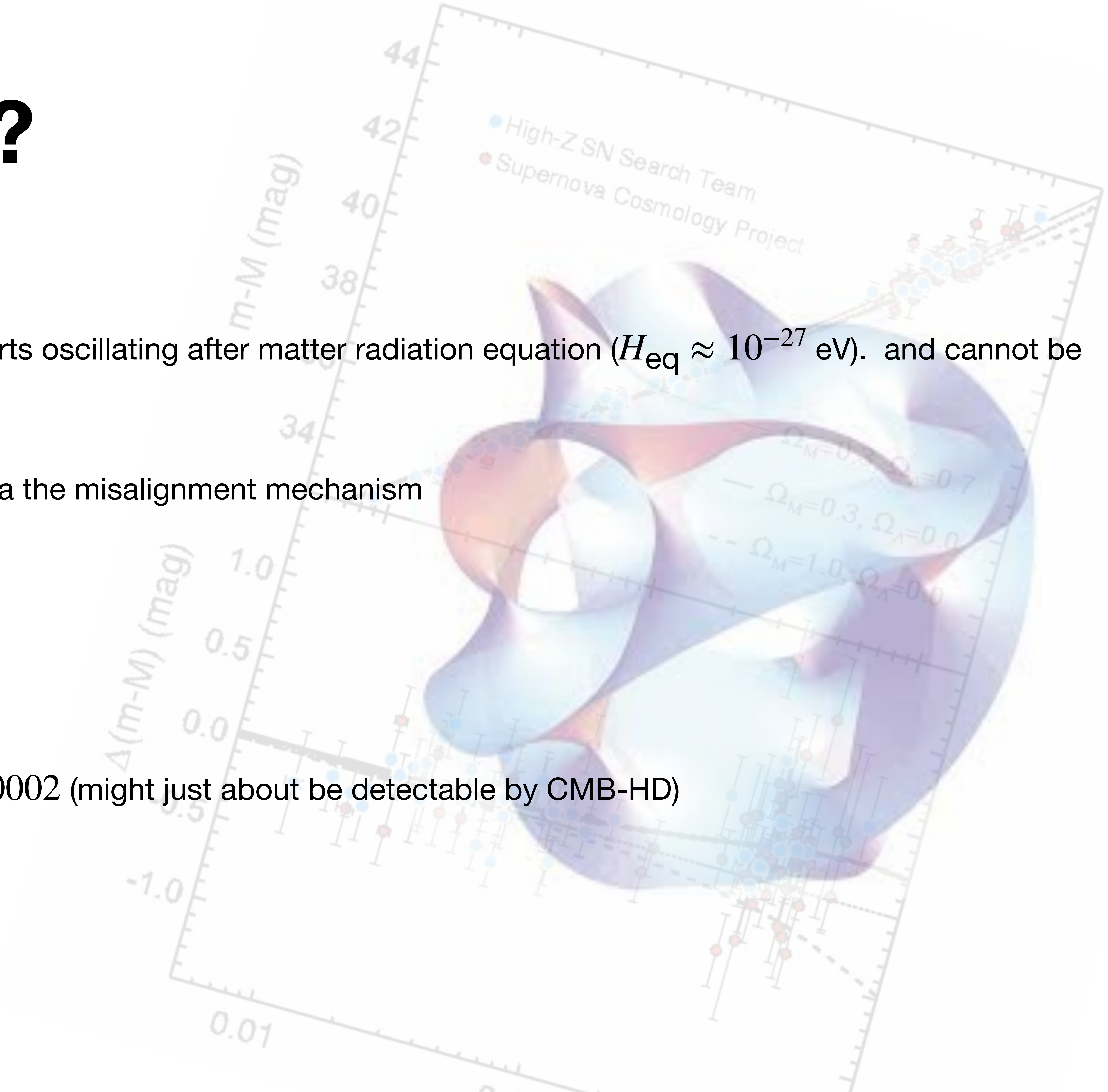


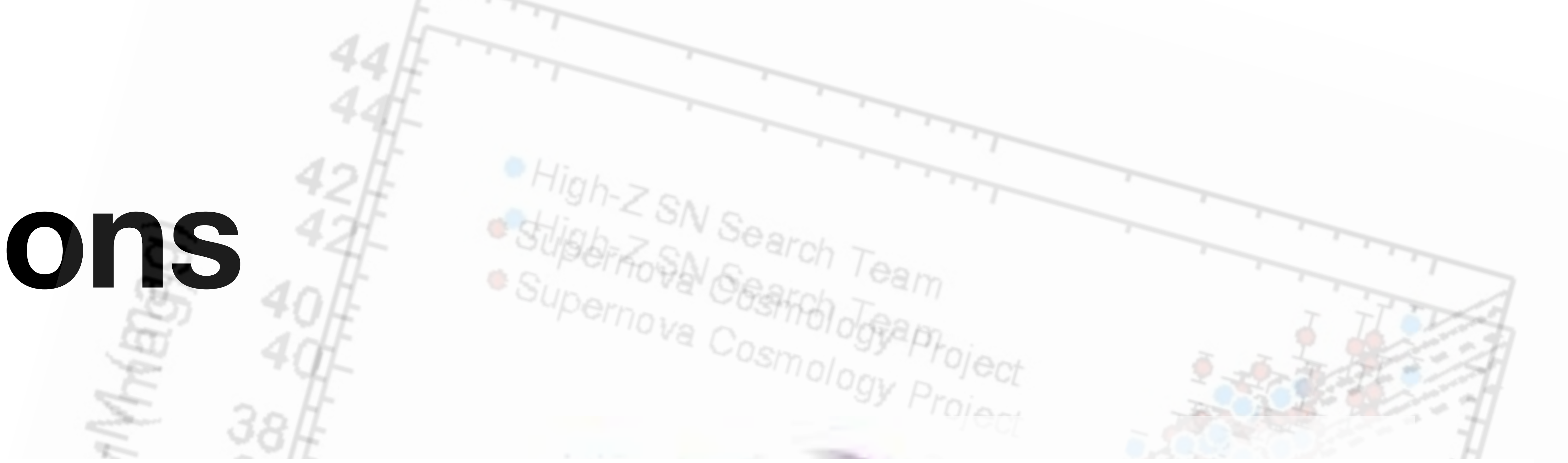
The heavier axion has mass $m_2 \sim 10^{-29}$ eV so it starts oscillating after matter radiation equation ($H_{\text{eq}} \approx 10^{-27}$ eV). and cannot be all of DM

Its contribution to the total DM abundance is given via the misalignment mechanism

$$\frac{\Omega_2}{\Omega_m} \simeq \frac{3}{2}\left(\frac{\delta\phi_2}{M_p}\right)^2$$

Since $\delta\phi_2 \lesssim \pi f_2 \sim 0.01 M_{pl}$ we find that $\frac{\Omega_2}{\Omega_m} \lesssim 0.0002$ (might just about be detectable by CMB-HD)

Summary and conclusions



Cicoli, Cunillera, Padilla, Pedro 2024

A complete history of the universe in ST is hard due to huge hierarchy of scales between inflation and dark energy. Bad things can happen.

Our blueprint was as follows:

Stabilise the volume at leading order, leaving at least two flat directions.

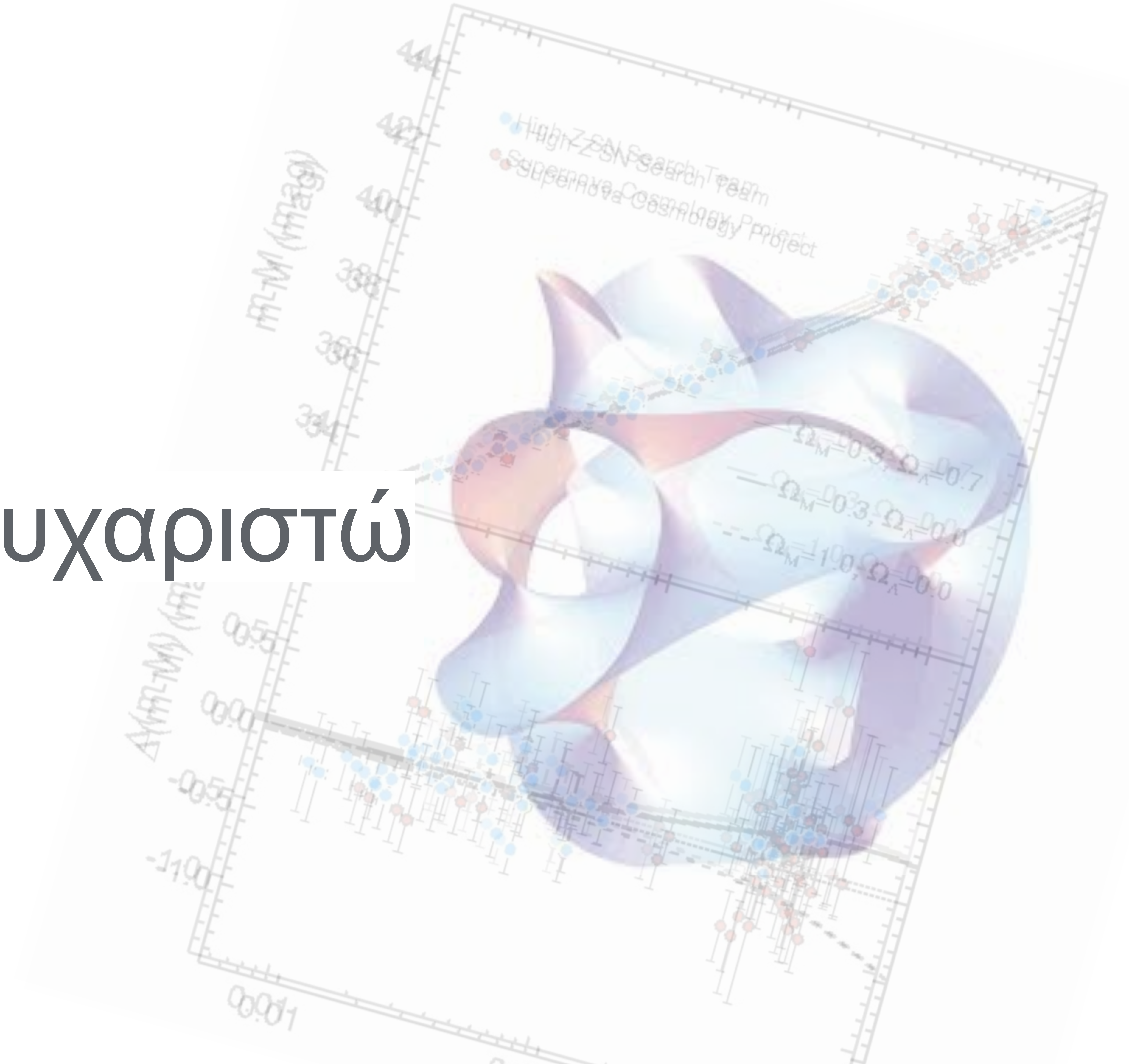
First flat direction is lifted perturbatively - this is the inflation. We do this with fibre inflation.

Another flat direction is lifted non-perturbatively - this is quintessence. We do this with poly-instanton corrections in order to get the right hierarchies and avoid issues with quantum diffusion of initial conditions

Dark energy is lighter of two axions. The heavier axion can make up a small but potentially detectable fraction of DM.

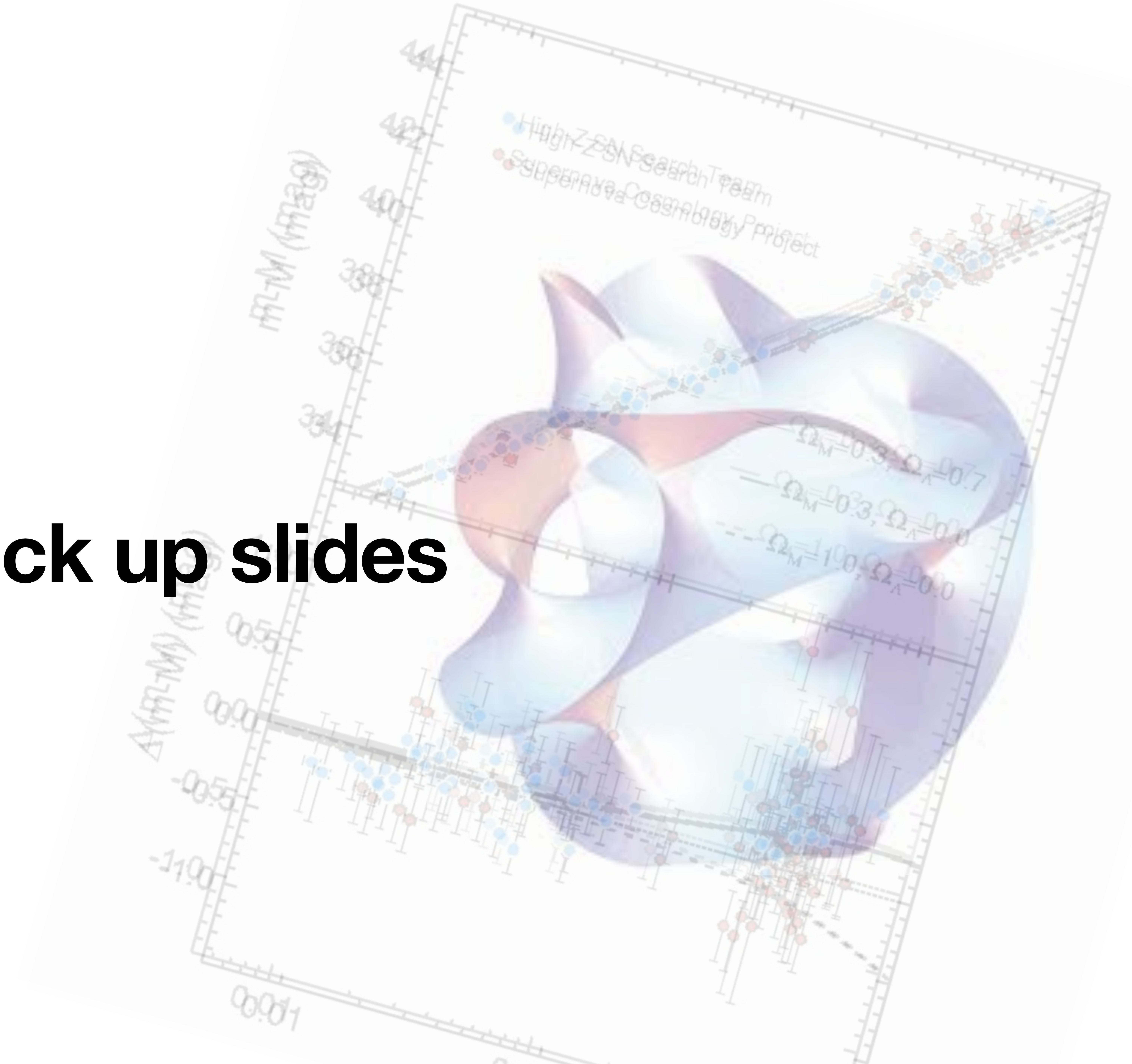
Would be interesting to explore observational predictions of the quintessence field in light of DESI

Ευχαριστώ



High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
Δ(m-M) (mag)
44
42
40
38
36
34
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
0.5
0.0
-0.5
-1.0
0.01

Back up slides



Cosmology from String Theory

Corrections to the scalar potential generically go as

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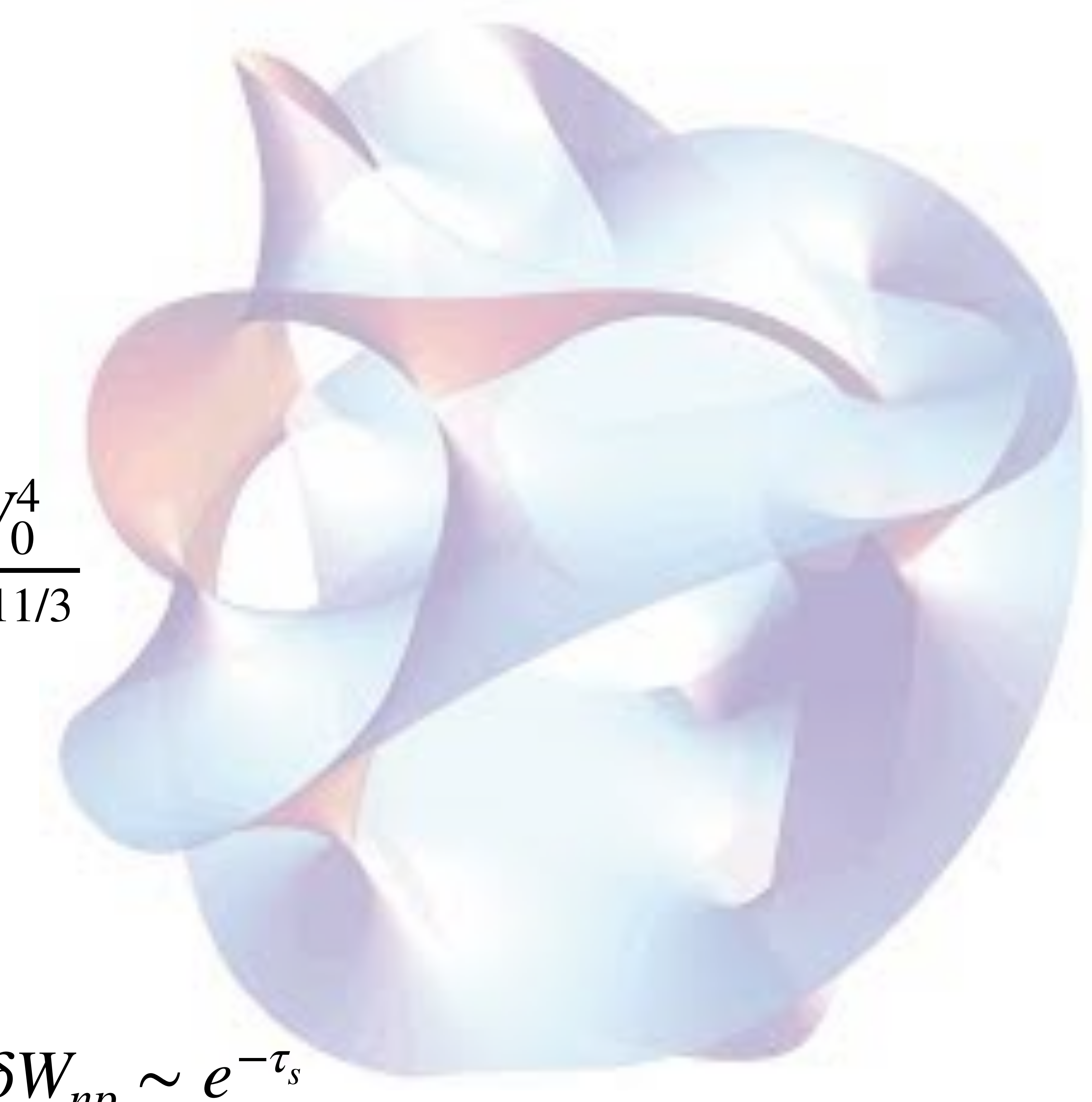

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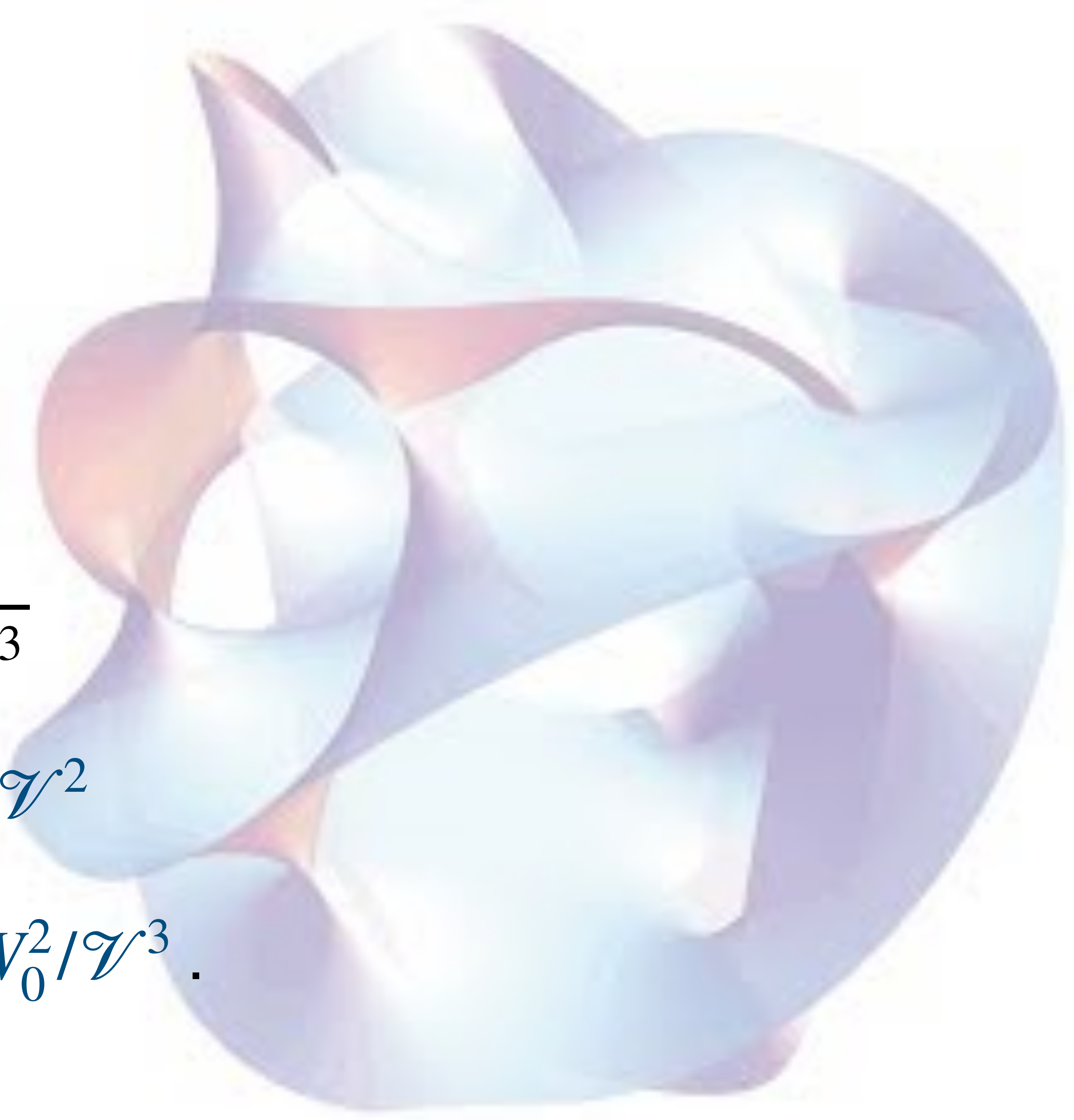
In LVS we include

- 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 $W_0^2 \delta K_p \sim W_0 \delta W_{np}$.

