HITCH-HIKERS' GUIDE TO THE SWAMPLAND

Why Black Holes Decay and We Cannot have a Cosmological Constant

YOUR GUIDE:
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- ✏️Contributor to *The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics*
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  - ∊ CosmoVerse: Addressing observational tensions in cosmology with systematics and fundamental physics
  - ∊ THEORY-CHALLENGES: Fundamental challenges in theoretical physics

SOURCES

Source to everything in this talk is my *Hitchhiker's Guide to the Swampland: The Cosmologist's Handbook to the string-theoretical Swampland Programme* and the sources within.

arXiv:2509.02632 [hep-th]

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(Dated: 30th August 2025)

String theory has strong implications for cosmology: it tells us that we cannot have a cosmological constant, that single-field slow-roll inflation is ruled out, and that black holes decay. We elucidate the origin of these statements within the string-theoretical swampland programme. The swampland programme is generating a growing body of insights that have yet to be incorporated into cosmological models. Taking a cosmologist's perspective, we highlight the relevance of swampland conjectures to black holes, dark matter, dark energy, and inflation, including their implications for scalar fields such as quintessence and axions. Our goal is to inspire cosmological model builders to examine the compatibility of effective field theories with quantum gravitational UV completions and to address outstanding cosmological tensions such as the Hubble tension. This comprehensive literature review presents clear definitions, cosmological implications, and the current status — including evidence and counterexamples — of the following swampland conjectures: the *anti–de Sitter distance conjecture (AdSDC)*, the *completeness conjecture (CC)*, the *cobordism conjecture*, the *de Sitter conjecture (dSC)*, the *swampland distance conjecture (SDC)*, the *emergence proposal (EP)*, the *Festina Lente Bound (FLB)*, the *finite number of massless fields conjecture* (or *finite flux vacua conjecture (FFV)*), the *no global symmetries conjecture*, the *no non-supersymmetric theories conjecture*, the *non-negative null energy condition conjecture*, the *positive Gauss–Bonnet term conjecture*, the *species scale conjecture*, the *gravitino swampland conjecture (GSC)*, the *tadpole conjecture*, the *tameness conjecture*, the *trans–Planckian censorship conjecture (tPCC/TCC)*, the *unique geodesic conjecture*, and the *weak gravity conjecture (WGC)*, including the *repulsive force conjecture (RFC)*.

PACS numbers: 04.50.Kd, 04.60.-m, 04.60.Bc, 04.60.Cf, 04.70.-s, 04.70.Dy, 11.15.-q, 11.30.Fs, 11.25.-w, 98.80.Cq, 98.80.Es
Keywords: Cosmology, String Theory, Quantum Gravity, Effective Field Theory, Swampland Programme, Swampland Conjectures, Inflation, Dark Energy, Dark Matter, Black Holes

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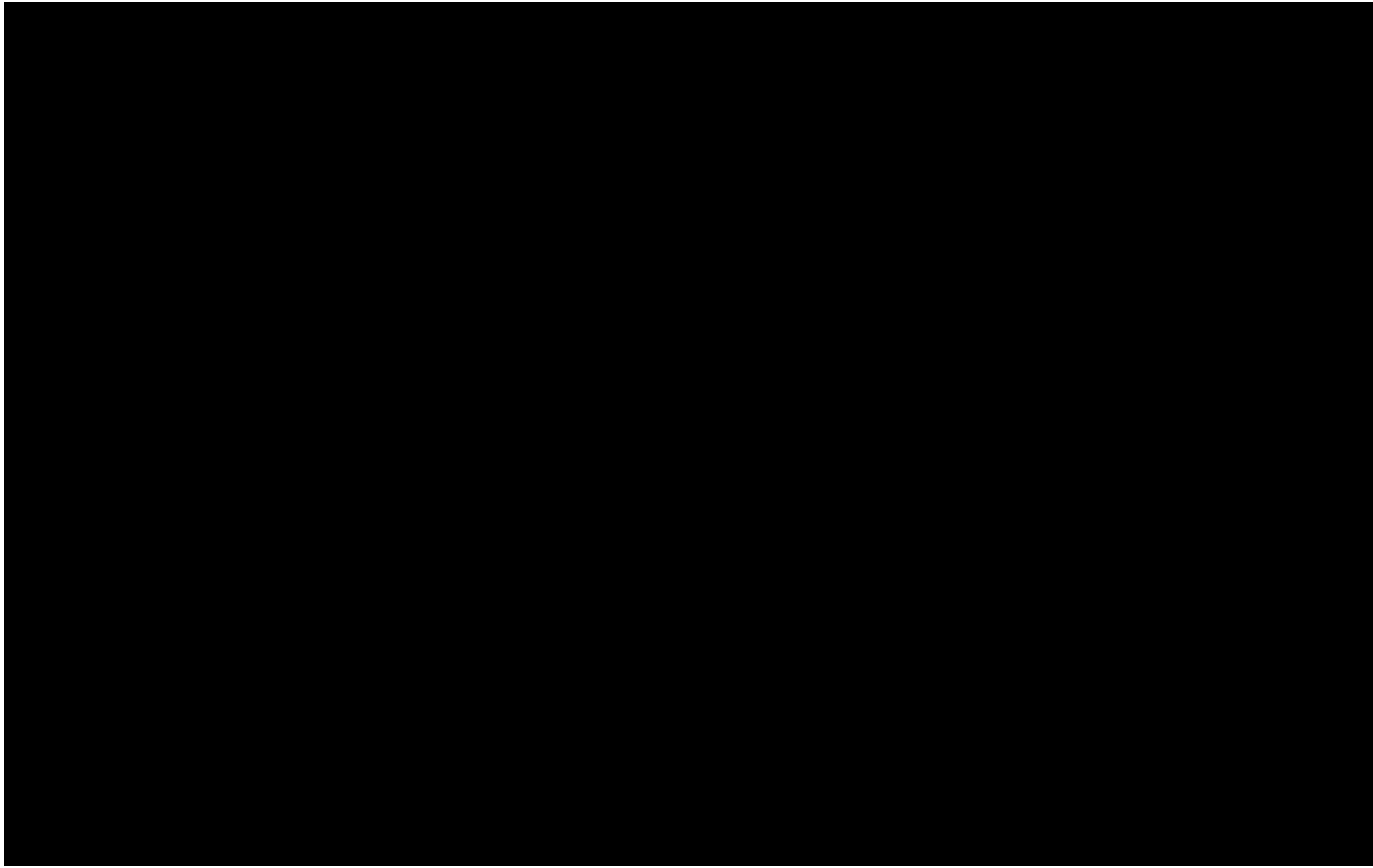
WHAT IS STRING THEORY?