Cosmology from String Theory



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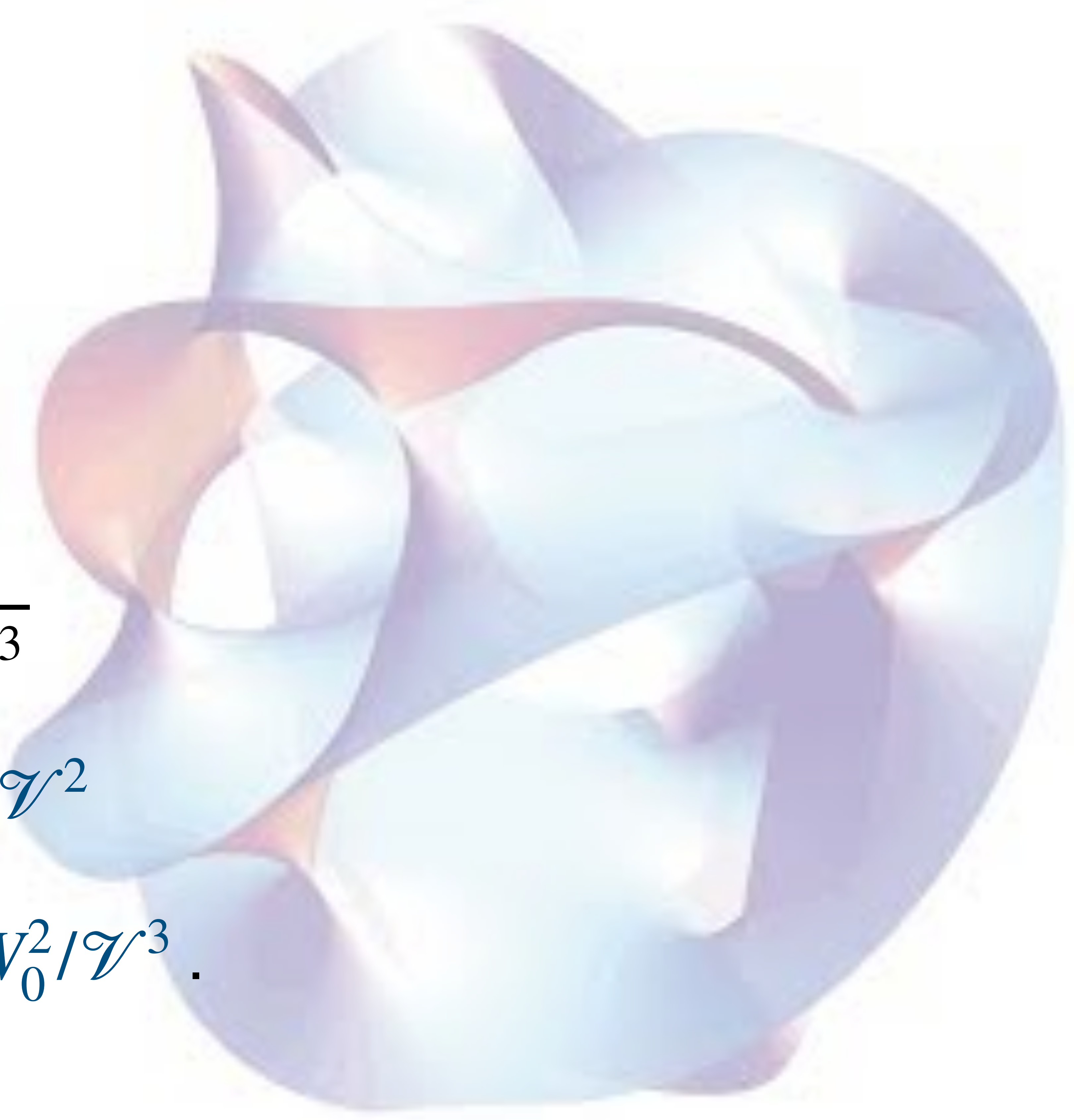

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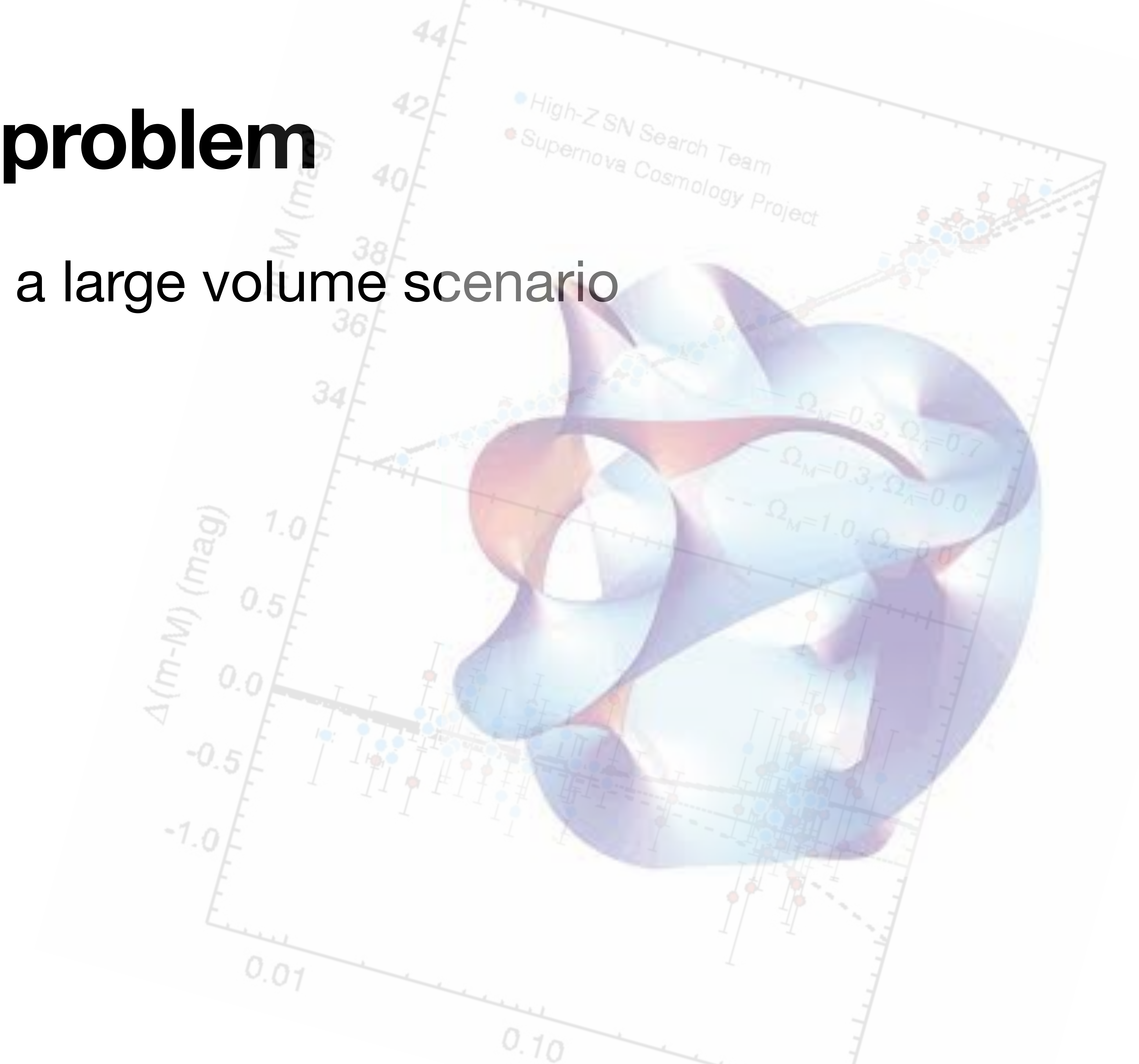
NEED TO UPLIFT TO GET DE SITTER VACUUM

The light volume problem

Hebecker 2019

Example: quintessence in a large volume scenario



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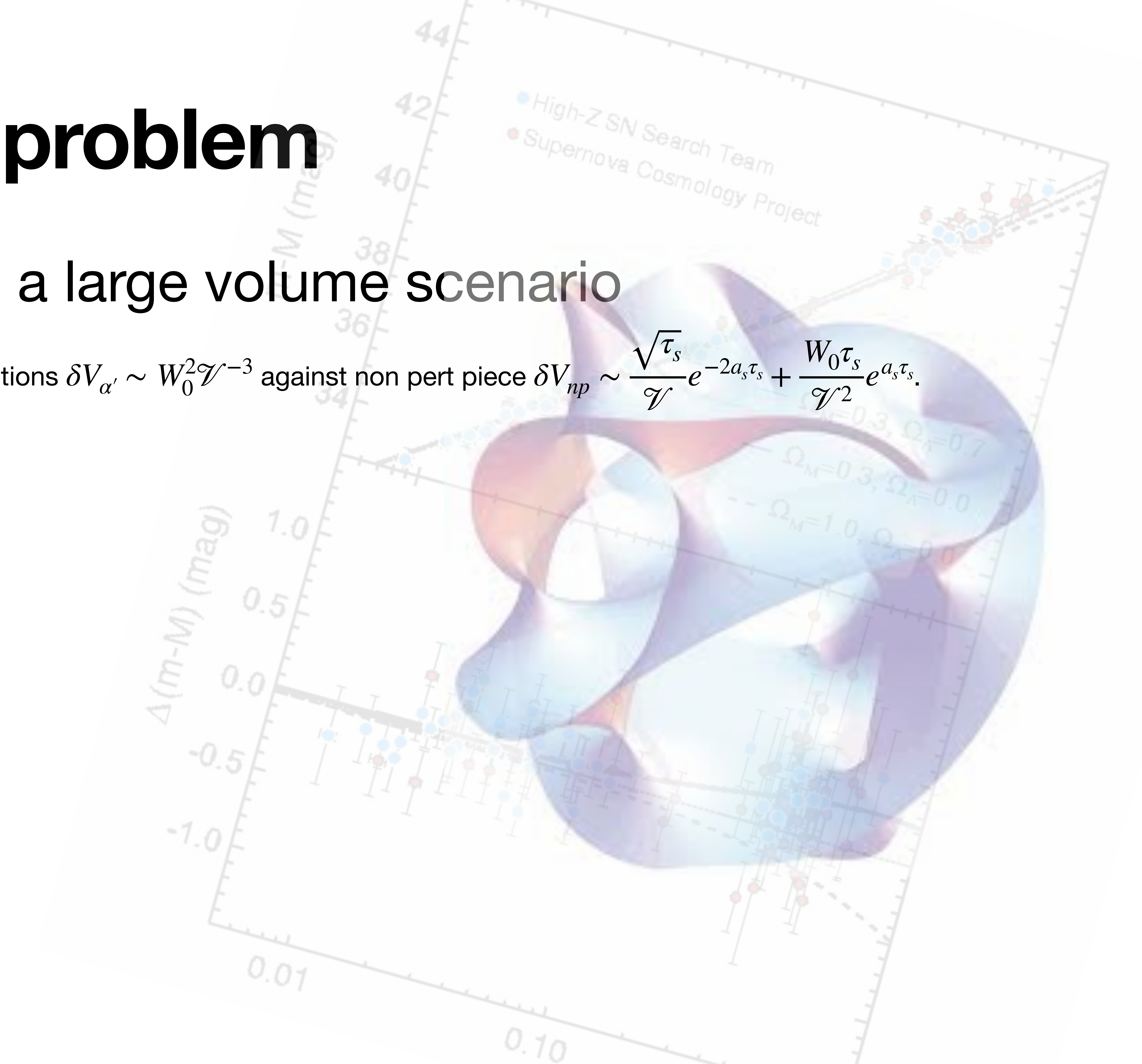

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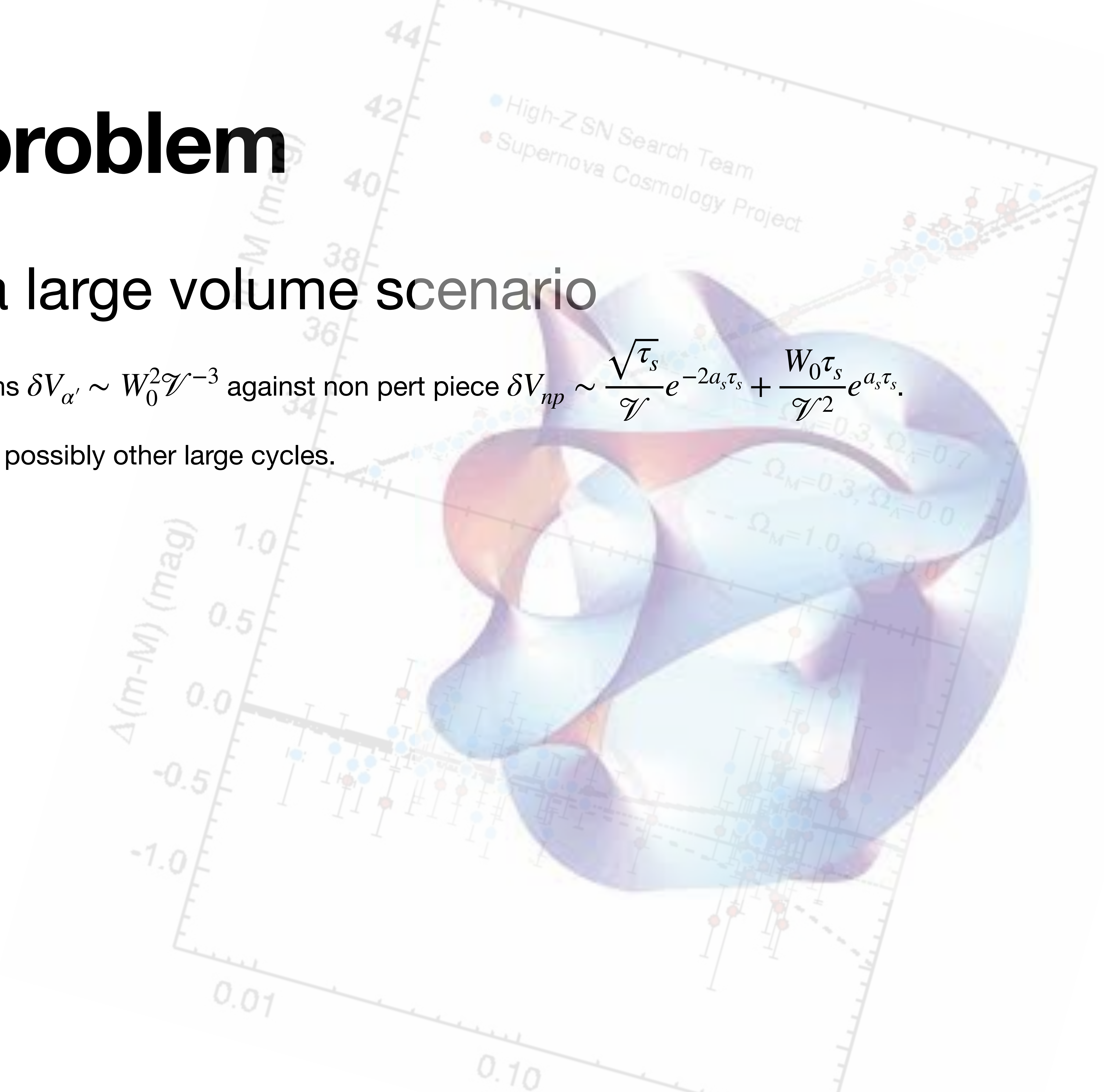

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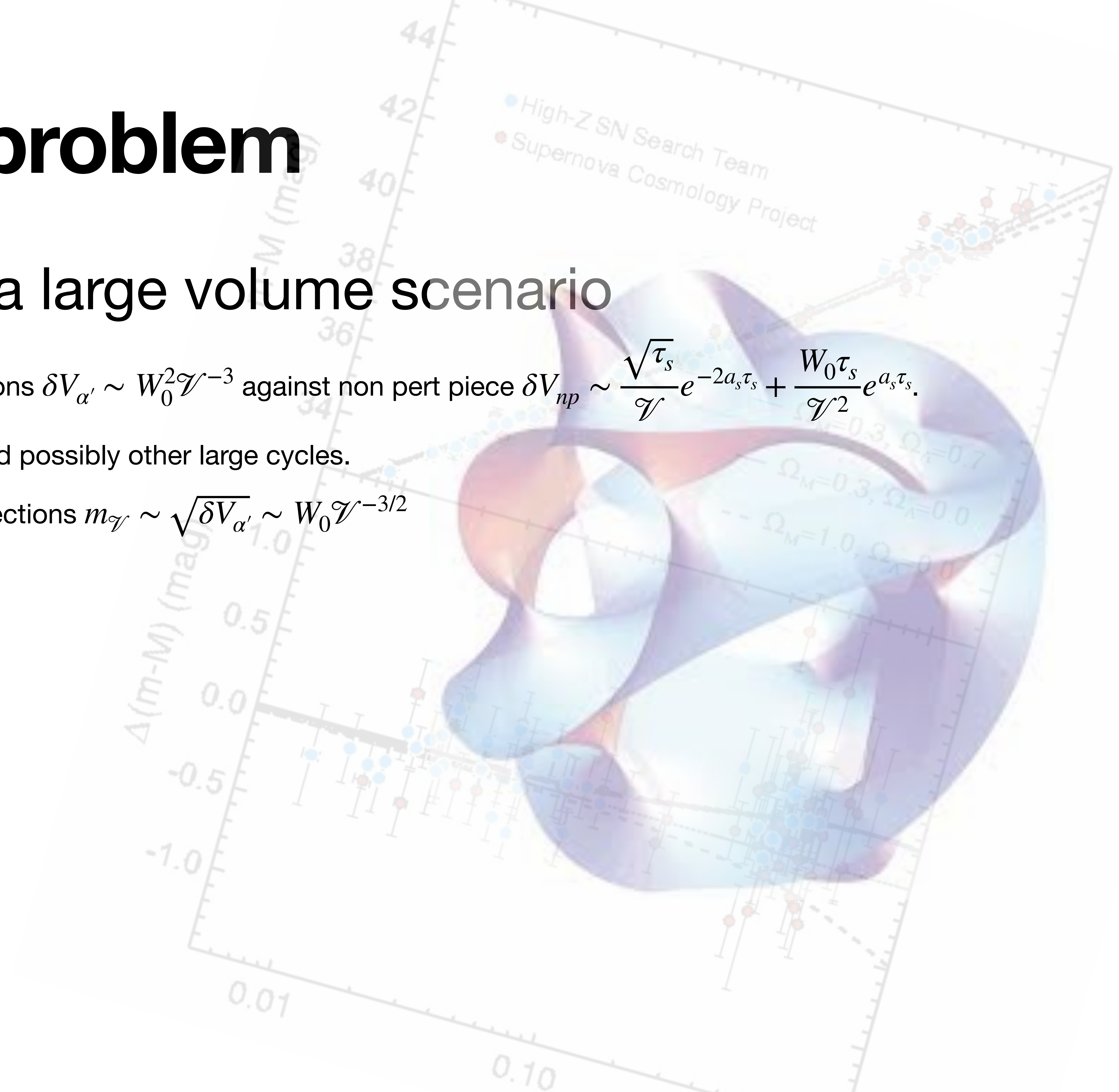

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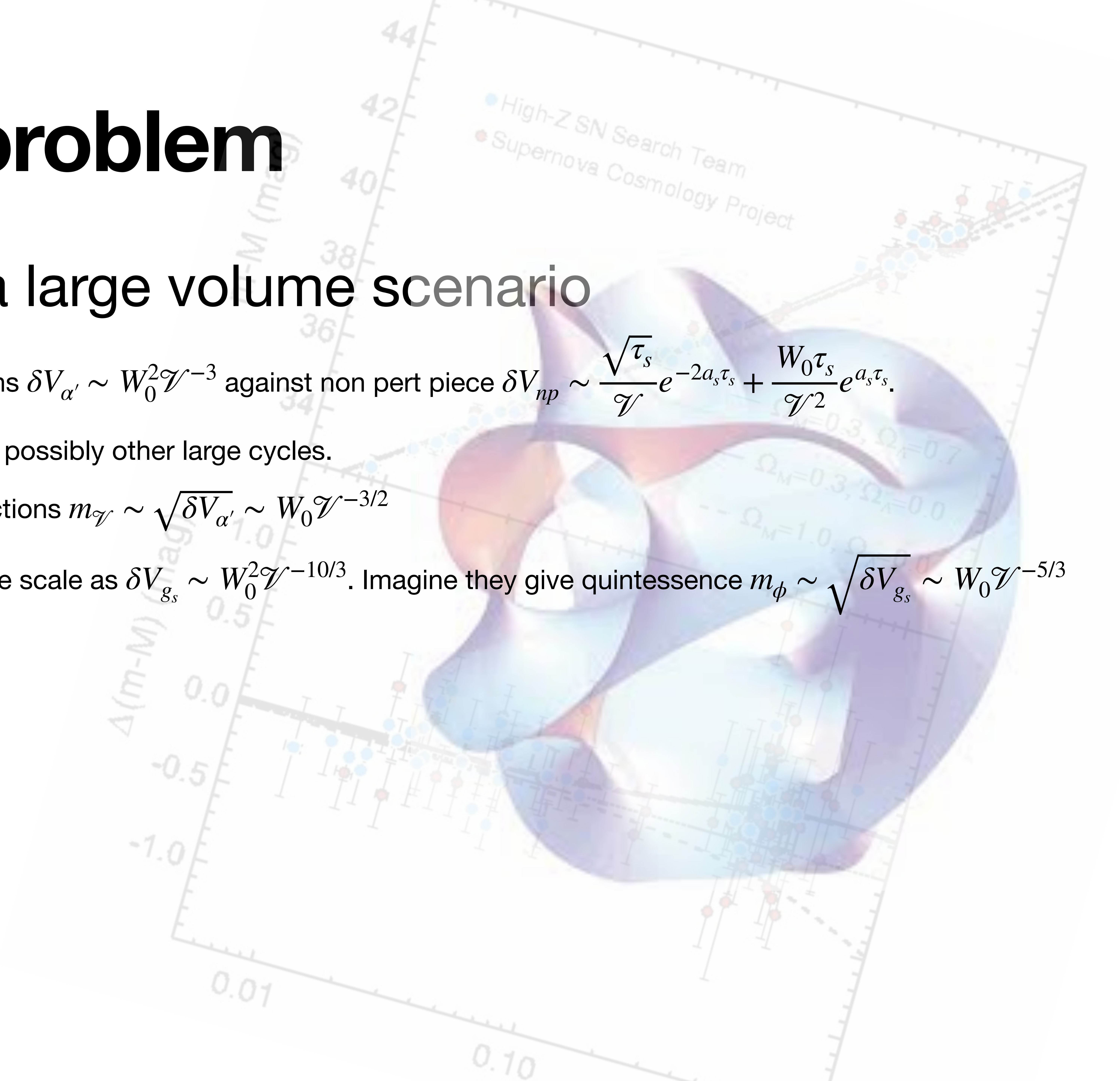