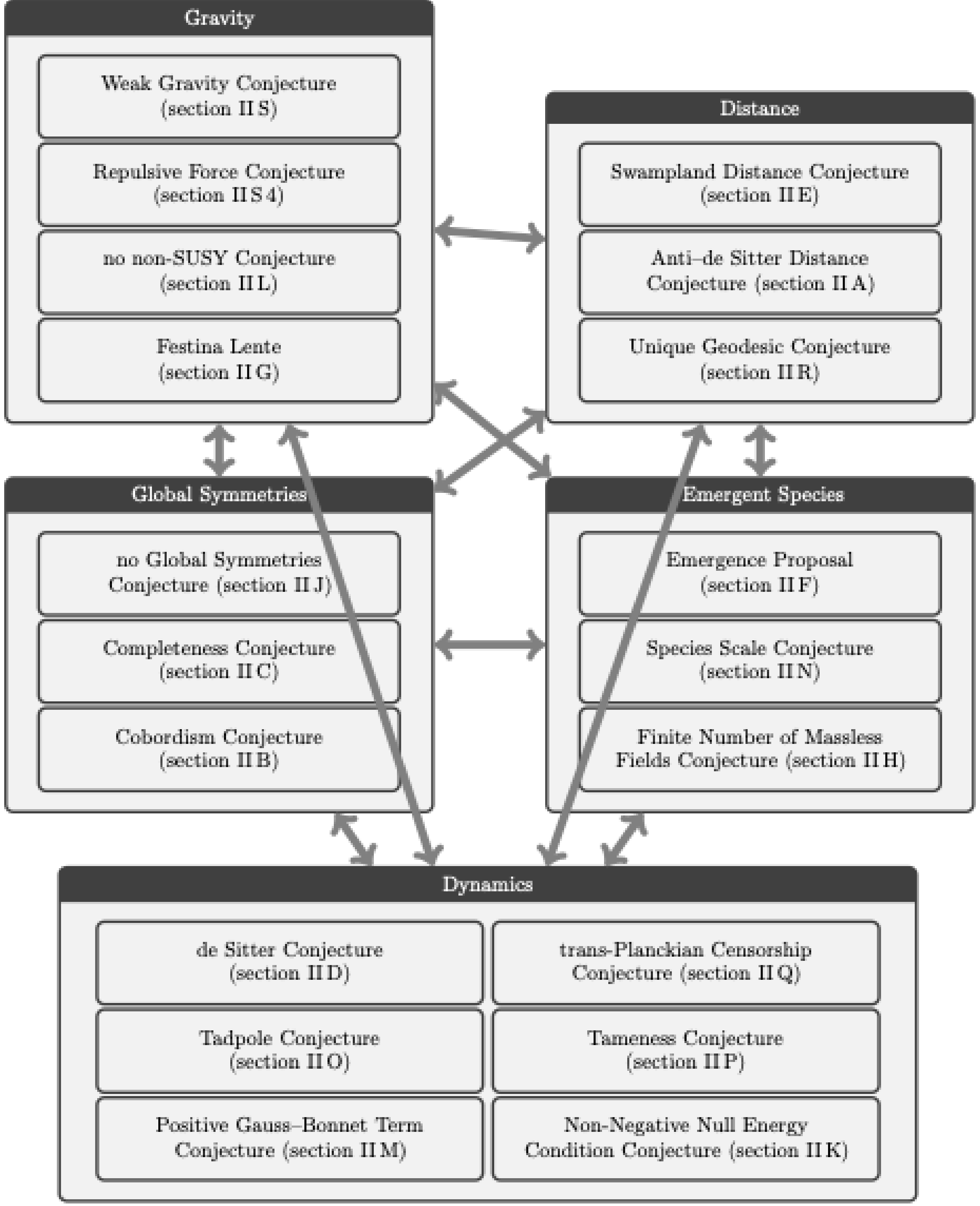


Credits: Deyanira Borisova & Kay Lehnert
https://www.youtube.com/@BeyondLambda

SWAMPLAND CONJECTURES

Disclaimer:

- Swampland Conjectures: Infinite boundary of moduli space
- Cosmology: Deep in the bulk!



WHAT SHOULD WE TALK ABOUT?

Black Holes

Dark Energy

Inflation

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Showing Results

WHAT SHOULD WE TALK ABOUT?

Black Holes

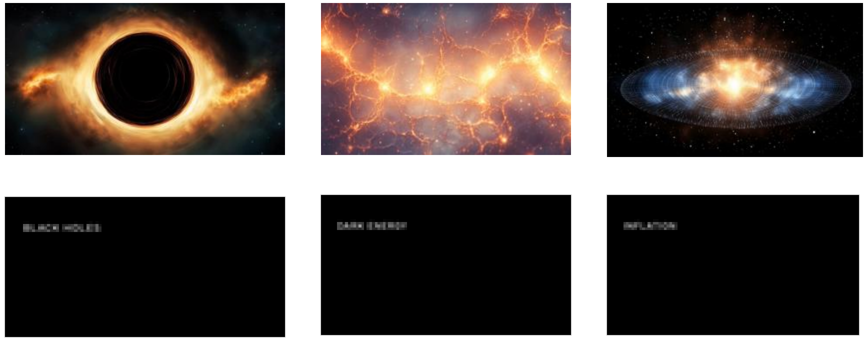
Dark Energy

Inflation

RESULTS SLIDE

WHAT SHALL WE TALK ABOUT?

The implications of the swampland programme for cosmology are diverse.



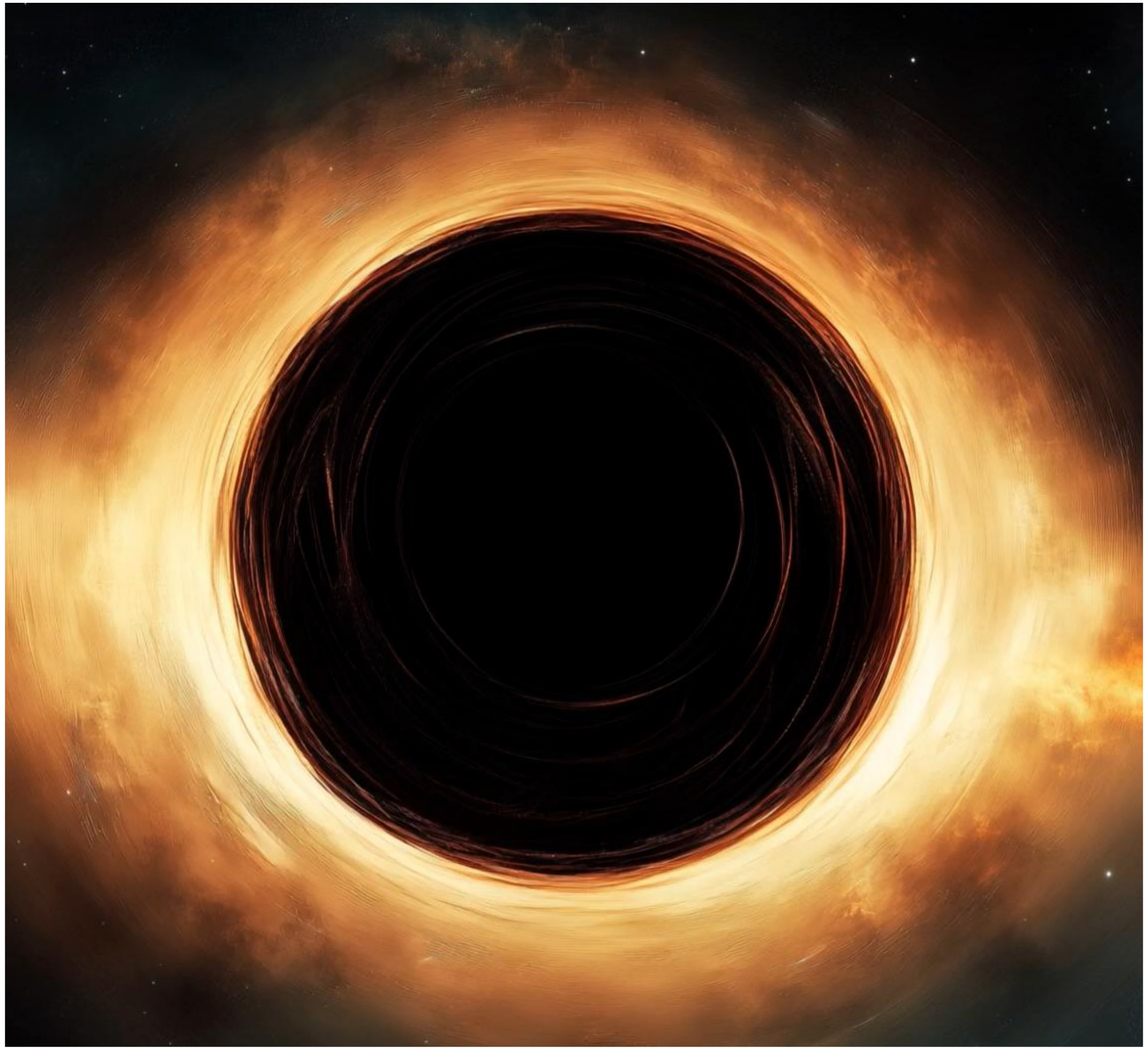
BLACK HOLES

BLACK HOLES...

... decay, because gravity is the weakest force

... fully evaporate, because there are no global symmetries

... have an upper mass limit in de Sitter space, because there are no naked singularities



THE WEAK GRAVITY CONJECTURE

- Gravity is the weakest force
- There is always *a* stable particle, which repulsive gauge force exceeds the attractive gravitational force.

In a theory with a $U(1)$ gauge symmetry and action

$$S = \int \mathrm{d}^d x \sqrt{-g} \left[\left(M_{\mathrm{P}}^d \right)^{d-2} \frac{R^d}{2} - \frac{F^2}{4g^2} + \dots \right],$$

- d the number of dimensions of the EFT
- g the gauge coupling
- M_{P}^d the d-dimensional Planck mass
- R^d the d-dimensional Ricci scalar
- $F^2 = \frac{1}{q!} F_{\mu_1 \dots \mu_q} F^{\mu_1 \dots \mu_q}$ the strength of the gauge field A_ν...
  - e.g. with the relation $F_{\mu\nu} = \frac{1}{2} \partial_{[\mu} A_{\nu]}$