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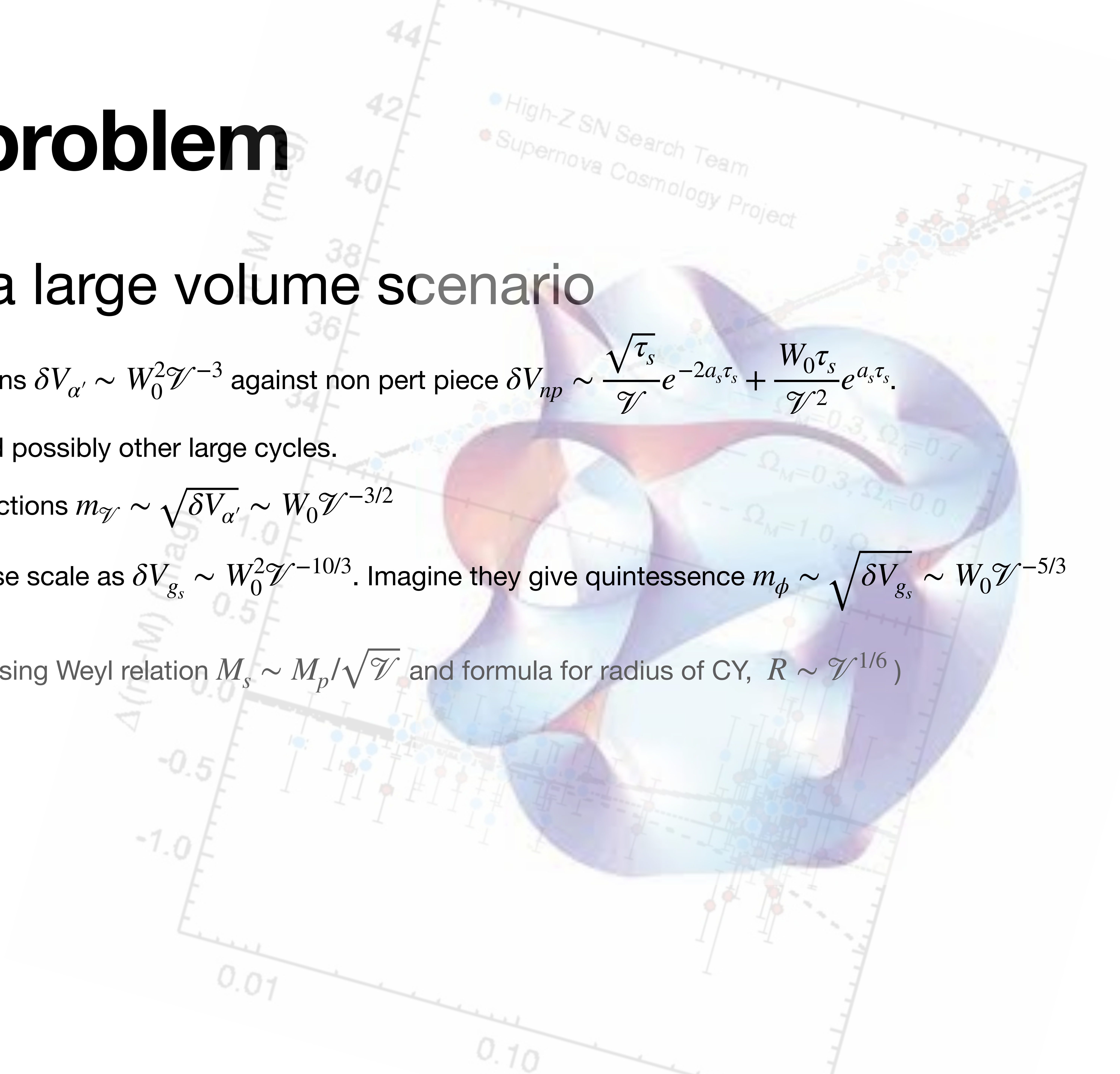

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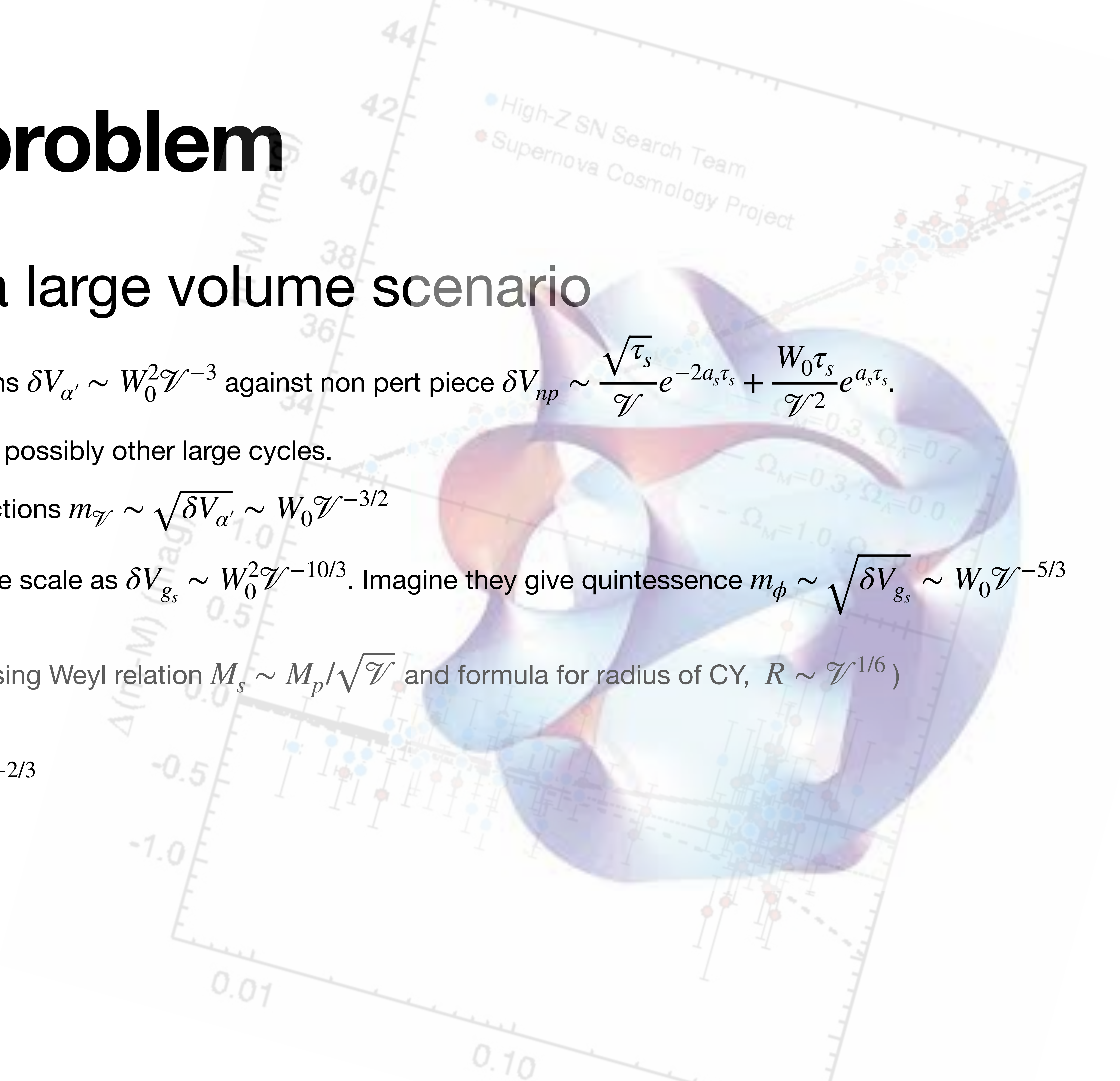

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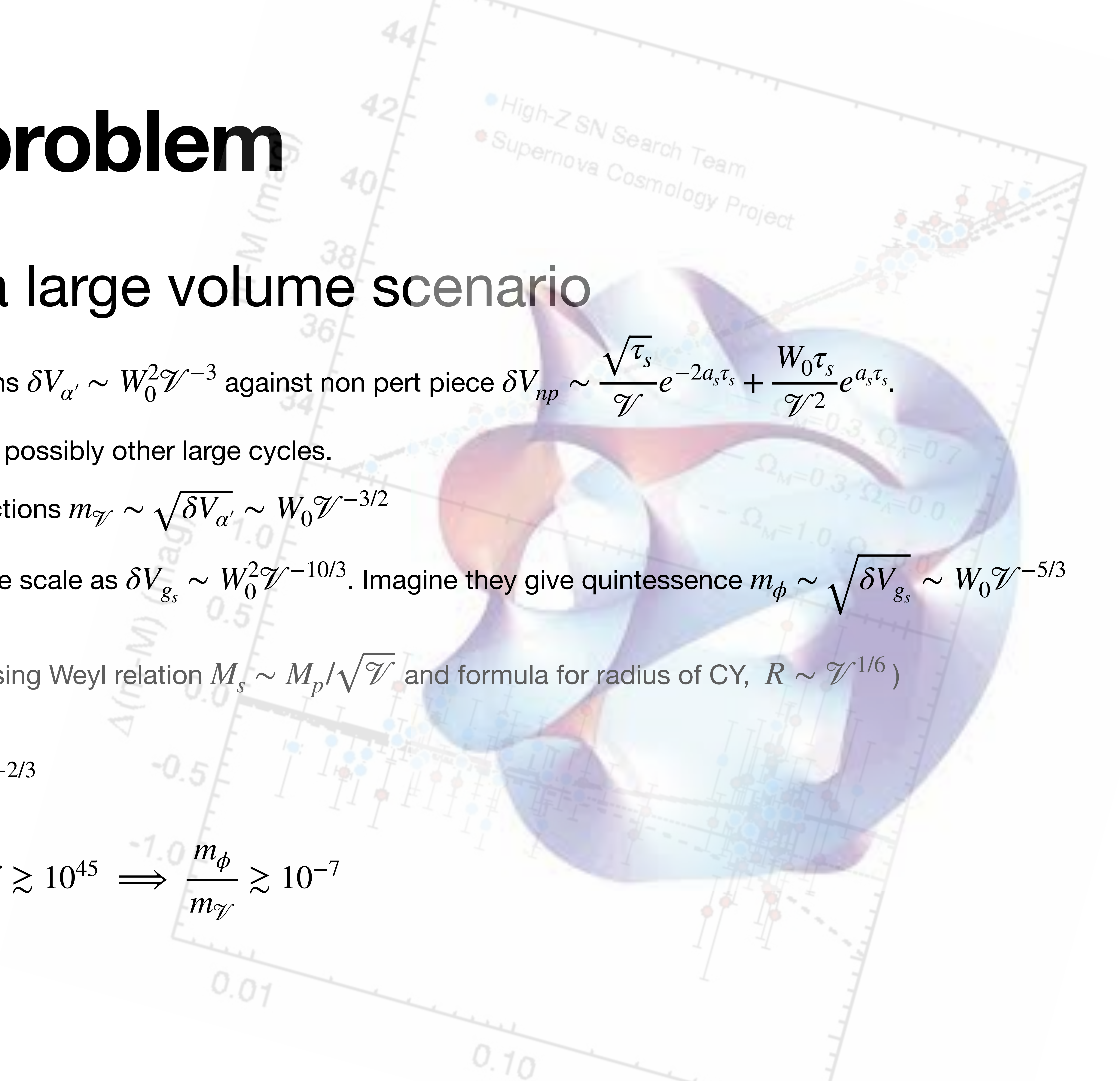

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Hebecker 2019

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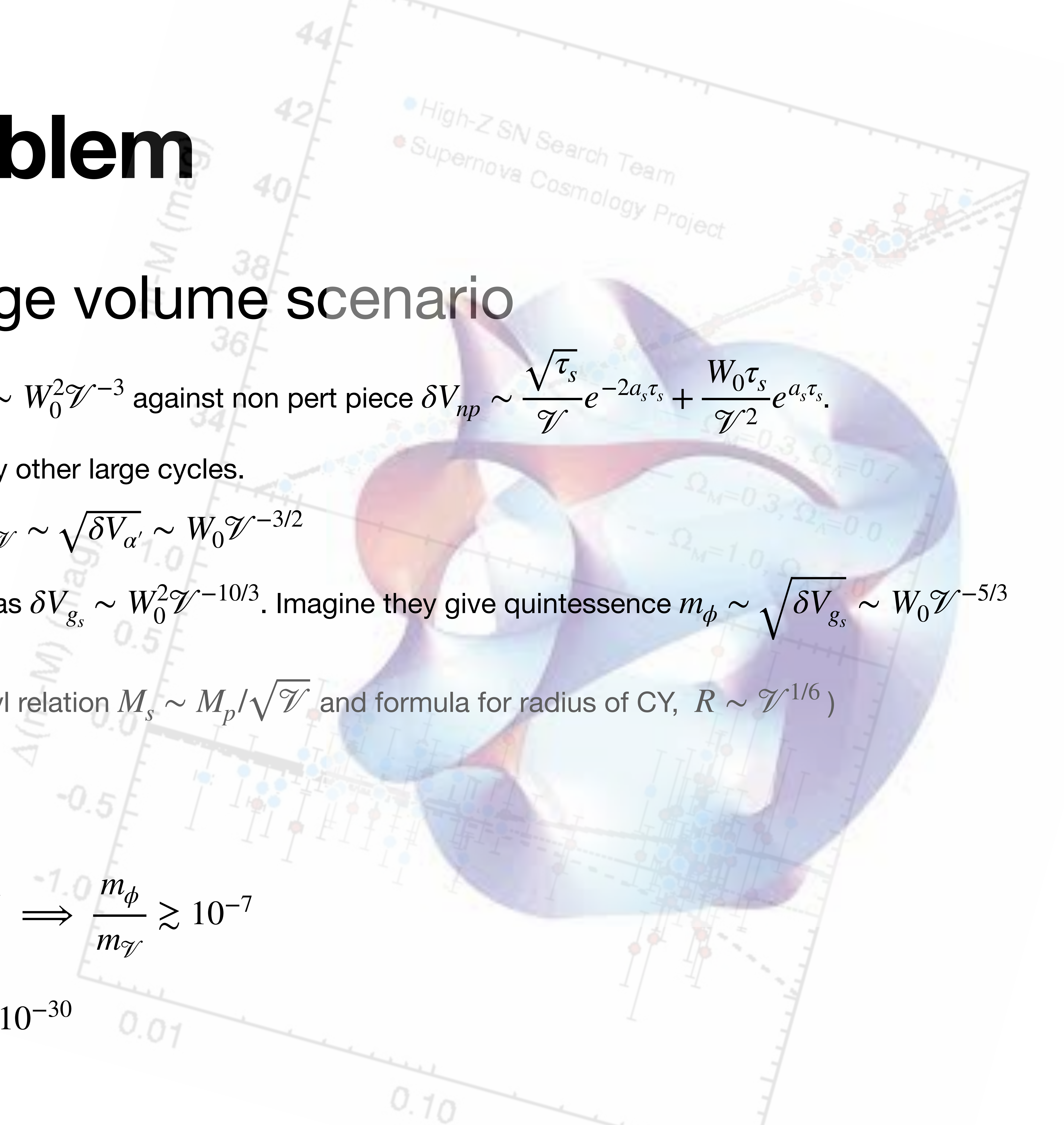

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Hebecker 2019

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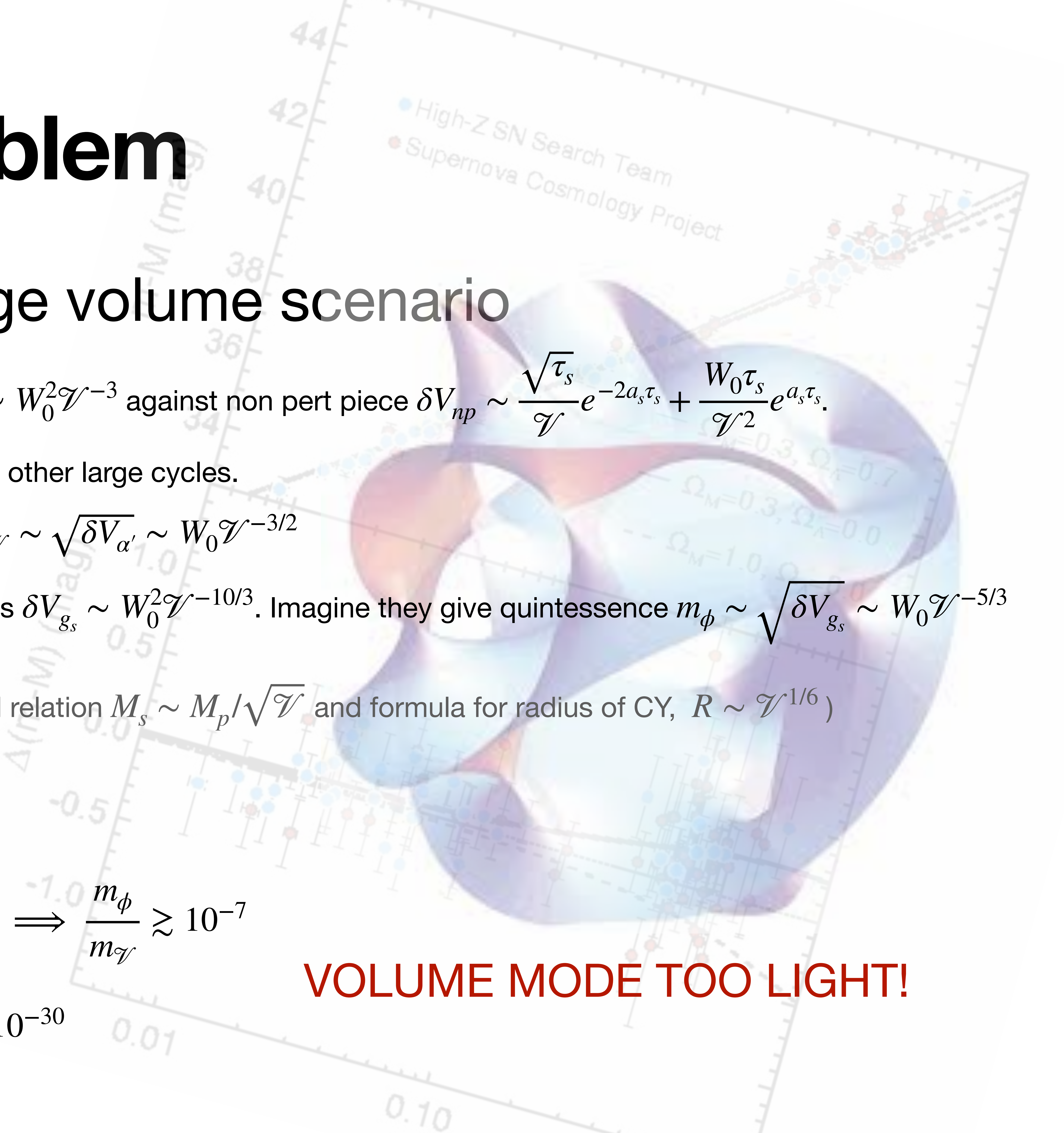

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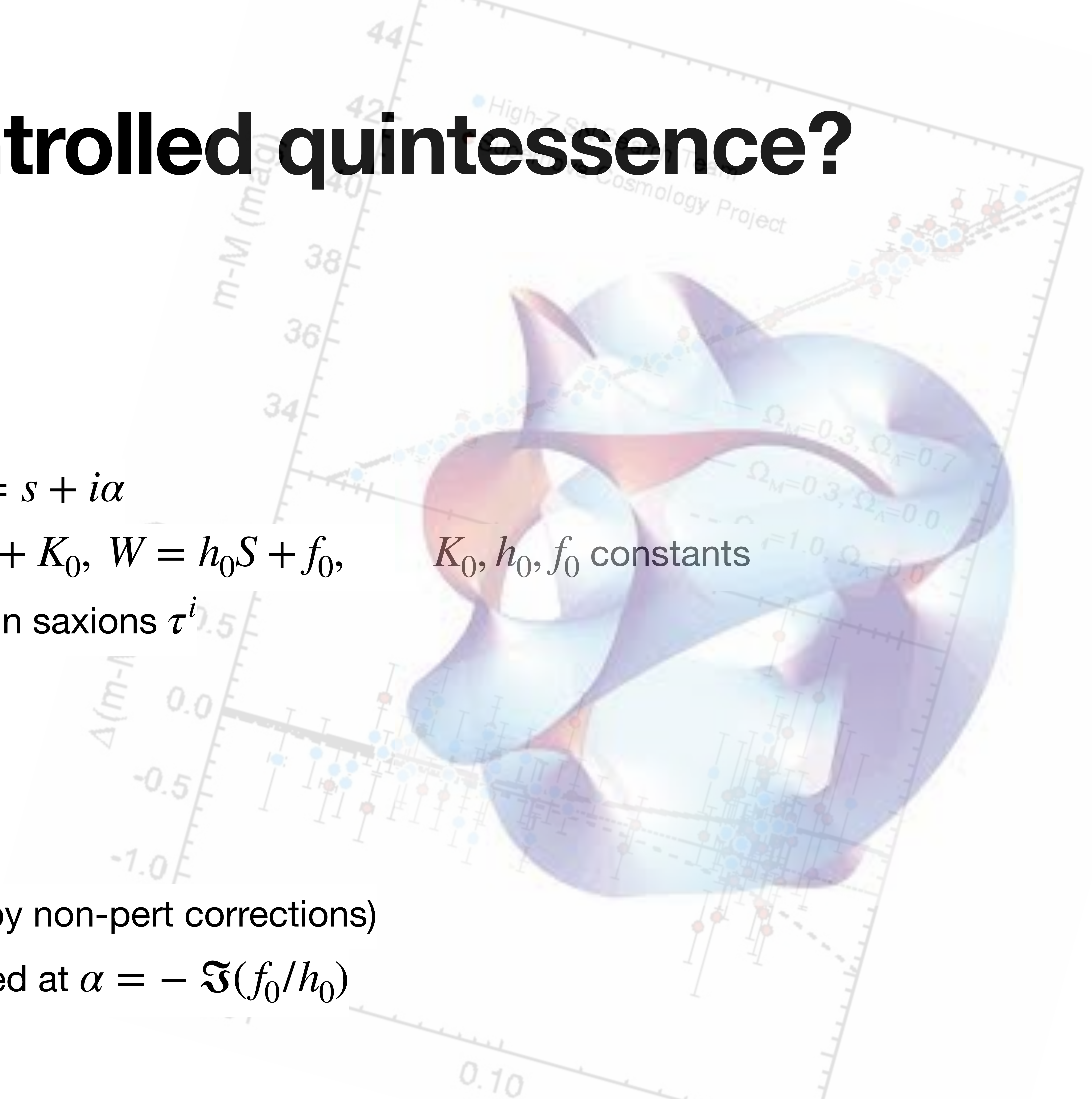
VOLUME MODE TOO LIGHT!