a particle of charge q with mass

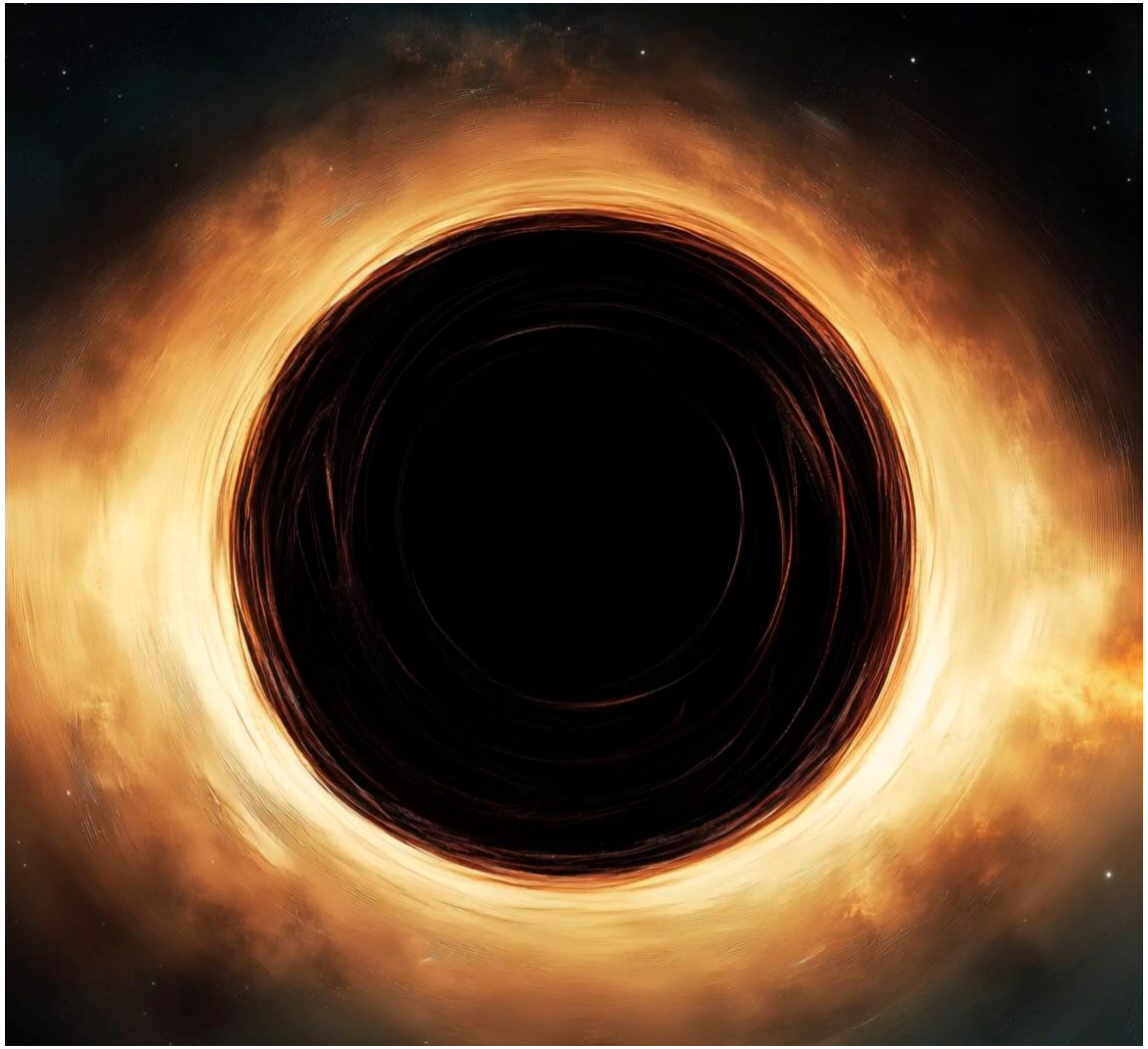
$$m \leq \sqrt{\frac{d-2}{d-3}} g q \left(M_{\mathrm{P}}^d \right)^{\frac{d-2}{2}},$$

exists.

BLACK HOLES DECAY

Assumptions:

- Gravity is the weakest force
- Hawking radiation takes place and is charge-neutral



COBORDISM CONJECTURE

CONJECTURE

The bordism group of QG is trivial.

WHAT IS A (CO)BORDISM?

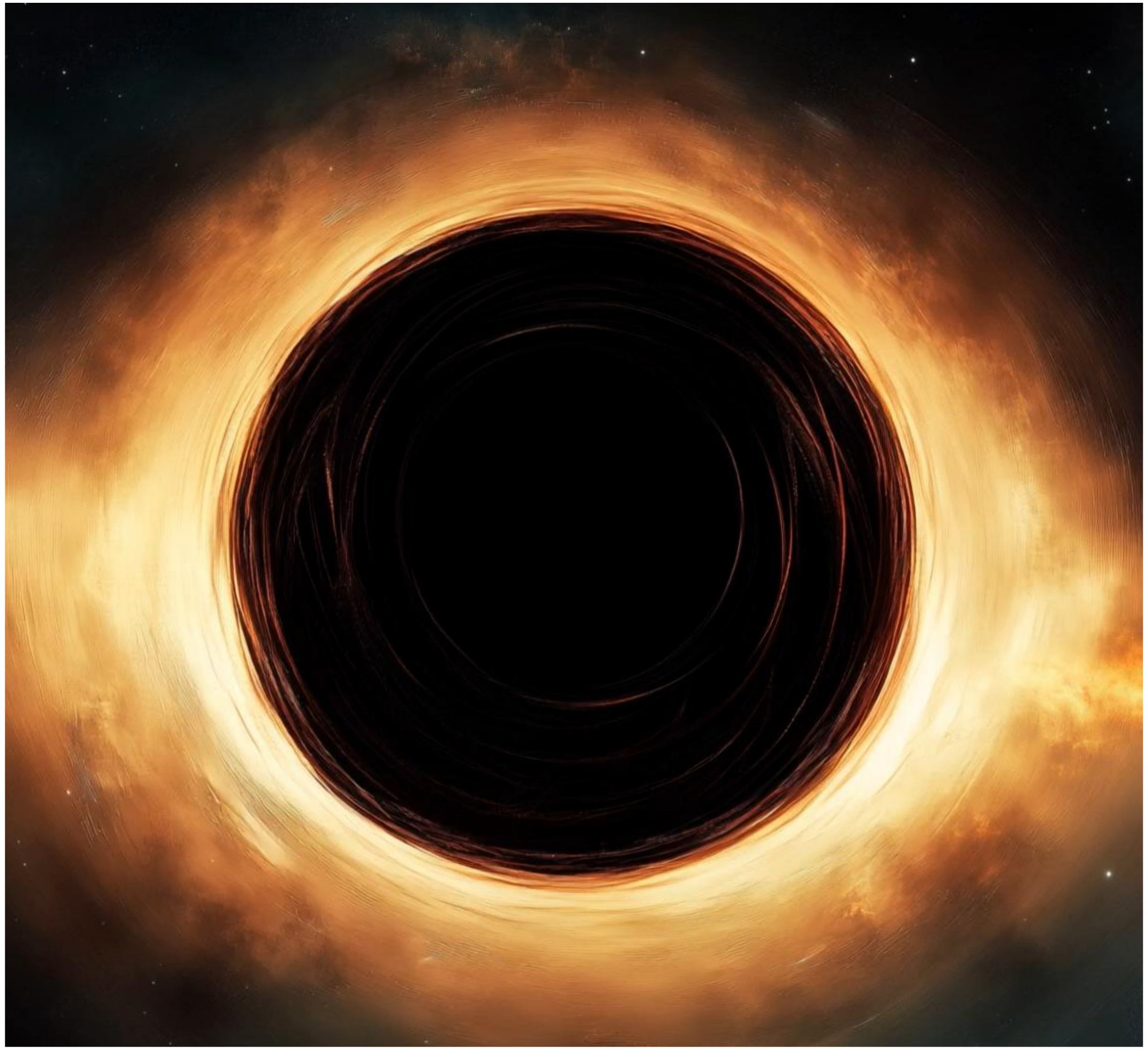
Two compact, d-dimensional manifolds $\mathcal{A}$ and $\mathcal{B}$ are called ***cobordant***, if a $(d+1)$-dimensional compact manifold $\mathcal{W}$ exists (called ***cobordism***), such that $\partial\mathcal{W} = \mathcal{A} \sqcup \mathcal{B}$.

BLACK HOLES FULLY EVAPORATE

Interior of black holes is a compact space that shrinks when black holes evaporate.

Shrinking = Bordism between initial compact space and empty set

➡ Remnants cannot be final state.



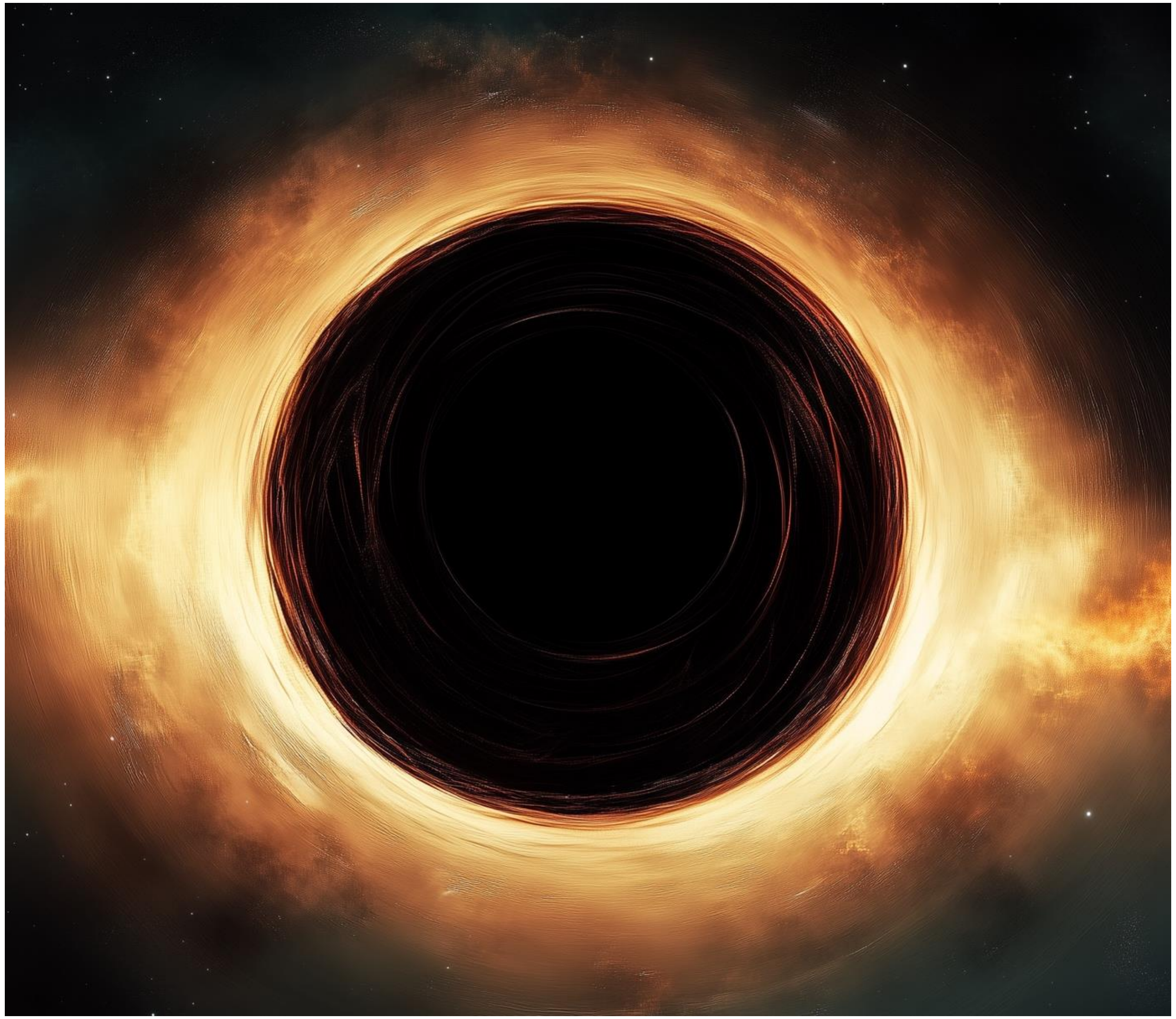
NO GLOBAL SYMMETRIES CONJECTURE

- '*In the presence of gravity, there are no continuous global symmetries*'
- Not really a swampland conjecture, as effective field theories are allowed to have global symmetries—but quantum gravity is not.
    - Global symmetries must be explicitly broken or gauged at high energies.
- Supported by black hole physics,
  and topological / heuristic / worldsheet / holographic / conformal field theories arguments