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, $K = -2\ln\mathcal{V} - \ln(S+\bar{S}) + K_0,\ W = h_0 S + f_0,$ 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 $\alpha = -\mathfrak{I}(f_0/h_0)$

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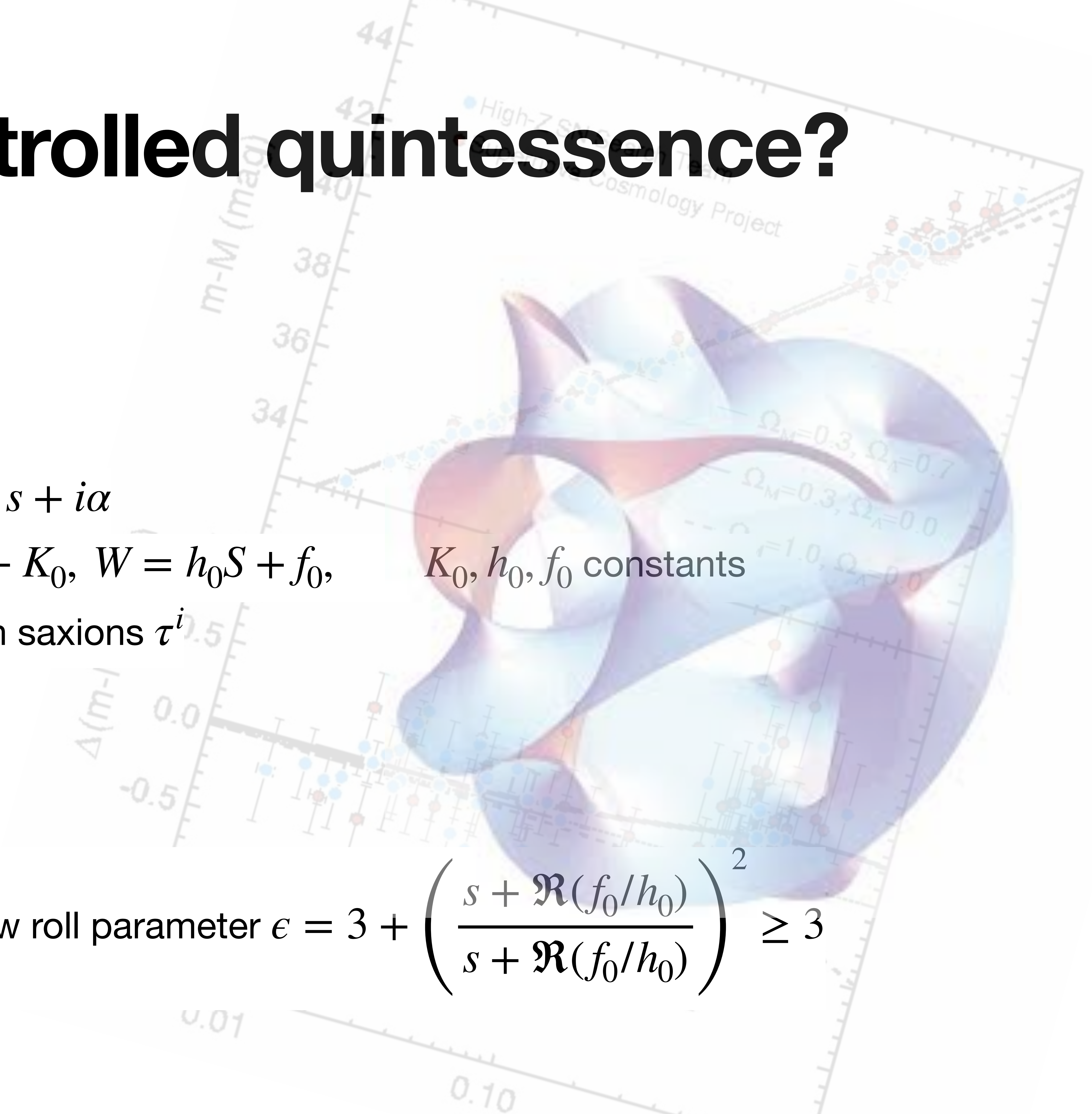

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Aftering integrating out α,

$V = \frac{e^{K_0}}{2s\mathscr{V}^2}|h_0|^2\left[s - \Re(f_0/h_0)\right]^2$ 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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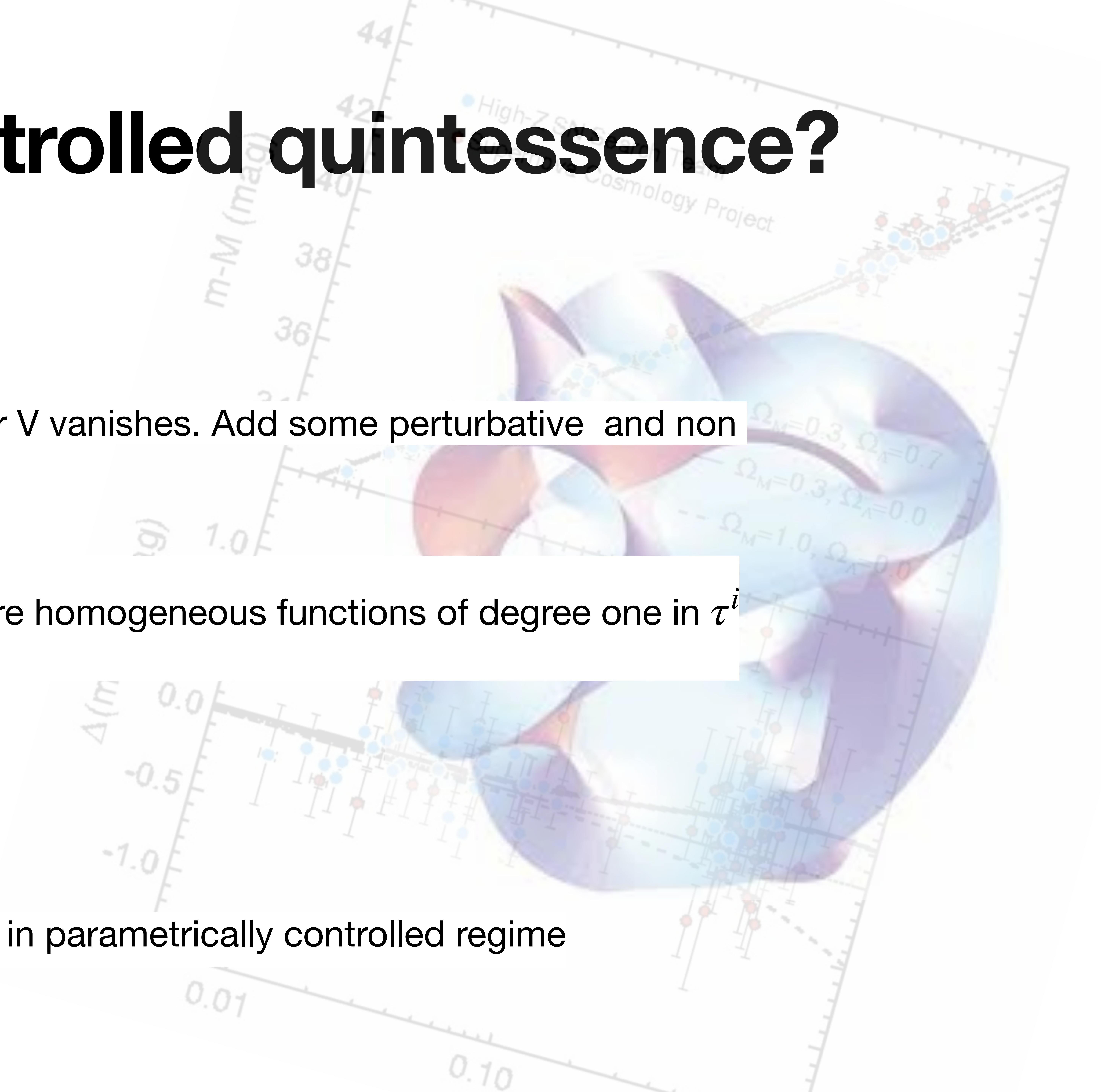

Stabilise dilaton at SUSY min so leading order V vanishes. Add some perturbative and non perturbative corrections

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

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

Parametrically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

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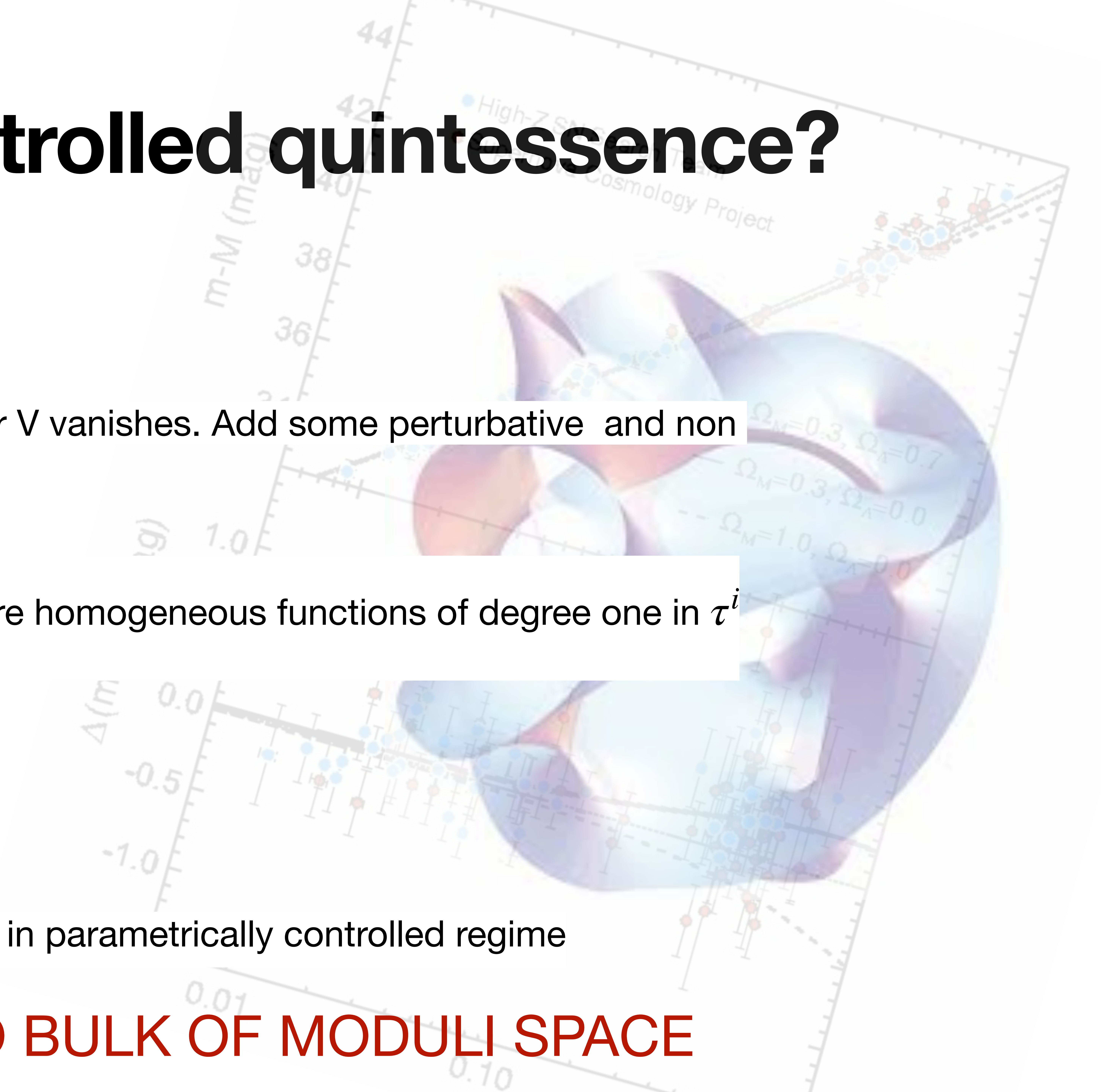
NEED TO GO INTO BULK OF MODULI SPACE



Numerically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

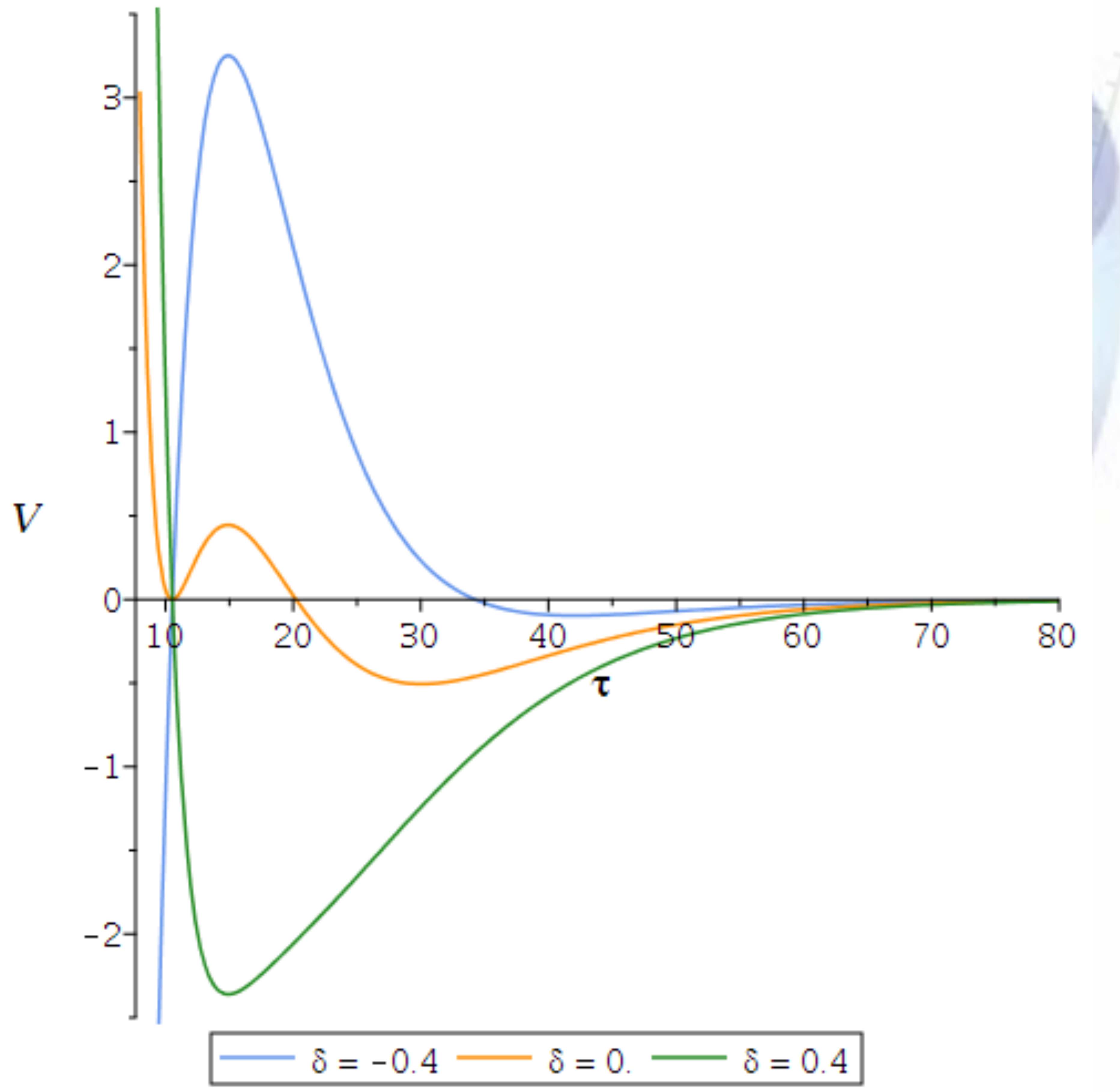
The KL Problem for Quintessence - a racetrack solution?

Racetracks break the link between barrier height and gravitino mass

$m_{3/2} \sim H_0$

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

Model admits SUSY vacuum for critical choice of W_0



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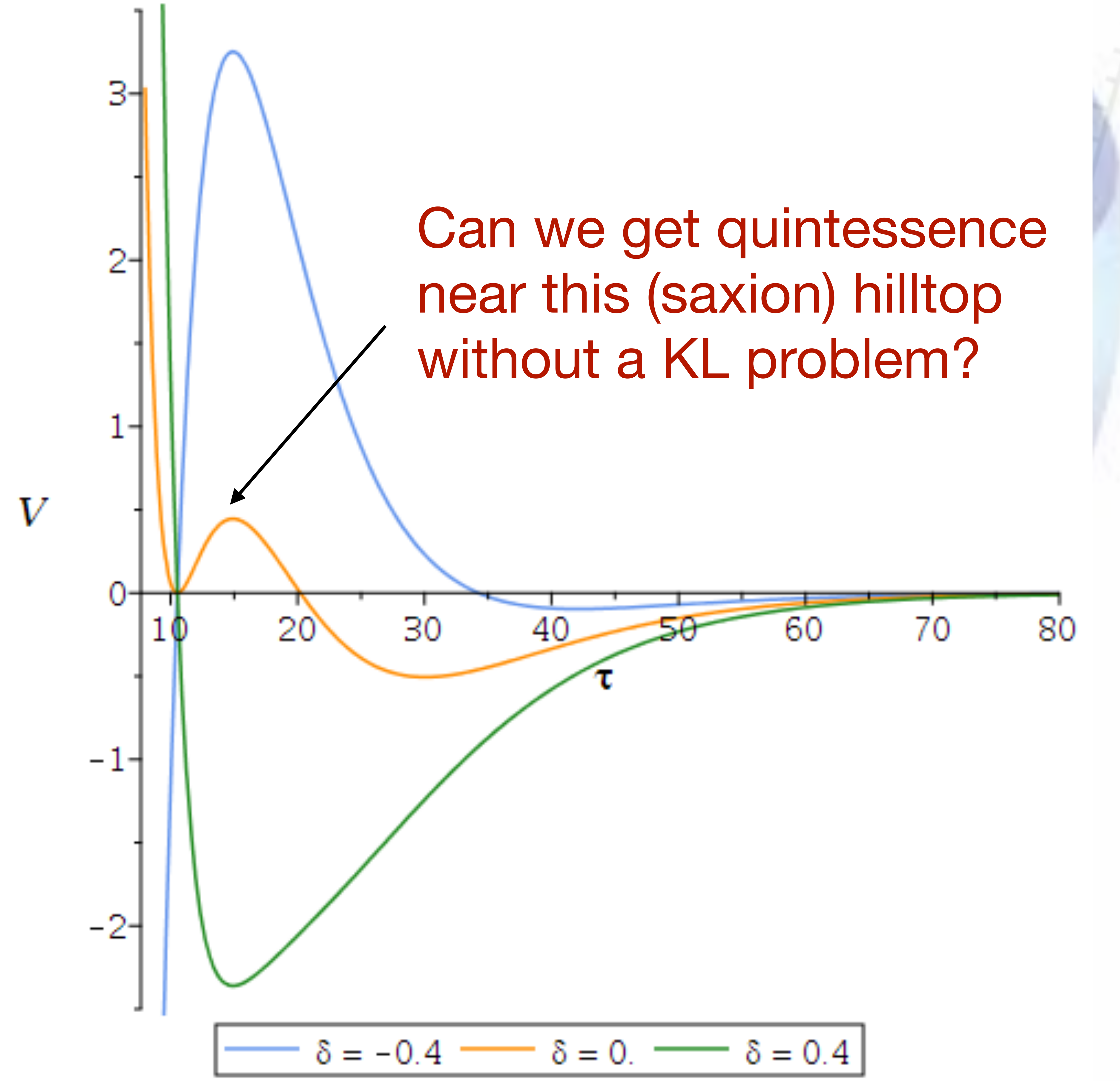

Can we get quintessence near this (saxion) hilltop without a KL problem?

Numerically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

The KL Problem for Quintessence - a racetrack solution?