GLOBAL SYMMETRIES AND BLACK HOLES

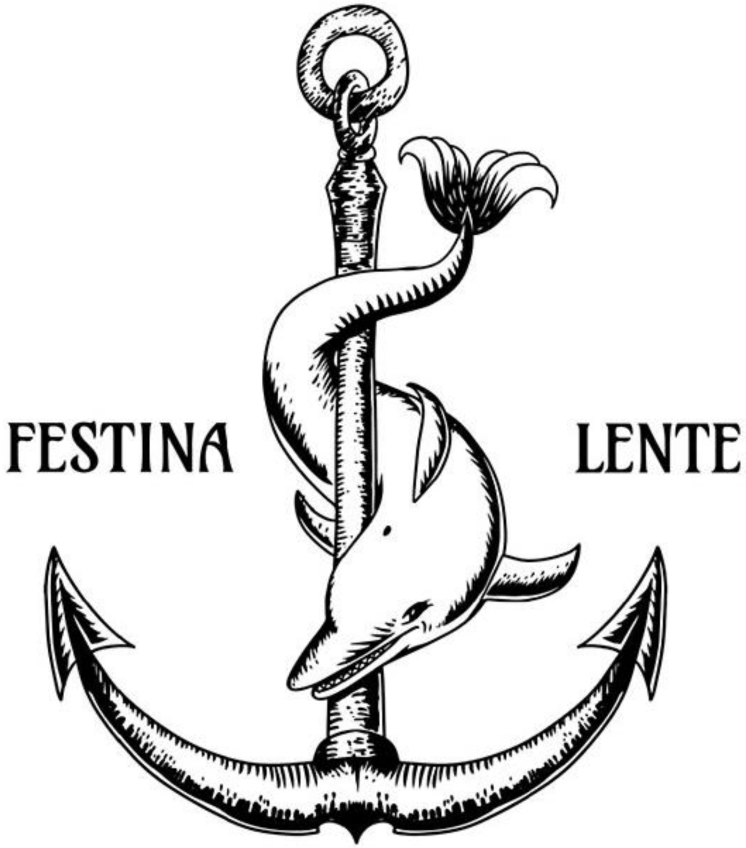
If there are global symmetries…

- … BHs have infinite entropy
- … BHs have hair
- … BHs can be naked singularities



ANOTHER CONJECTURE AGAINST NAKED SINGULARITIES

- σπεῦδε βραδέως
- Eile mit Weile
- Hasten Slowly



FESTINA LENTE

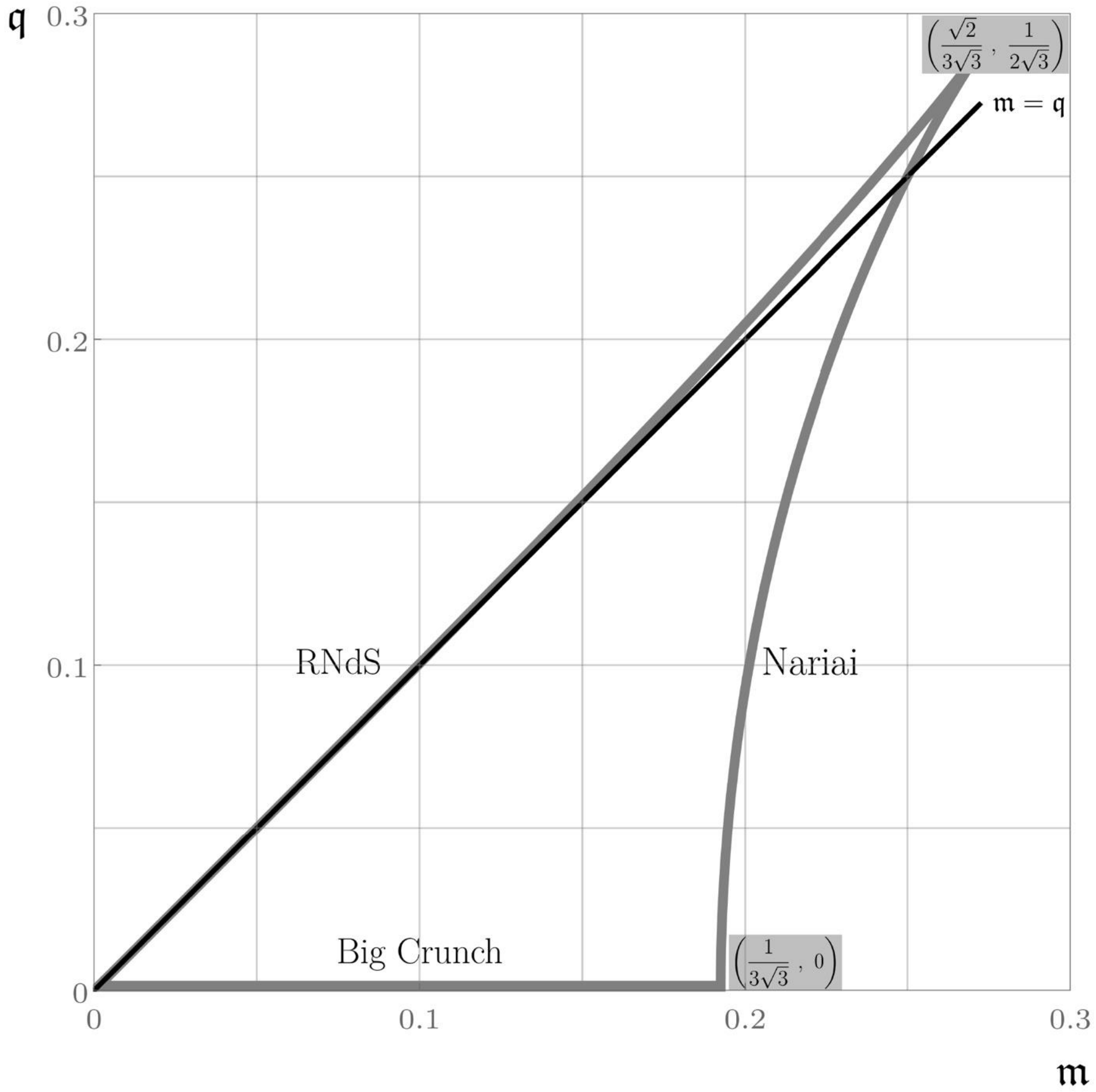
$$m^4 \gtrsim 6\,(gqM_\mathsf{P}H)^2$$

BLACK HOLES HAVE A SIZE LIMIT

The FLB assures that no naked singularities are revealed while the BH evaporates.

It also assures that a BH remains smaller than the cosmological horizon.