Racetracks break the link between barrier height and gravitino mass

$m_{3/2} \sim H_0$

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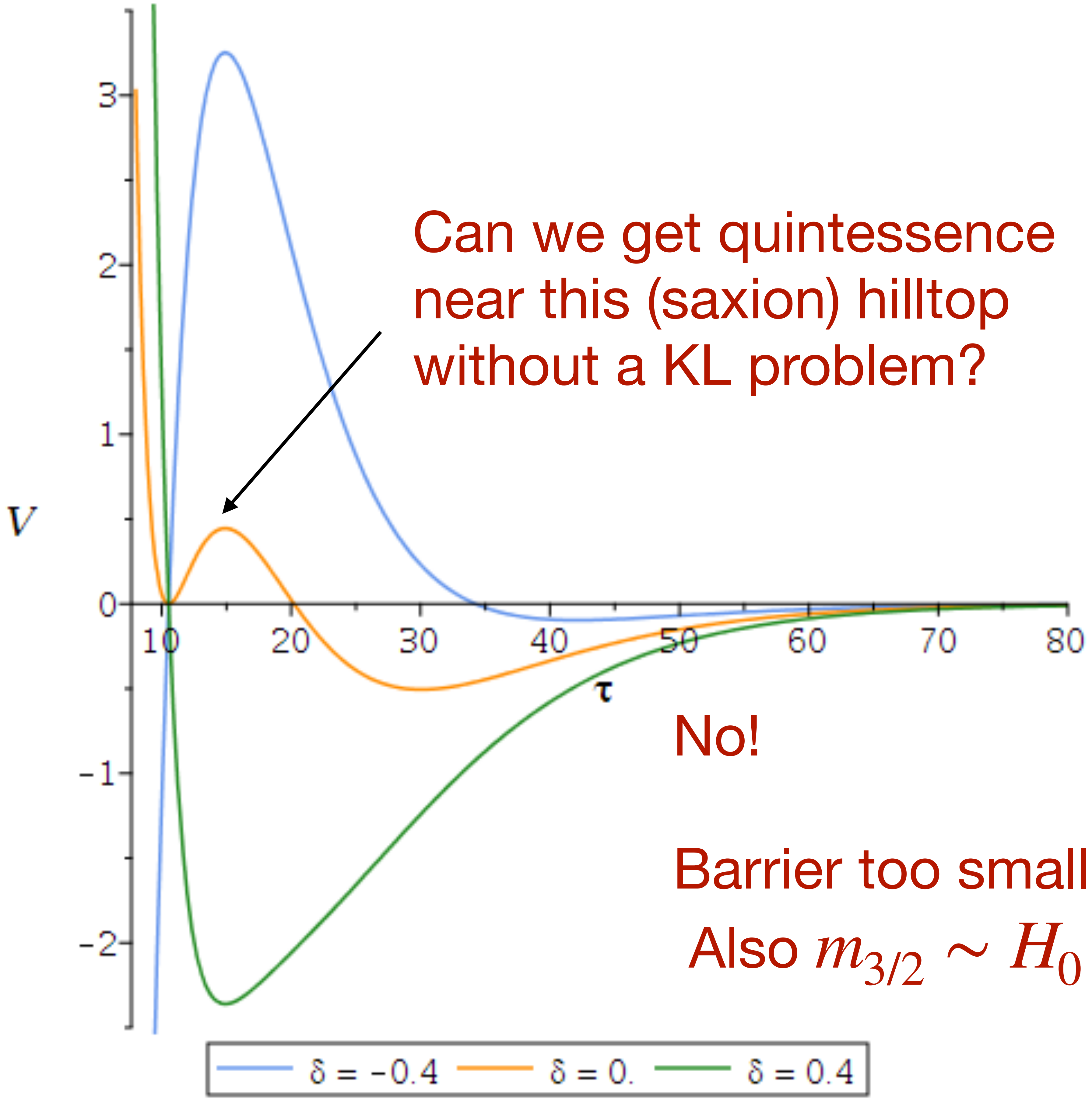

Can we get quintessence near this (saxion) hilltop without a KL problem?

No!

Barrier too small

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

Numerically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

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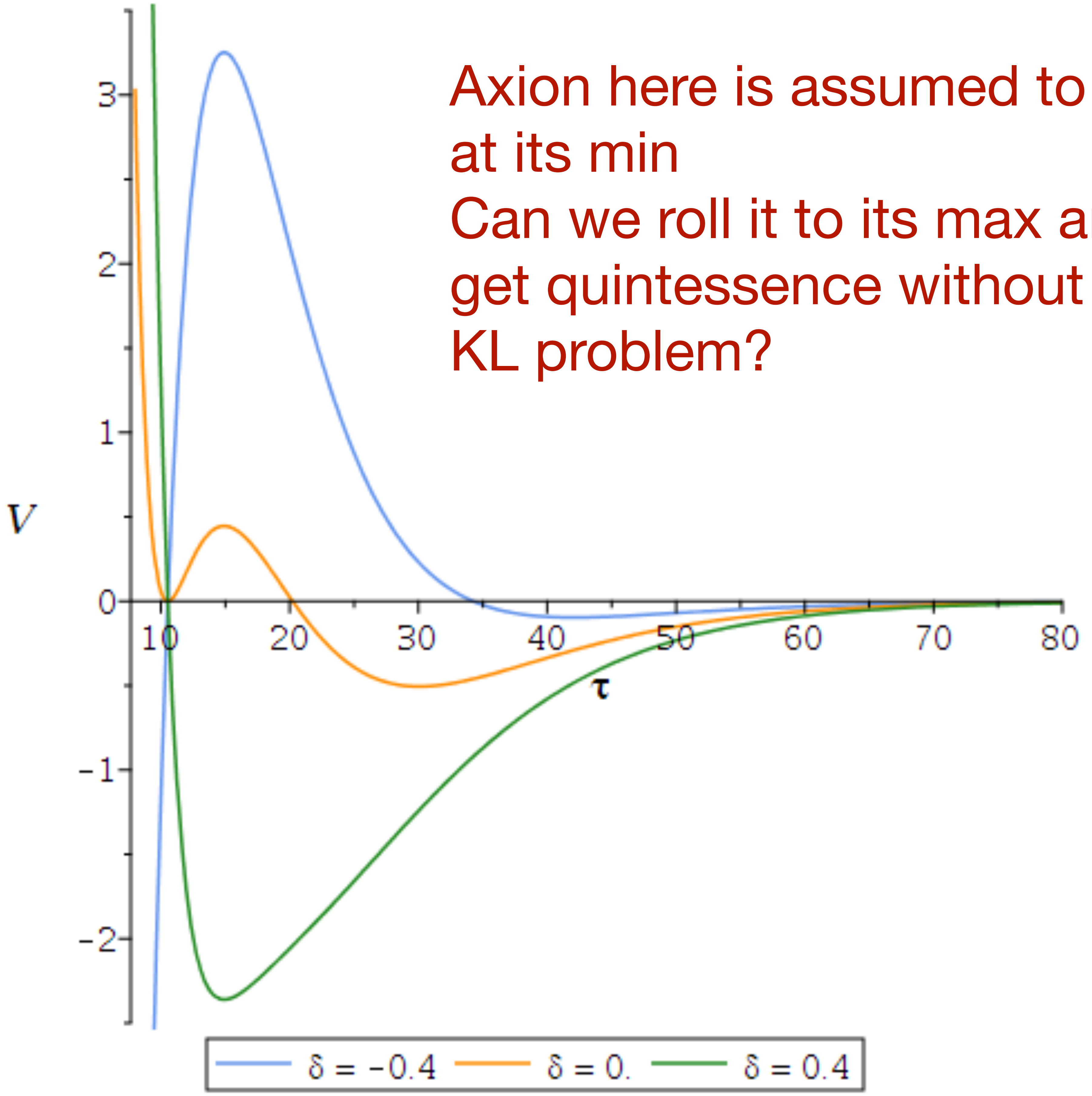
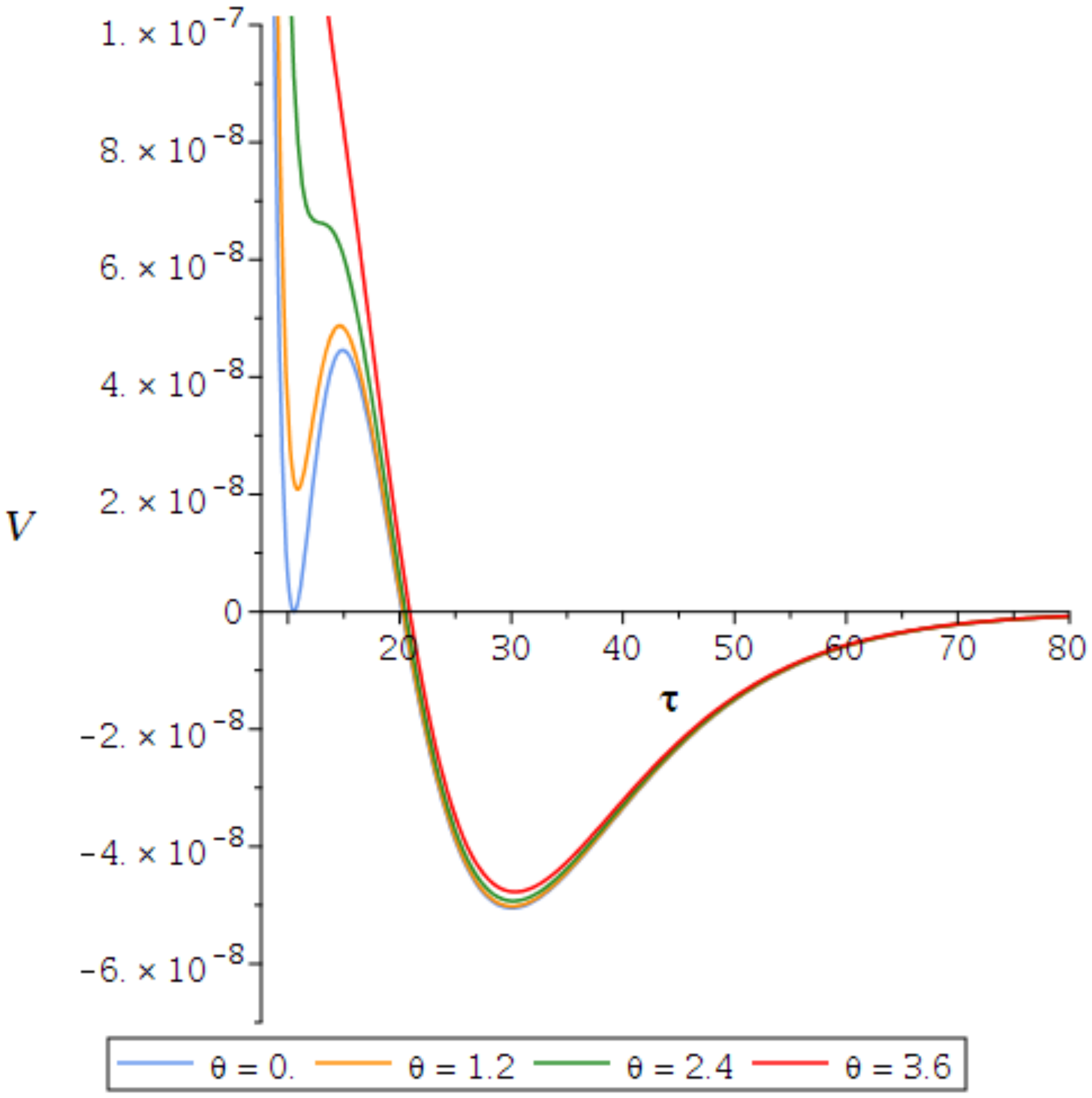


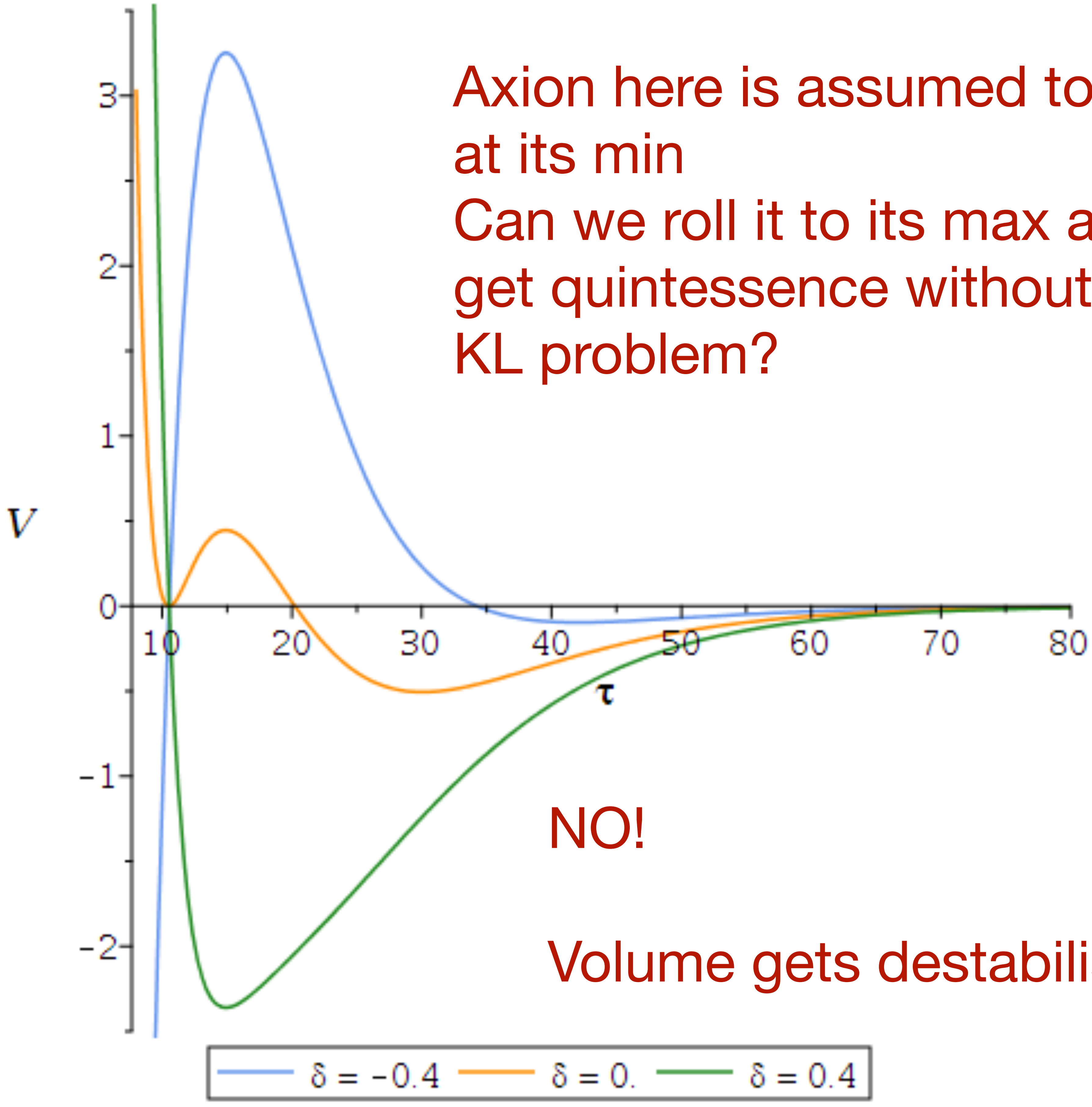
Axion here is assumed to be at its min
Can we roll it to its max and get quintessence without a KL problem?

Numerically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

The KL Problem for Quintessence - a racetrack solution?





Axion here is assumed to be at its min

Can we roll it to its max and get quintessence without a KL problem?

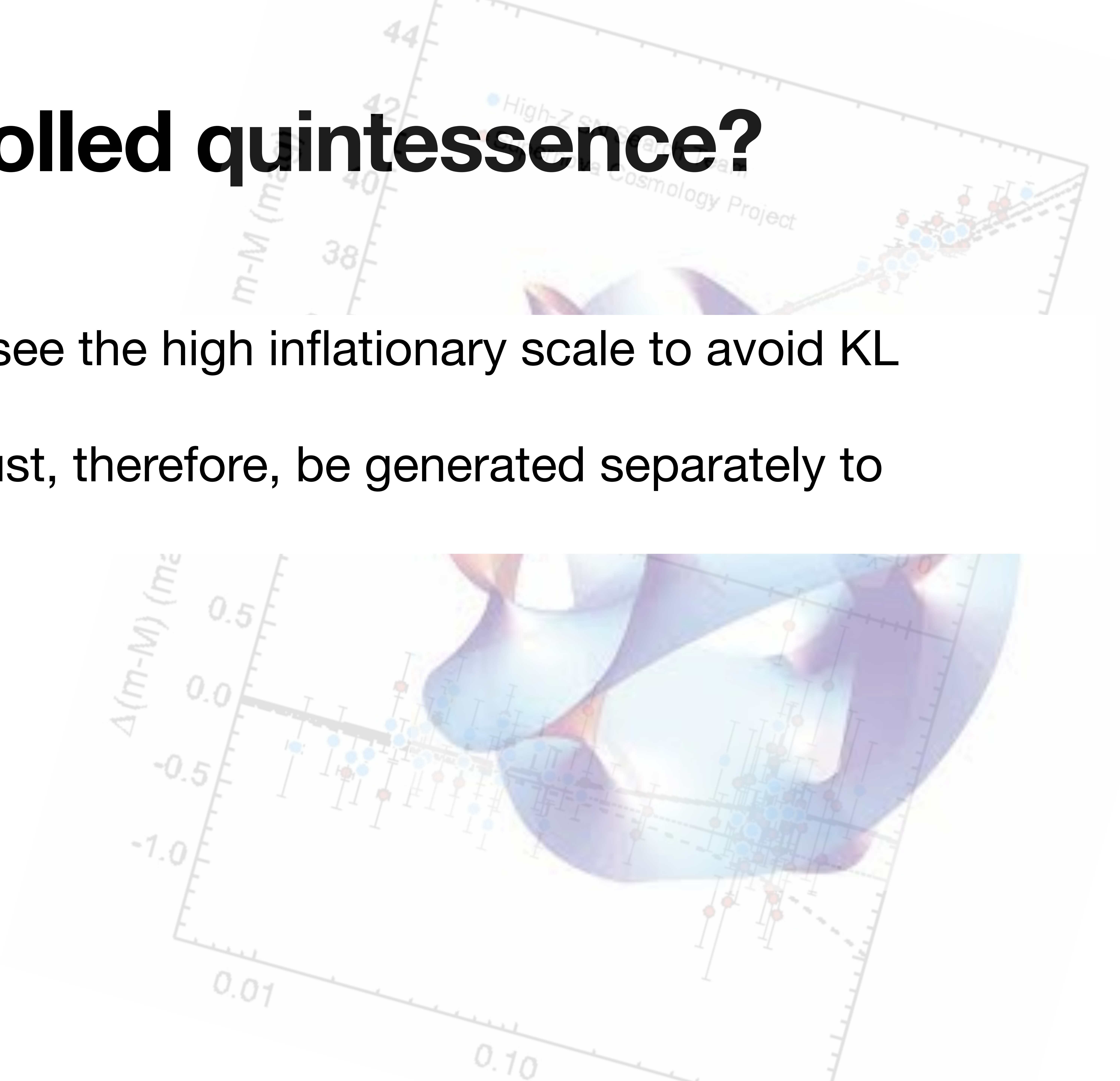
NO!

Volume gets destabilised

Numerically controlled quintessence?

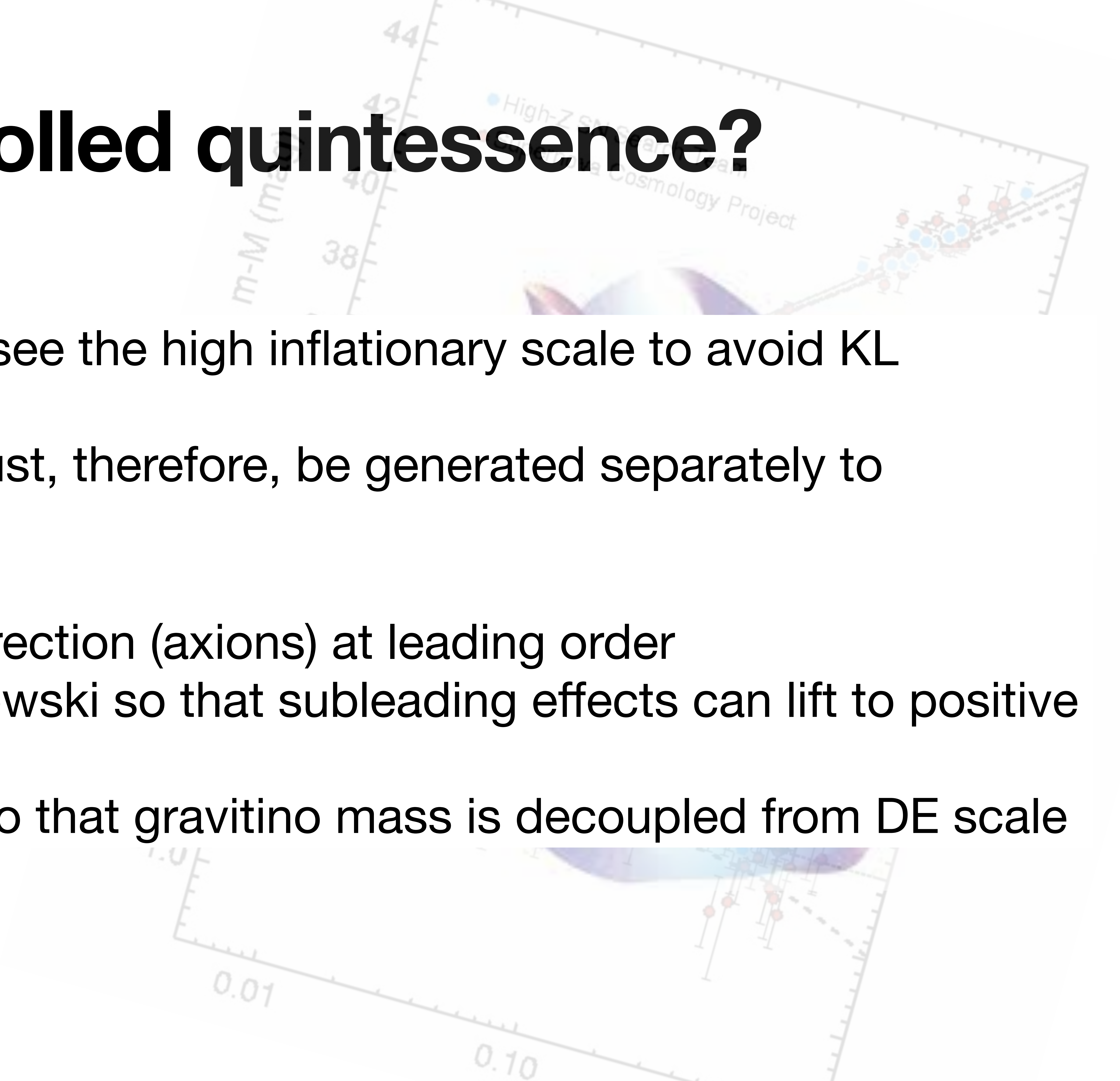
Cicoli, Cunillera, Padilla, Pedro 2021

- Stabilisation of volume must see the high inflationary scale to avoid KL problem.
- Dynamics of low scale DE must, therefore, be generated separately to decouple it



Numerically controlled quintessence?

Cicoli, Cunillera, Padilla, Pedro 2021

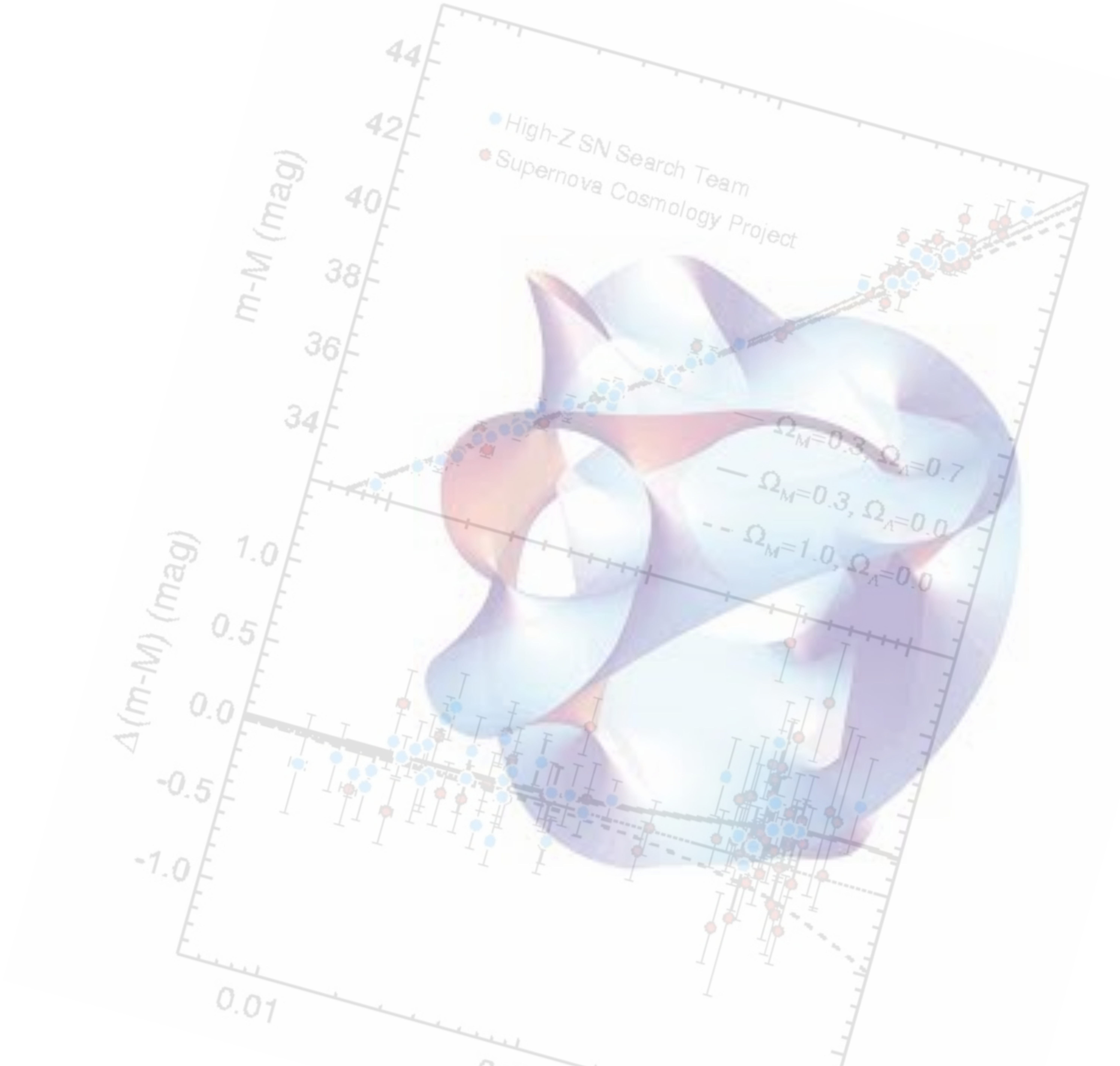


- Stabilisation of volume must see the high inflationary scale to avoid KL problem.
- Dynamics of low scale DE must, therefore, be generated separately to decouple it

- 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

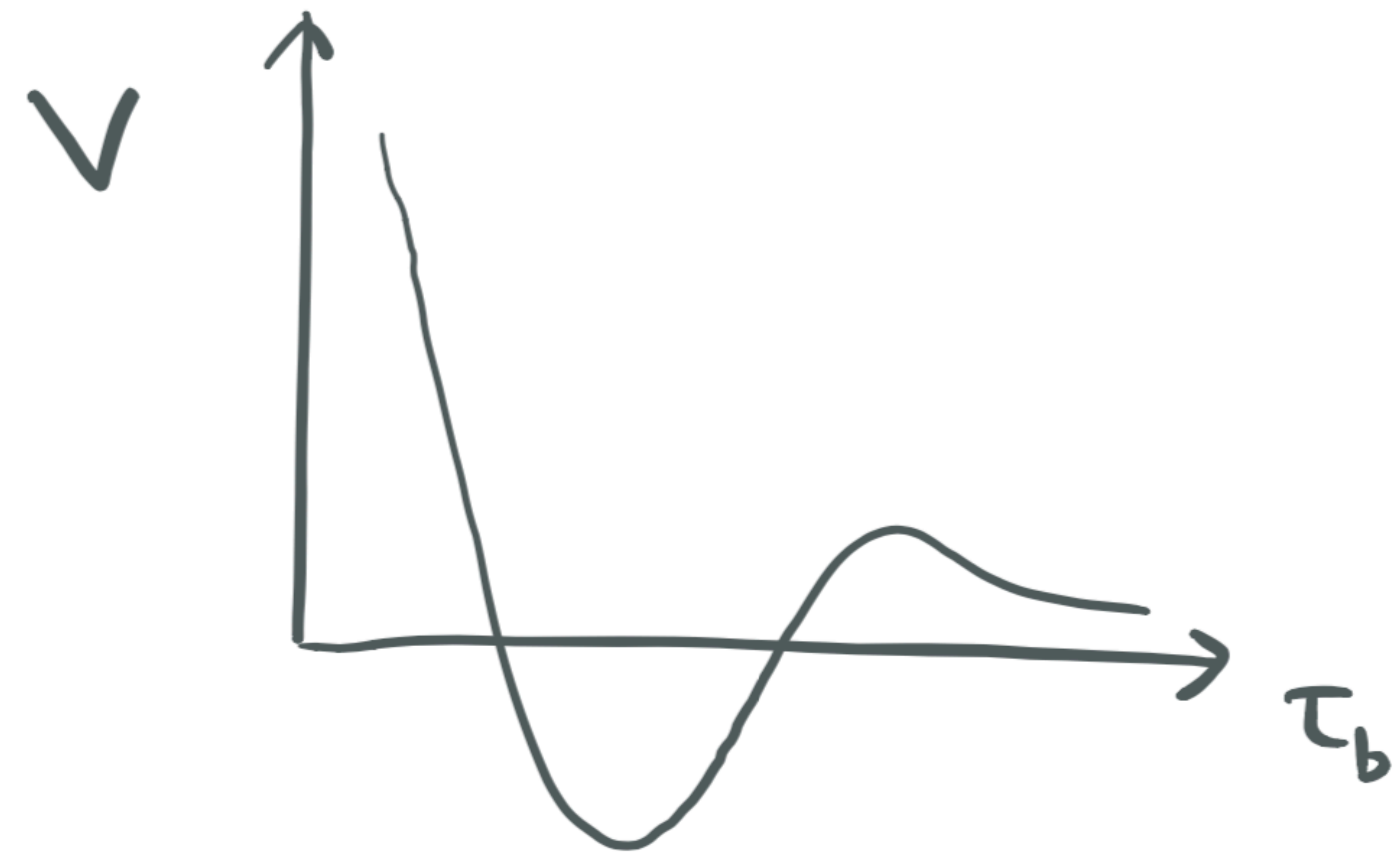
Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

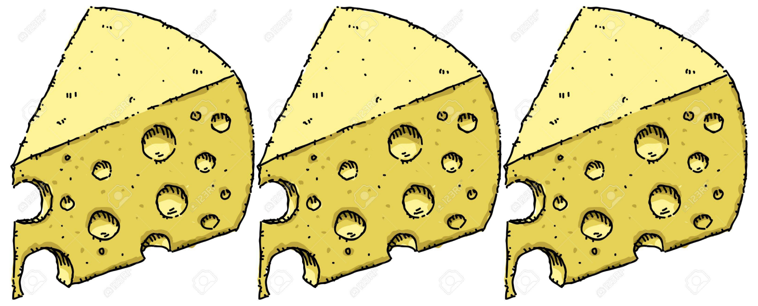


Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021



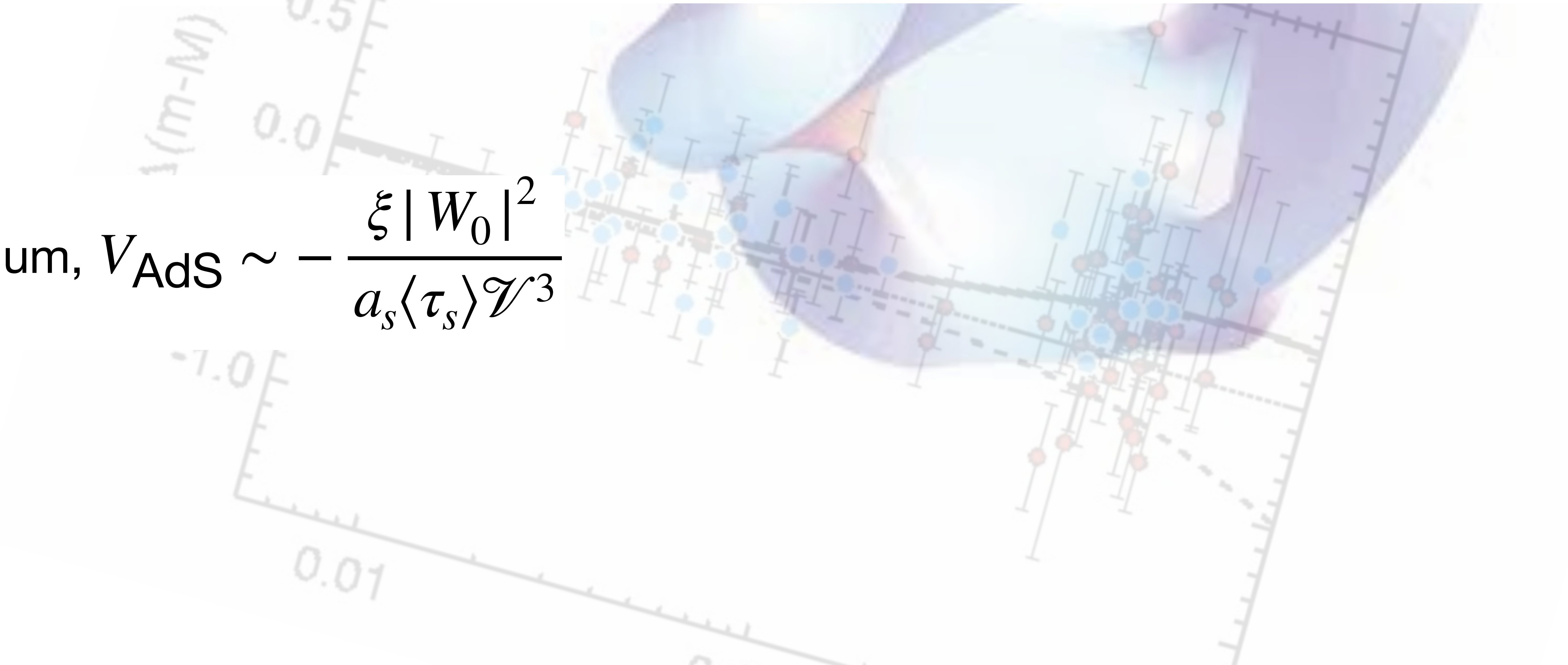
LVS model with two Kahler moduli $T_b = \tau_b + i\theta_b$ and $T_s = \tau_s + i\theta_s$



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

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

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



Axion hilltops

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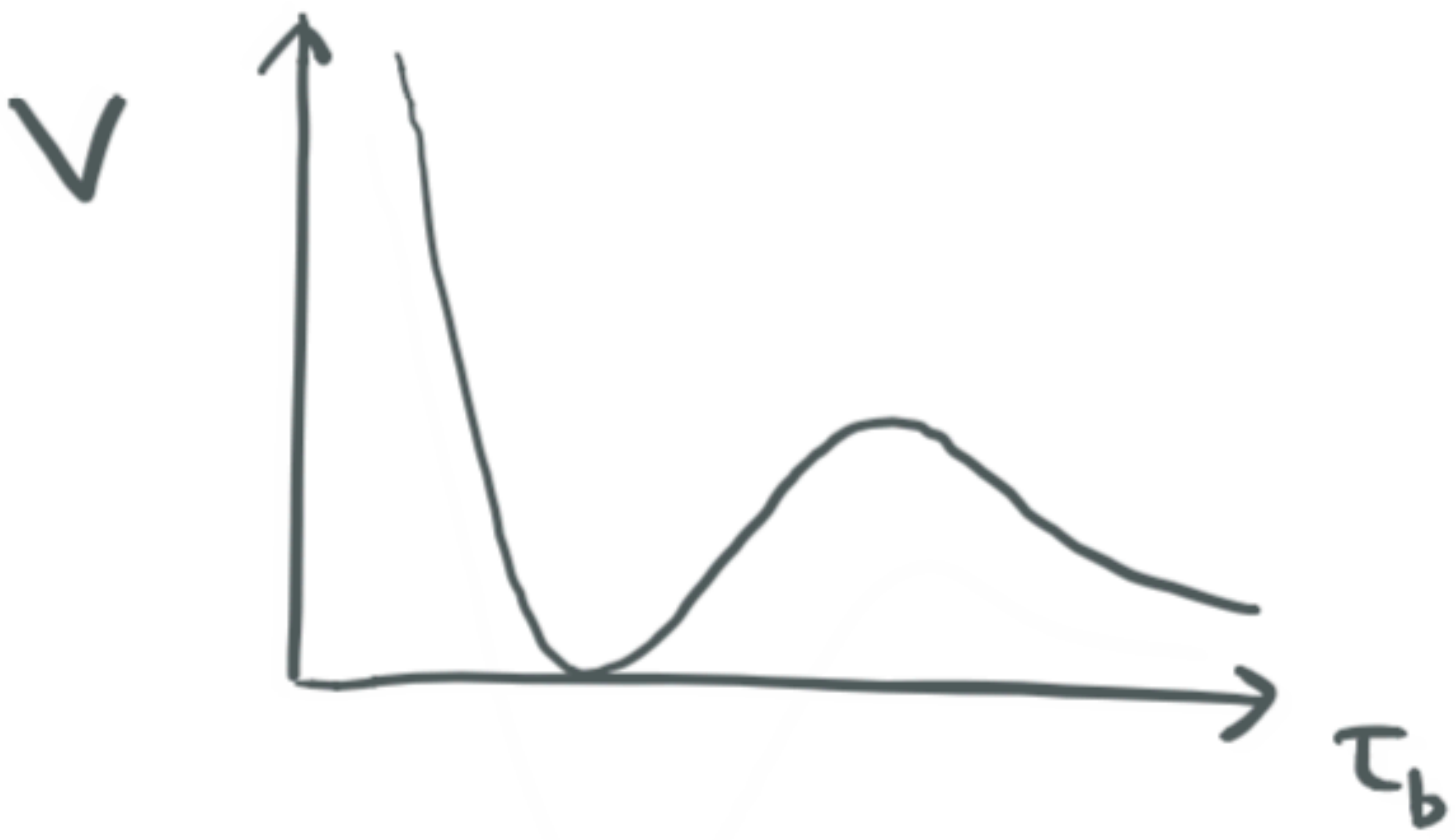

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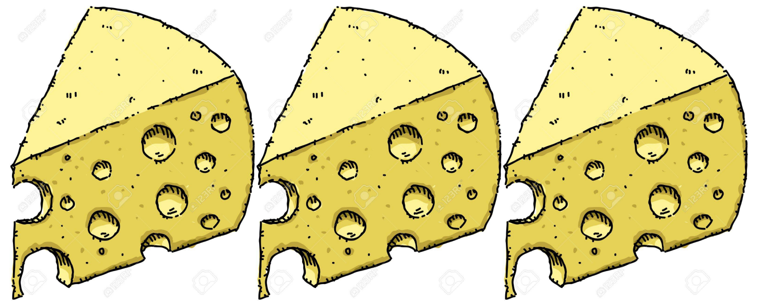

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Obtain scalar potential with (non SUSY) AdS minimum, $V_{\text{AdS}} \sim -\dfrac{\xi |W_0|^2}{a_s\langle\tau_s\rangle\mathscr{V}^3}$

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

Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

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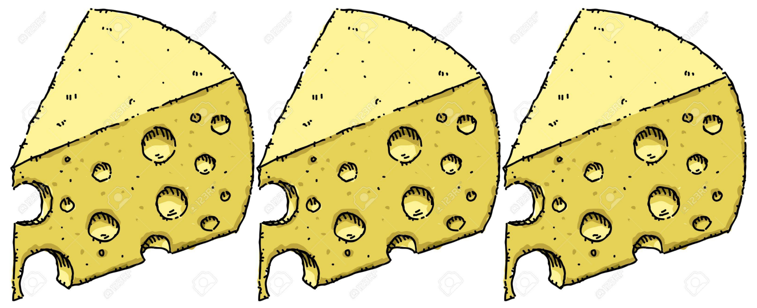

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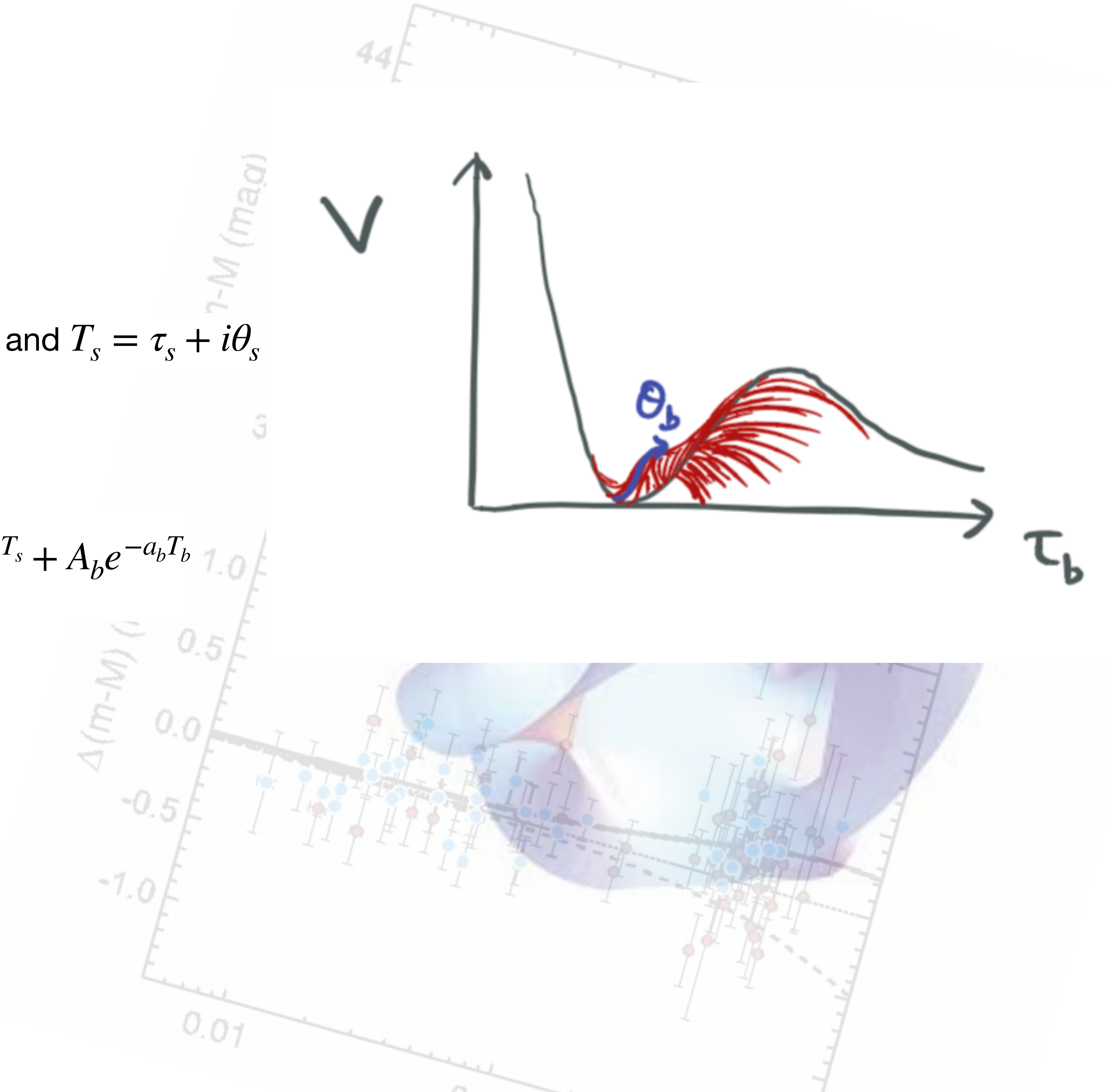
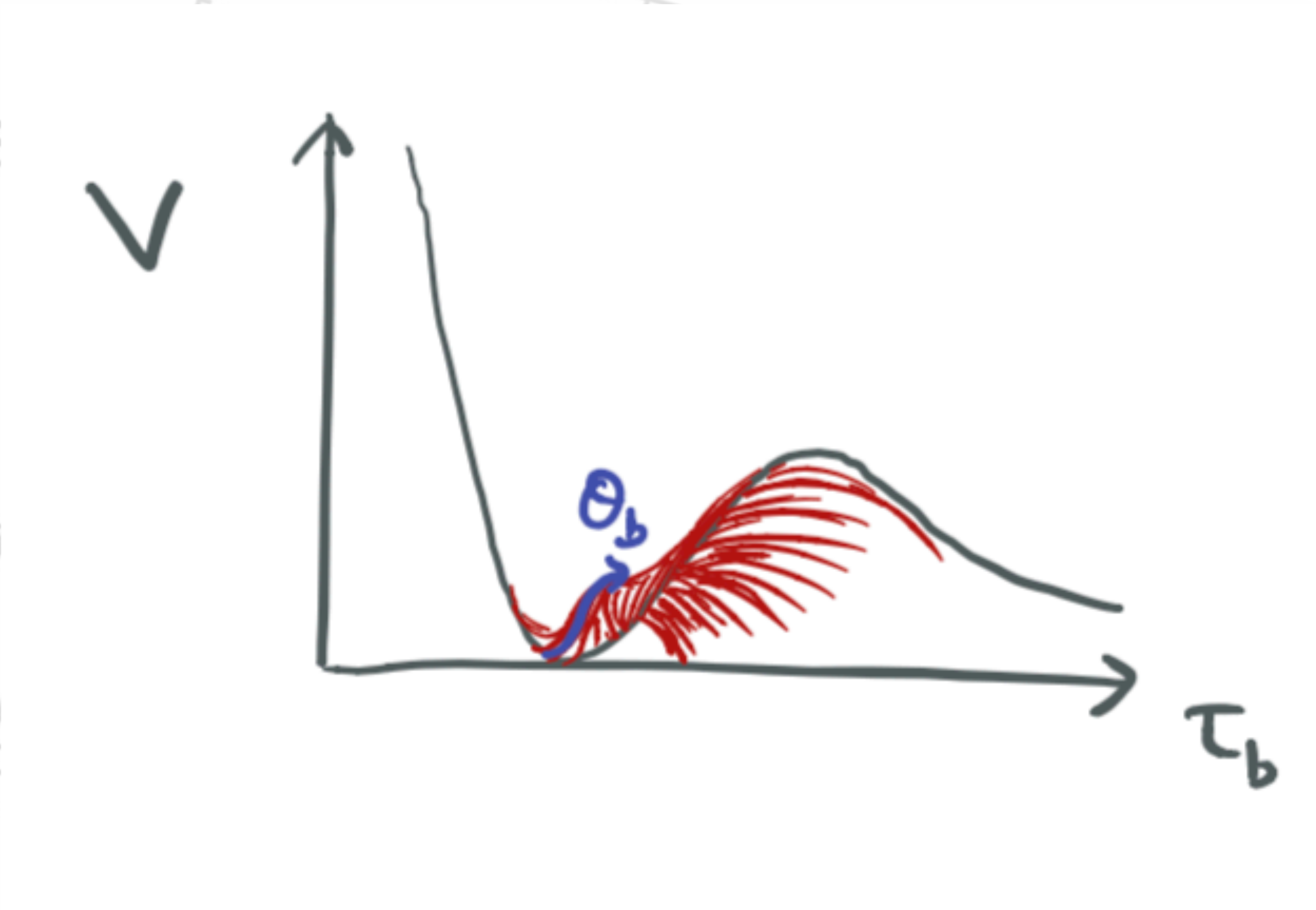
EXCITE THE BIG AXION



Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021



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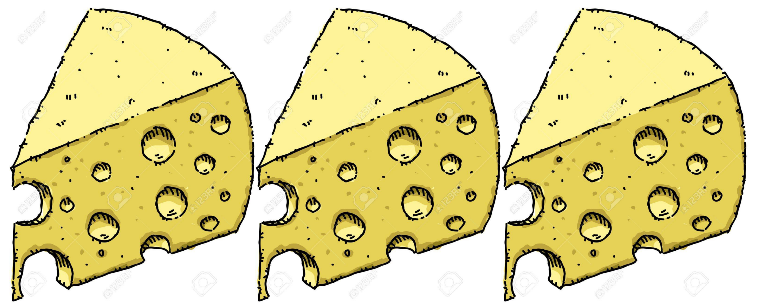

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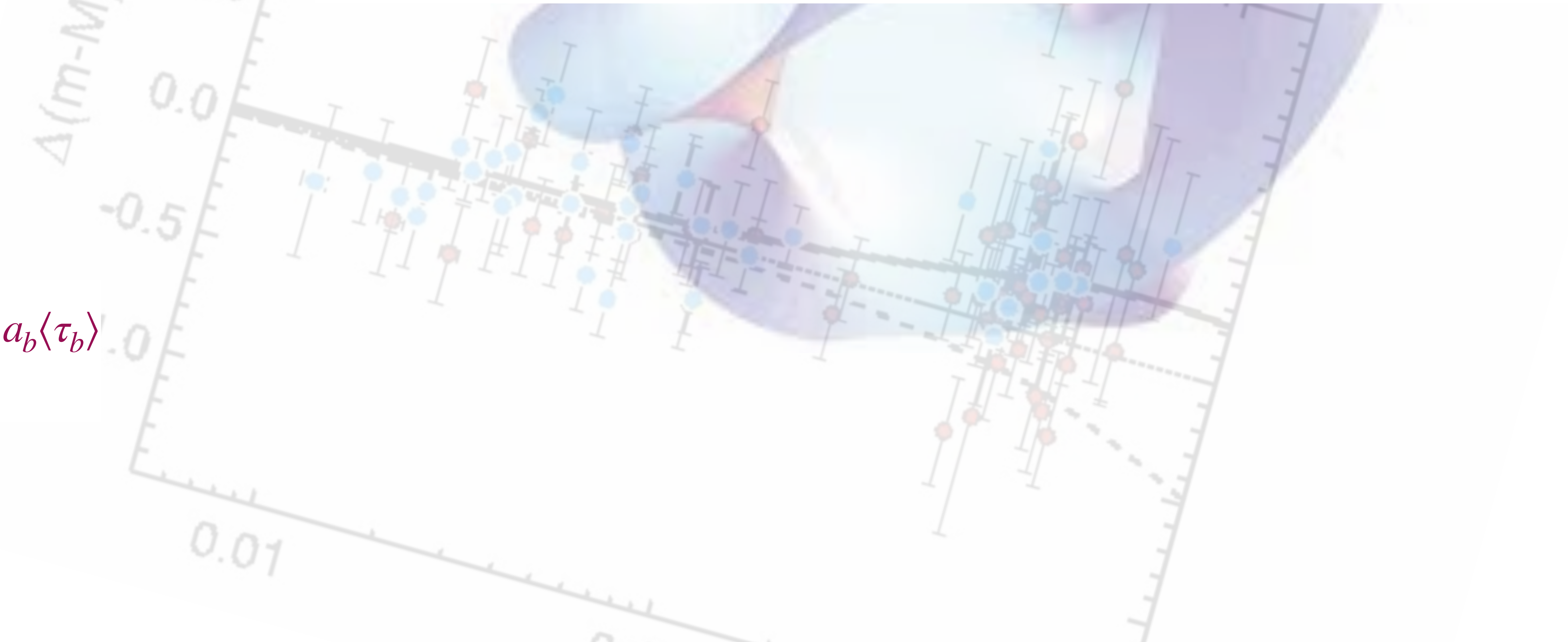
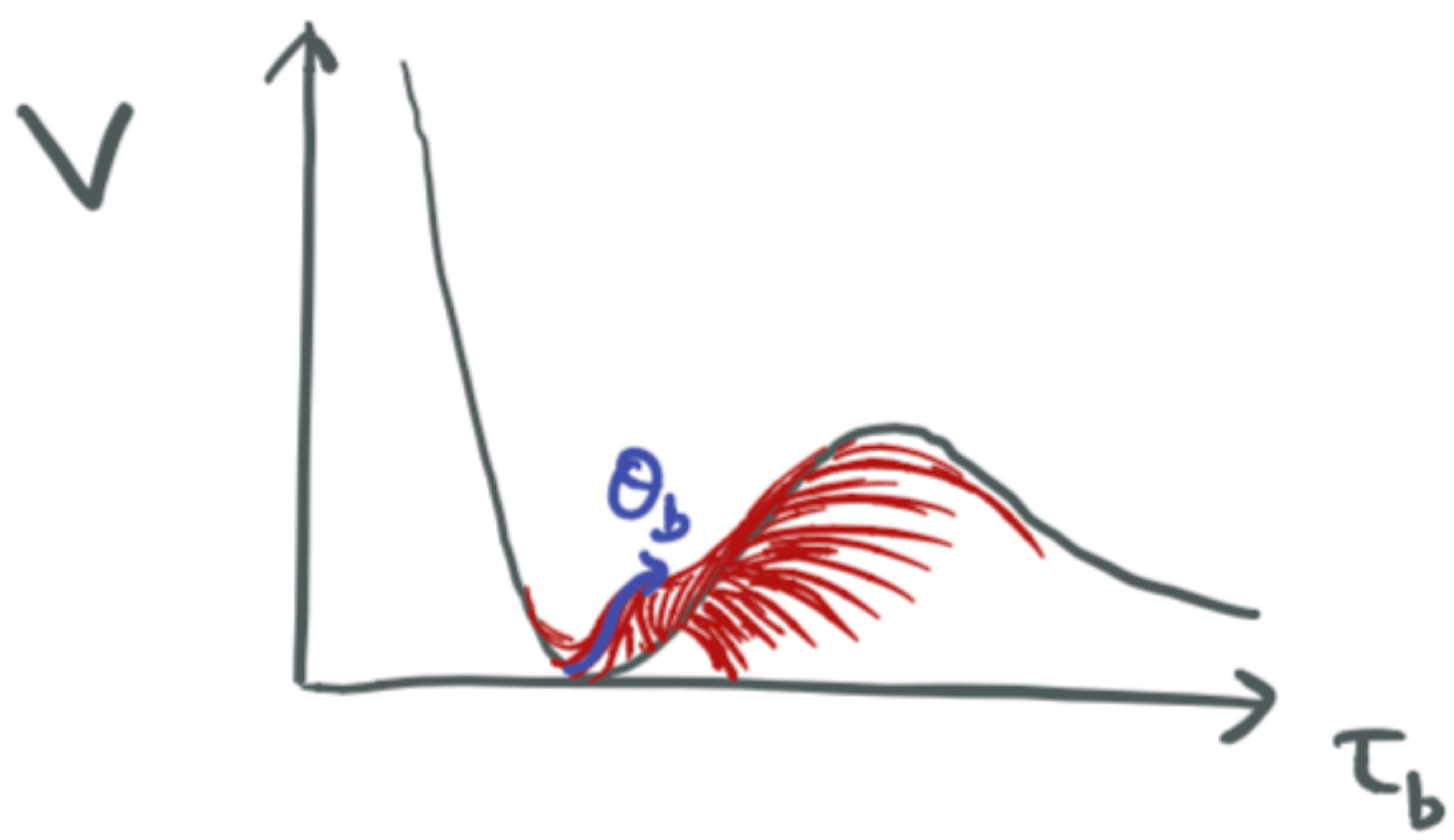
EXCITE THE BIG AXION

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



Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021



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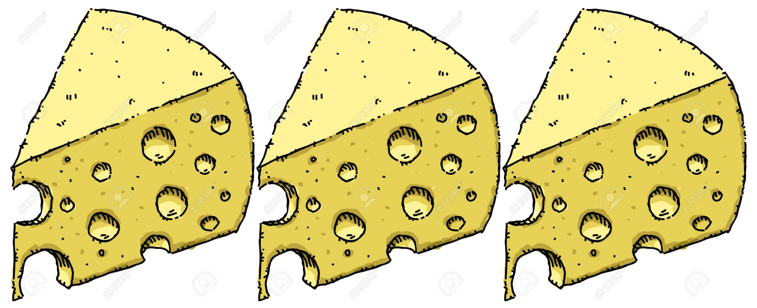

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EXCITE THE BIG AXION

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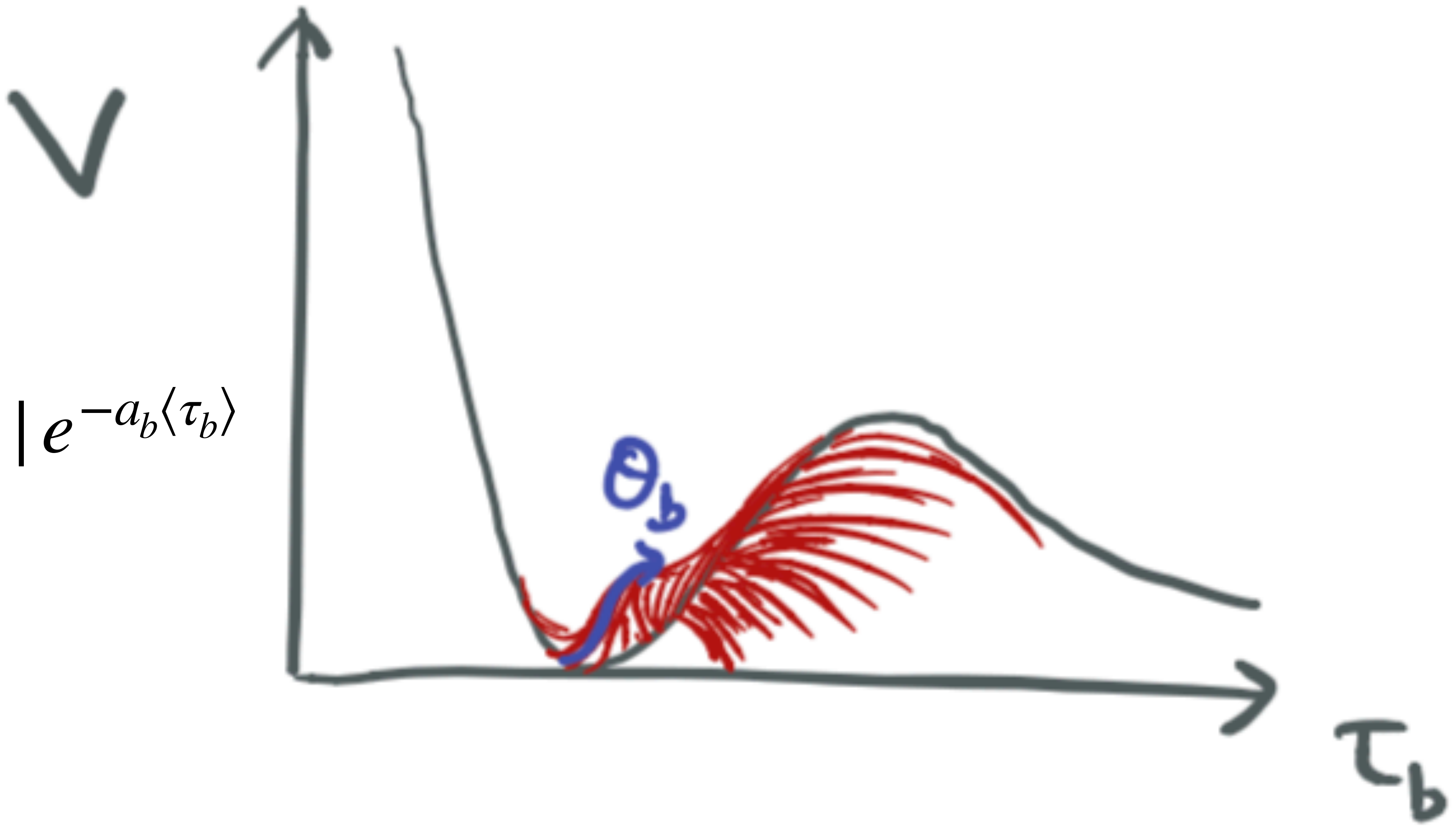
Go to canonical field

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

Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

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



How flat is the hilltop?

Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

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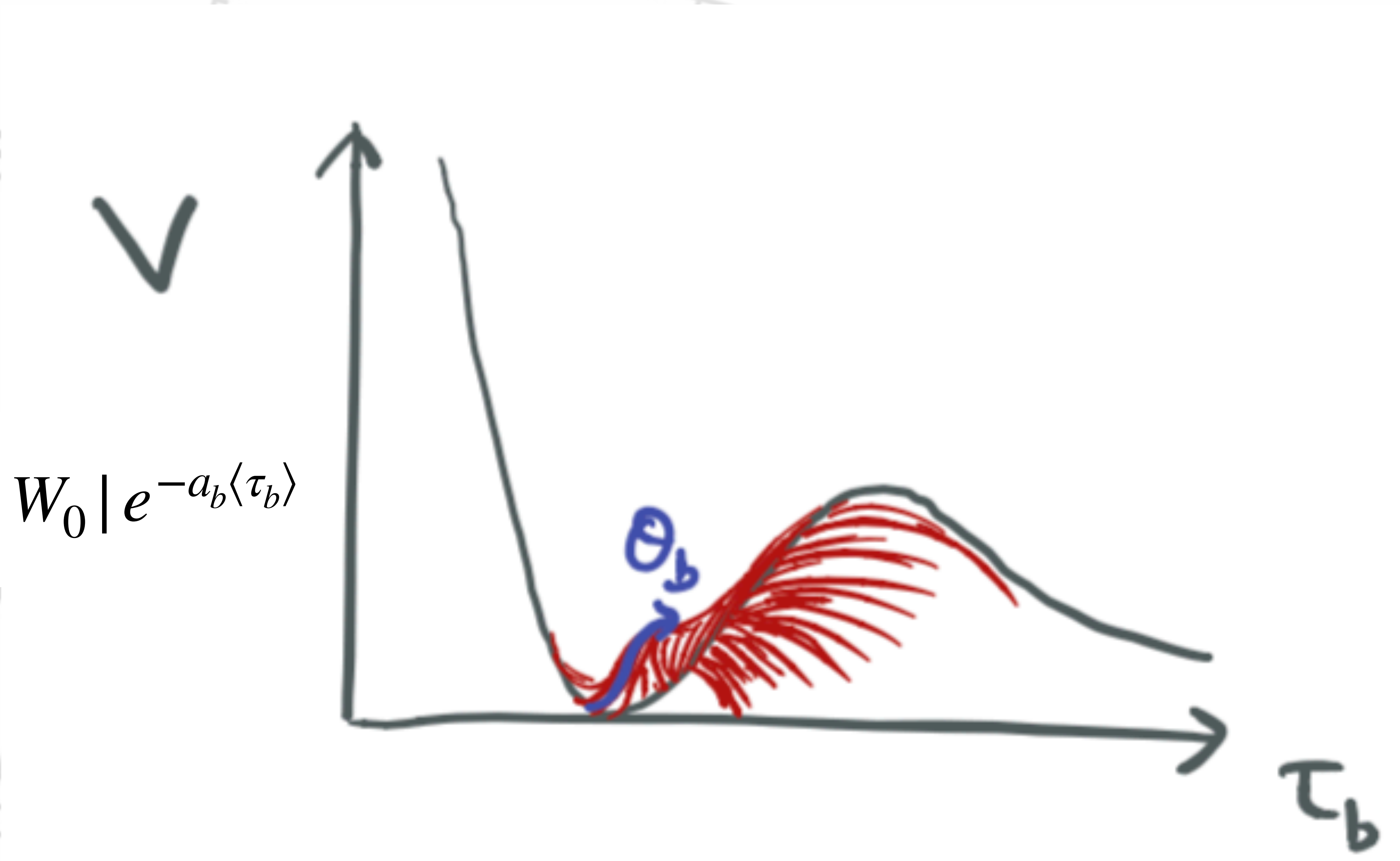
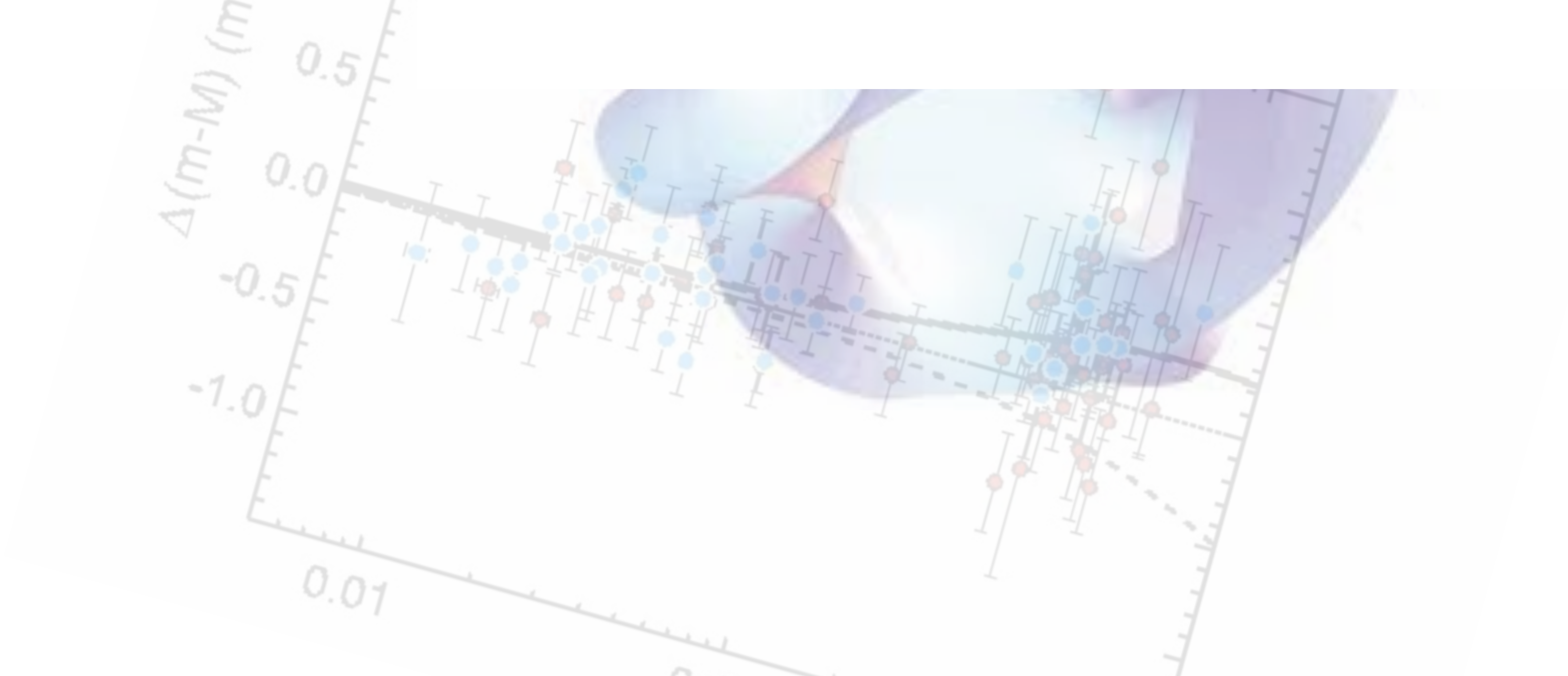


How flat is the hilltop?

$$\boxed{\eta_{\text{hilltop}} = \frac{V_{\text{DE},\phi\phi}}{V_{\text{DE}}} \sim -\frac{1}{3}a_b^2\langle\tau_b\rangle^2}$$



Axion hilltops

Cicoli, Cunillera, Padilla, Pedro 2021

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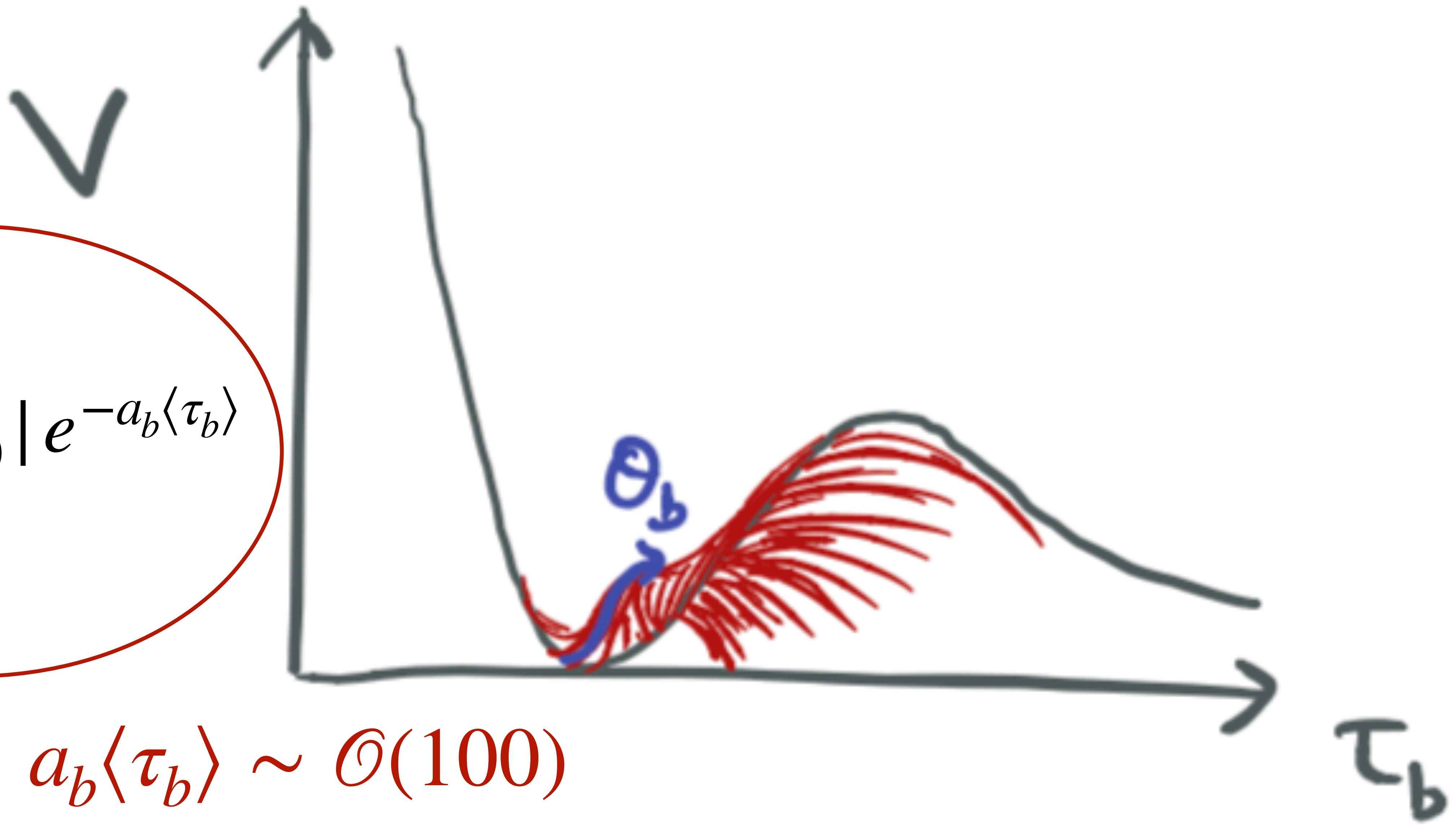

match to DE scale $a_b\langle\tau_b\rangle \sim \mathcal{O}(100)$

How flat is the hilltop?

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Axion hilltops

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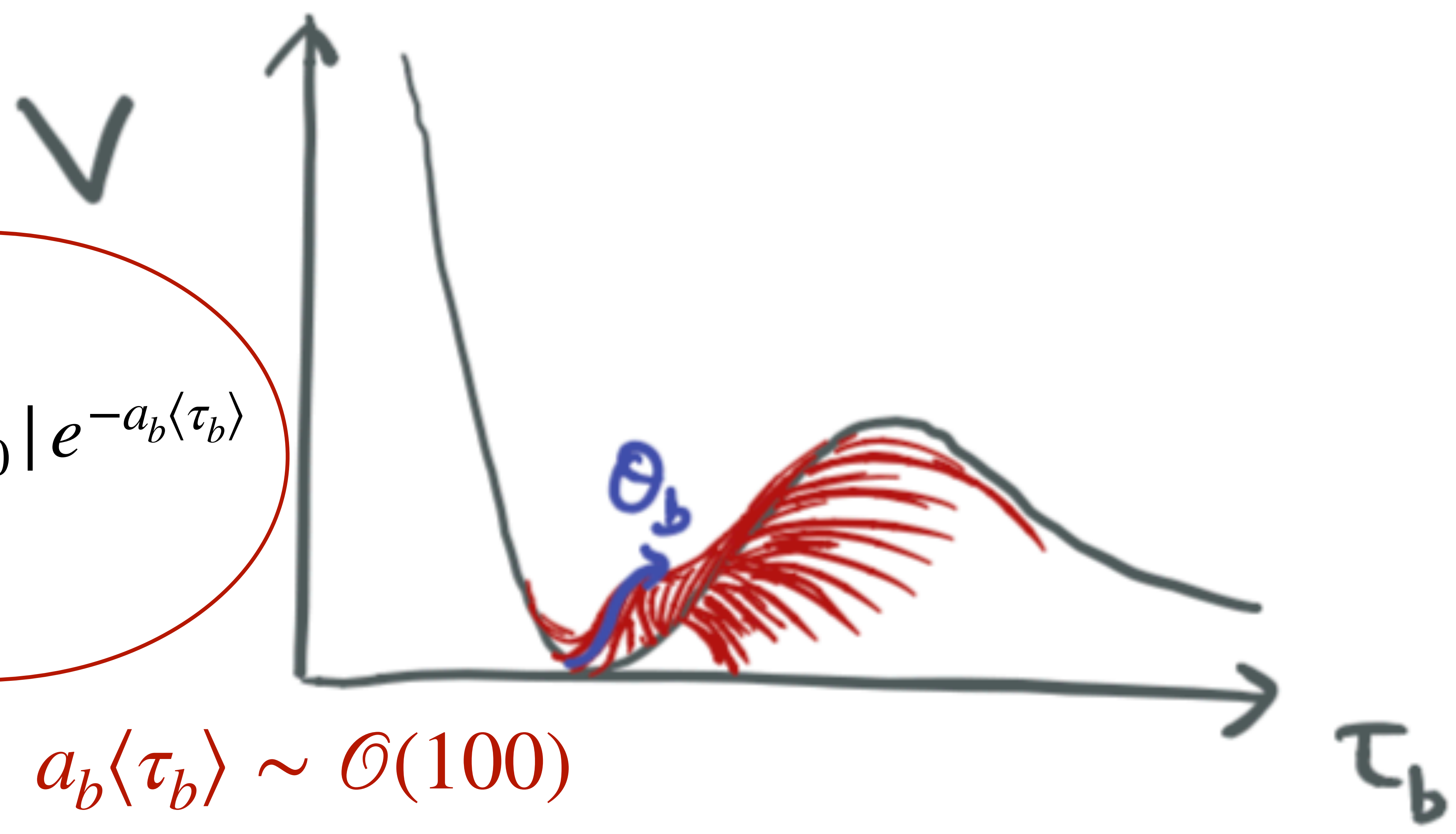


match to DE scale $a_b\langle\tau_b\rangle \sim \mathcal{O}(100)$

How flat is the hilltop?

$$\boxed{\eta_{\text{hilltop}} = \frac{V_{\text{DE},\phi\phi}}{V_{\text{DE}}} \sim -\frac{1}{3}a_b^2\langle\tau_b\rangle^2} \longrightarrow \eta_{\text{hilltop}} \sim -\mathcal{O}(3000)$$

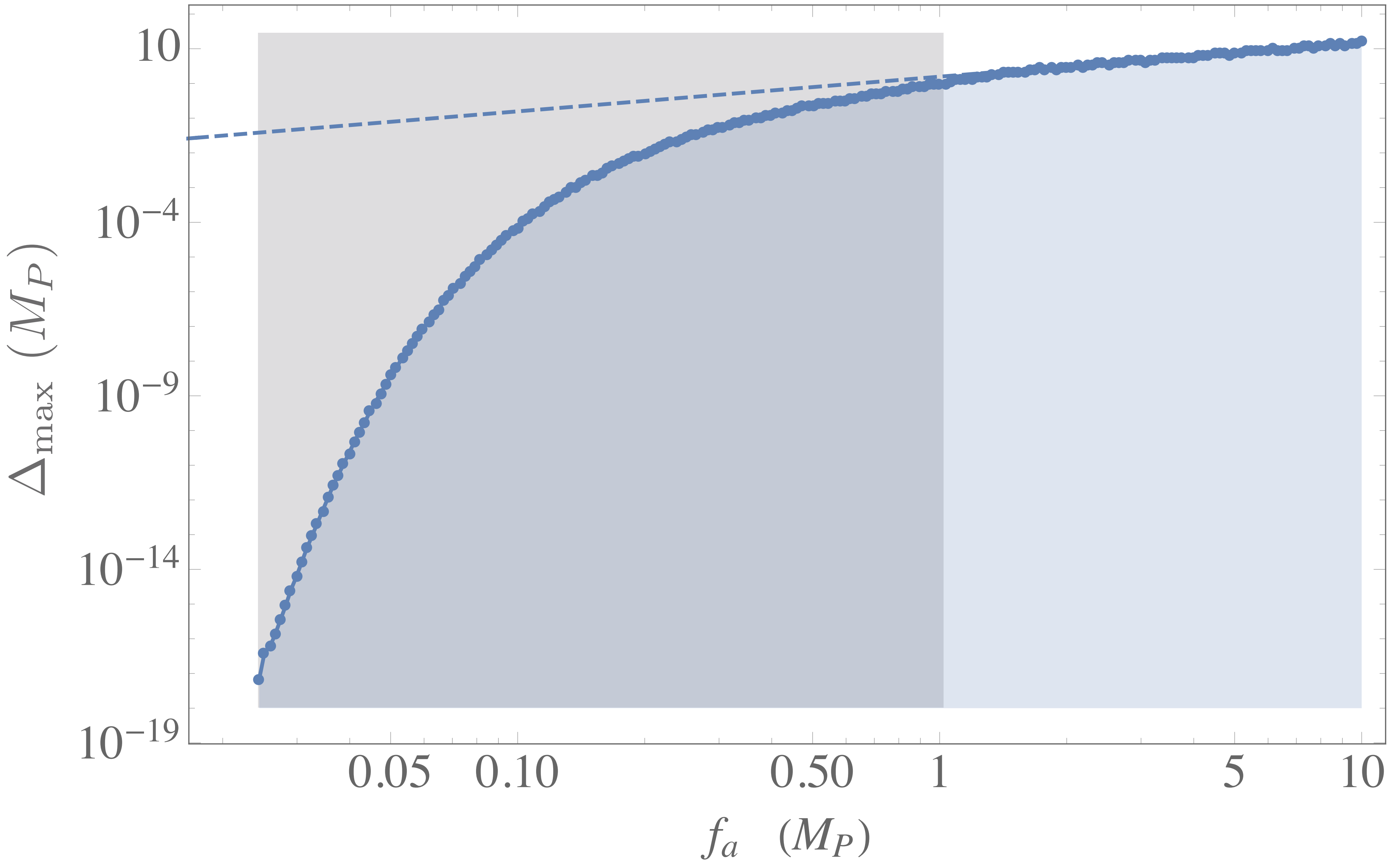
NEED TO BE EXTREMELY CLOSE TO THE HILLTOP!

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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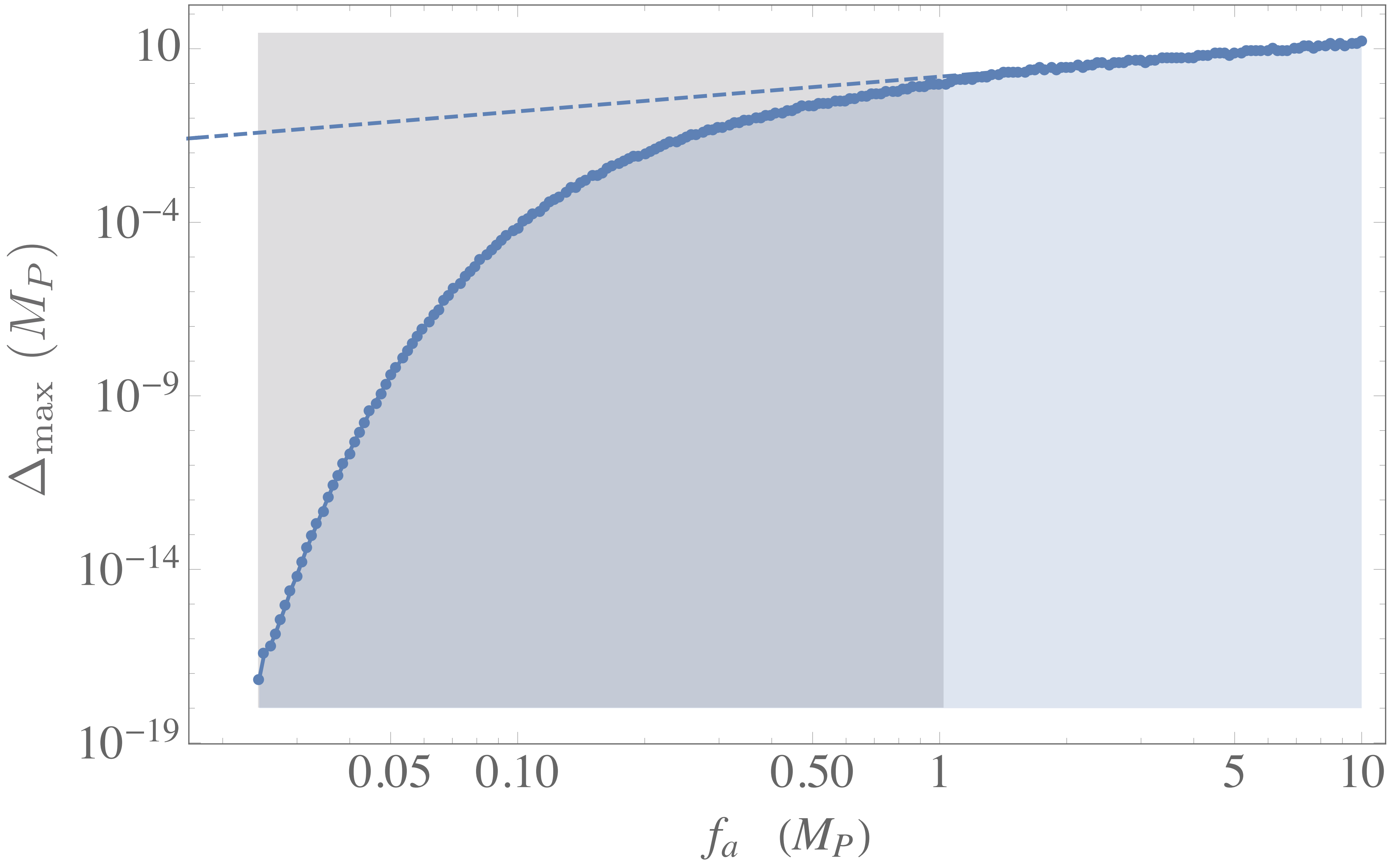
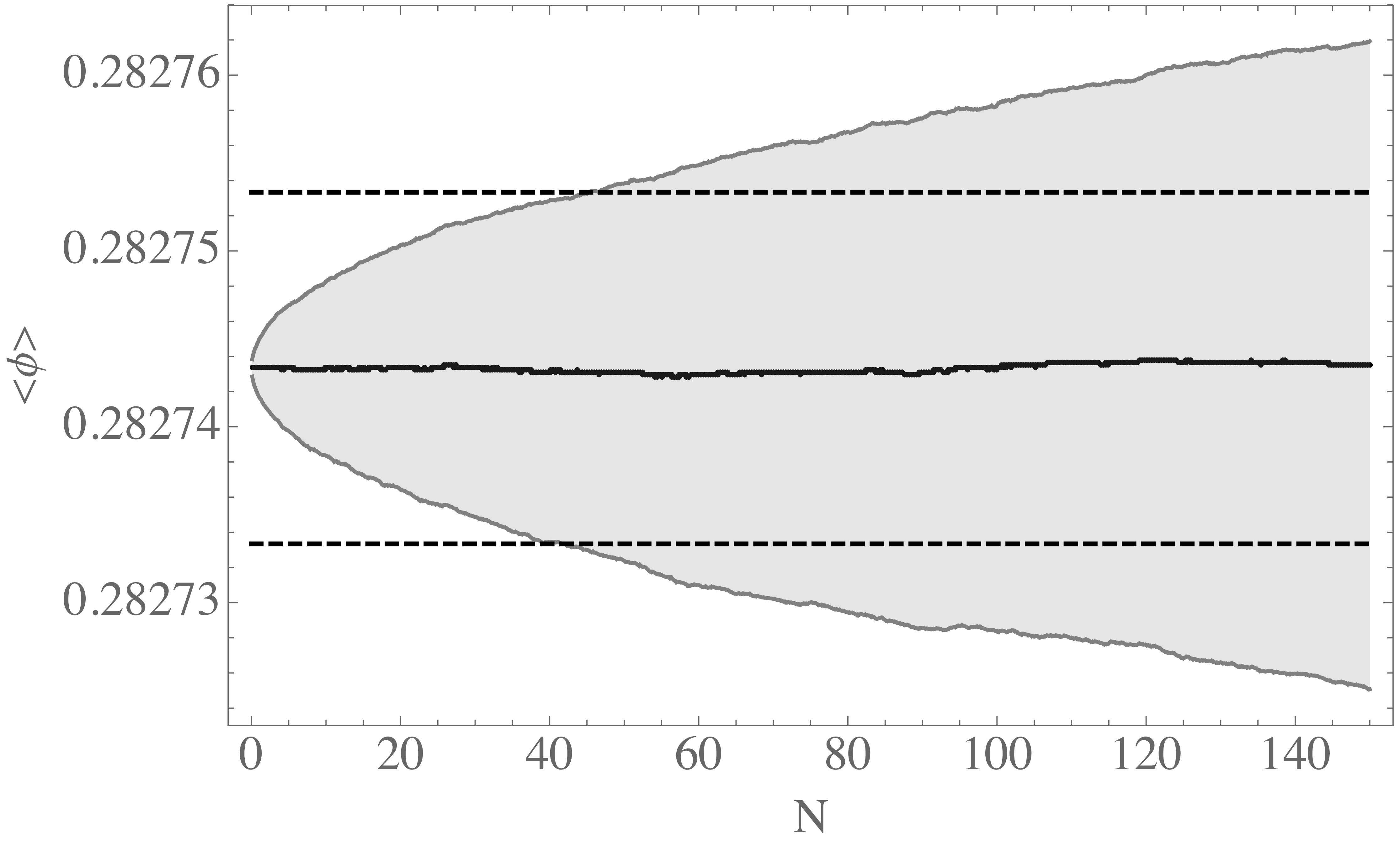


Quantum diffusion will push axion away from its maximum during inflation



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

Reheating

Details of reheating depend on brane construction realising SM

1. SM lives on D7 branes wrapping inflation

2. SM lives on D& branes wrapping blow up mode

3. DM lives on D3 branes at a CY singularity

In all cases, number of efolds is around N=52

On top of SM particles, inflation produce closed string axions (dark radiation)

Contribution to eff number of neutrinos tamed by inflation decay into SM gauge bosons and Higgs

Dark matter:

High susy scale, so any stable neutralinos would overproduce DM. Need to break R parity to allow these to decay.

PBHs?

QCD axion?