- $m < \dfrac{8\pi}{\hbar c l_{\mathrm{P}}^2 3\sqrt{3}}$ for a neutral BH
- $m < \sqrt{2}\dfrac{8\pi}{\hbar c l_{\mathrm{P}}^2 3\sqrt{3}}$ for a maximally charged BH



BLACK HOLES IN THE SWAMPLAND

CONJECTURES

- Weak Gravity Conjecture
  - Gravity is the weakest force
- No Global Symmetries Conjecture
  - There are no global symmetries in QG
- Cobordism Conjecture
  - There is only one theory of quantum gravity
- Festina Lente
  - Horizons don't leak out of their de Sitter patch

PREDICTIONS FOR BLACK HOLES

- No naked singularities
- Black holes decay
- Size / mass limit

DISCLAIMER

Swampland Conjectures: Infinite boundary of moduli space

Cosmology: Deep in the bulk!

DARK ENERGY

DARK ENERGY…

… is positive today $\Lambda_0 > 0$ (nnSUSYC)

… cannot be a constant (dSC)

… has a maximum field range (DC)

… has an $\omega \geq -1$ (nnNECC)

… has a lower bound on interactions (WGC)

… has an absolute upper bound (FLB)

NO NON-SUSY CONJECTURE

There are no non-supersymmetric stable anti–de Sitter vacuum solutions in 4d.

$\Lambda_0 \geq 0$

- If there are no (meta-)stable anti-de Sitter vacua, the cosmological constant is either positive or zero
  - Either we live in de Sitter space or in Minkowski space, or dark energy is dynamical.

DE SITTER CONJECTURE

There are no (meta-)stable de Sitter vacua in string theory.

Eq. (1) rules out local maxima and saddle points and is violated by the Higgs field.

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_{\mathrm{P}}} \qquad (1)$$

$$\frac{\min\left(\nabla_i \nabla_j V\right)}{V} \leq -\frac{c'}{M_{\mathrm{P}}^2} \qquad (2)$$

Λ AND THE DE SITTER CONJECTURE

- Since $V'' = \nabla V = 0 \not> 0$, $\Lambda =$ cst. is incompatible
- Quintessence, k-essence, Axions, … are all constrained by observations and eqs. 1 & 2

LIMITED LIFETIME OF DS PHASE (TPCC)

- The trans-Planckian Censorship Conjecture forbids trans-Planckian quantum fluctuations to classicalise by expanding. What is quantum remains quantum.

- $\frac{a_\mathrm{f}}{a_\mathrm{i}} < \frac{M_\mathrm{P}}{H_\mathrm{f}}$

- This limits the lifetime of meta-stable dS phases: $\tau < \frac{1}{H_\mathrm{f}} \log \frac{M_P}{H_\mathrm{f}}$

- and constrains scalar field potentials in the asymptotic limit of moduli space:

  $\left.\frac{|\nabla V|}{V}\right|_\mathrm{asympt} \geq \frac{2}{\sqrt{(d-1)(d-2)}}.$

DISTANCE CONJECTURE

In a theory that couples to gravity, with a moduli space $\mathcal{M}$ parametrised by the expectation values of a scalar field $\phi \in \mathcal{M}$ with no potential,

$$\forall \phi \in \mathcal{M} \, \exists \, \phi_{\mathrm{b}} \in \partial \mathcal{M}$$

such that the geodesic distance $d(\phi, \phi_{\mathrm{b}})$ between ϕ_{b} on the boundary and ϕ in the bulk is infinite, and that there is an infinite tower of states with an associated mass scale m, where

$$m(\phi) \sim m(\phi_0) \exp(-\alpha d(\phi, \phi_0)),$$

where ϕ_0 is sufficiently far away from ϕ and $\alpha \sim \mathcal{O}(1)$

APPLICATION OF DISTANCE CONJECTURE

$$\frac{\Delta\phi}{M_{\mathrm{P}}} \lesssim \mathcal{O}(1)$$

NON-NEGATIVE NULL ENERGY CONDITION CONJECTURE

- The Null Energy Condition (NEC) states that parallel lines do not cross: $T_{\mu\nu} l^{\mu} l^{\nu} \geq 0$
- Promoted to a swampland conjecture, it limits the DE EoS to $\omega \geq -1$

THE WEAK GRAVITY CONJECTURE

- Gravity is the weakest force
- There is always *a* stable particle, which repulsive gauge force exceeds the attractive gravitational force.

In a theory with a $U(1)$ gauge symmetry and action

$$S = \int \mathrm{d}^d x \sqrt{-g} \left[\left(M_\mathrm{P}^d\right)^{d-2} \frac{R^d}{2} - \frac{F^2}{4g^2} + \ldots \right],$$

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a particle of charge q with mass

$$m \leq \sqrt{\frac{d-2}{d-3}} g q \left(M_\mathrm{P}^d\right)^{\frac{d-2}{2}},$$

exists.

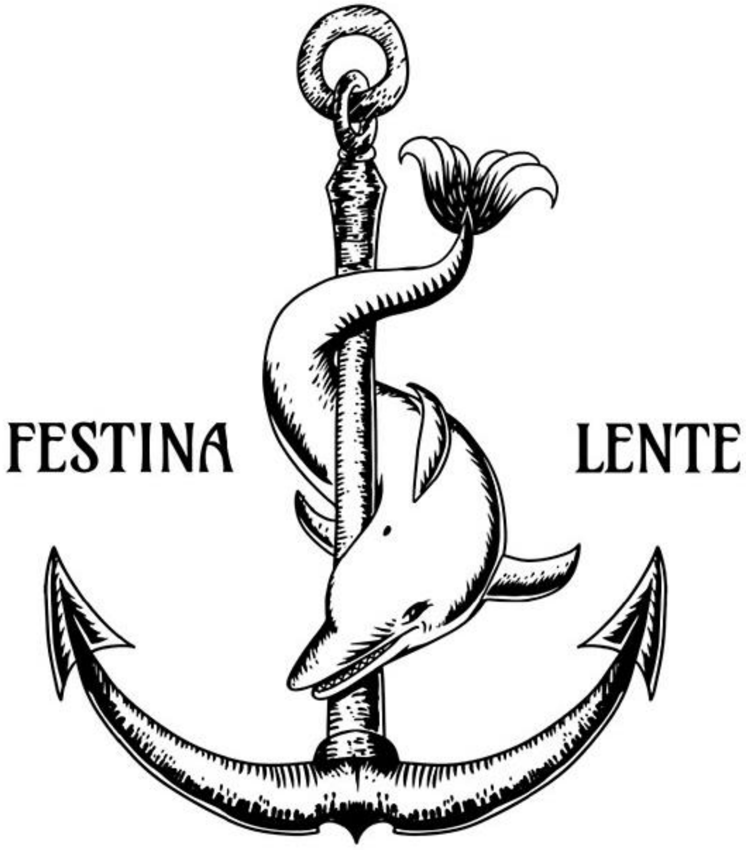
THE SCALAR WGC

- Every scalar interaction is stronger than the gravitational interaction:

$$\frac{1}{M_\mathrm{P}^2}\left(\frac{\mathrm{d}^2 V}{\mathrm{d}\phi^2}\right)^2 \leq 2\left(\frac{\mathrm{d}^3 V}{\mathrm{d}\phi^3}\right)^2 - \frac{\mathrm{d}^2 V}{\mathrm{d}\phi^2}\frac{\mathrm{d}^4 V}{\mathrm{d}\phi^4}$$

FESTINA LENTE

- σπεῦδε βραδέως
- Eile mit Weile
- Hasten Slowly



FESTINA LENTE

$$\Lambda \lesssim \frac{m^4}{4\pi\alpha} \sim 3 \times 10^{-89}$$

DARK ENERGY AND THE SWAMPLAND

CONJECTURES

- no non-supersymmetric Theories Conjecture
  - There are no stable non-SUSY 4d AdS vacua
- de Sitter Conjecture
  - dS is unstable
- Distance Conjecture
  - Field ranges are sub-Planckian
- non-negative NEC Conjecture
  - The NEC is not violated in 4d EFTs
- Weak Gravity Conjecture
  - Gravity is the weakest force
- Festina Lente
  - Horizons don't leak out of their dS patch

IMPLICATIONS

$\Lambda_0 \geq 0$

$\Lambda \neg$cst.

$\Delta\varphi < M_P$

$\omega \geq -1$

$V(\phi)$ constrained

$\Lambda < 10^{-89}$

DISCLAIMER

Swampland Conjectures: Infinite boundary of moduli space

Cosmology: Deep in the bulk!

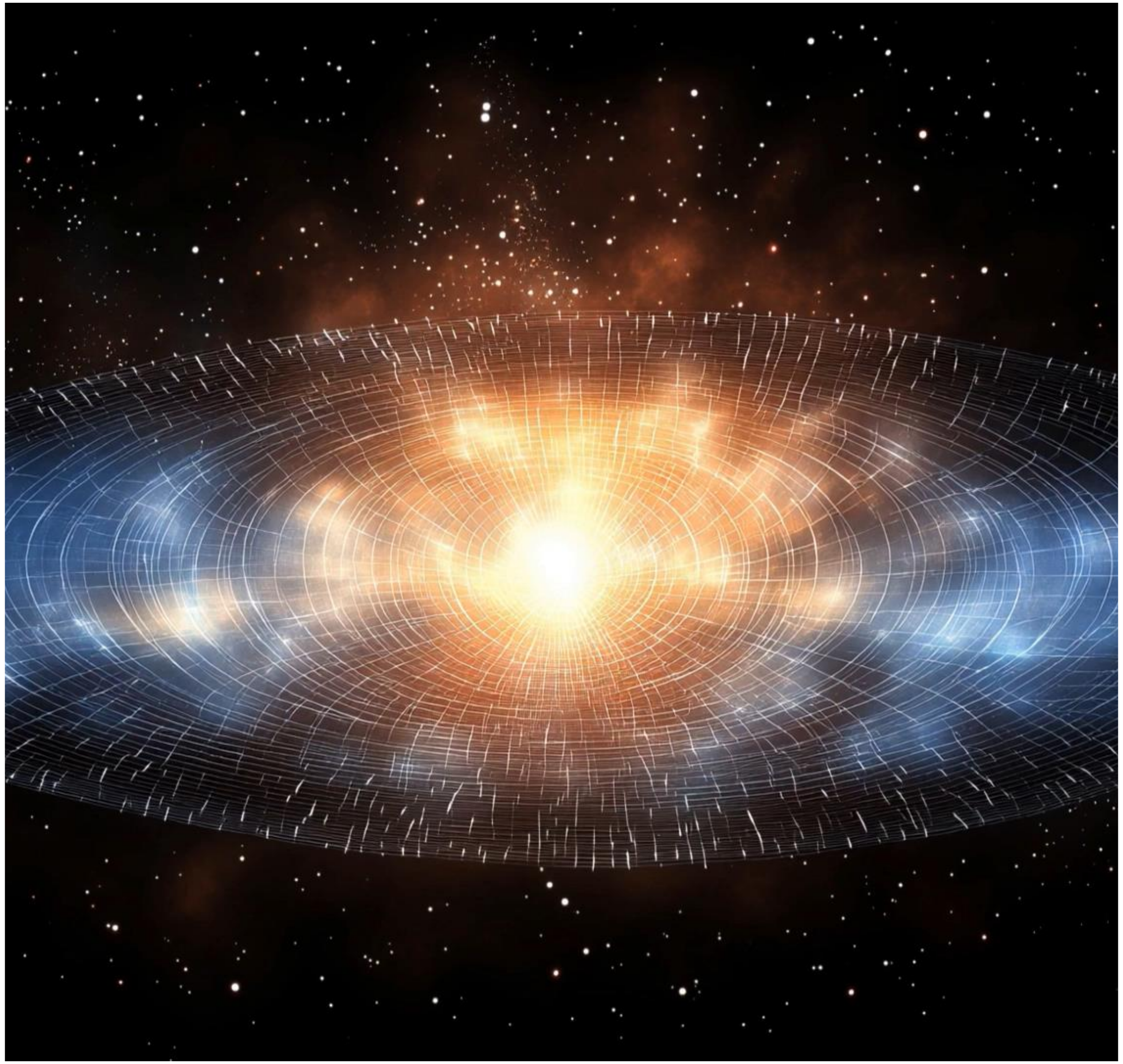
INFLATION

INFLATION...

… has a limited inflaton field displacement (DC, SSC, WGC)

… is not eternal (dSC, DC, Finiteness, TCC, UGC)

… is not a single, slow-rolling field (dSC, TCC)



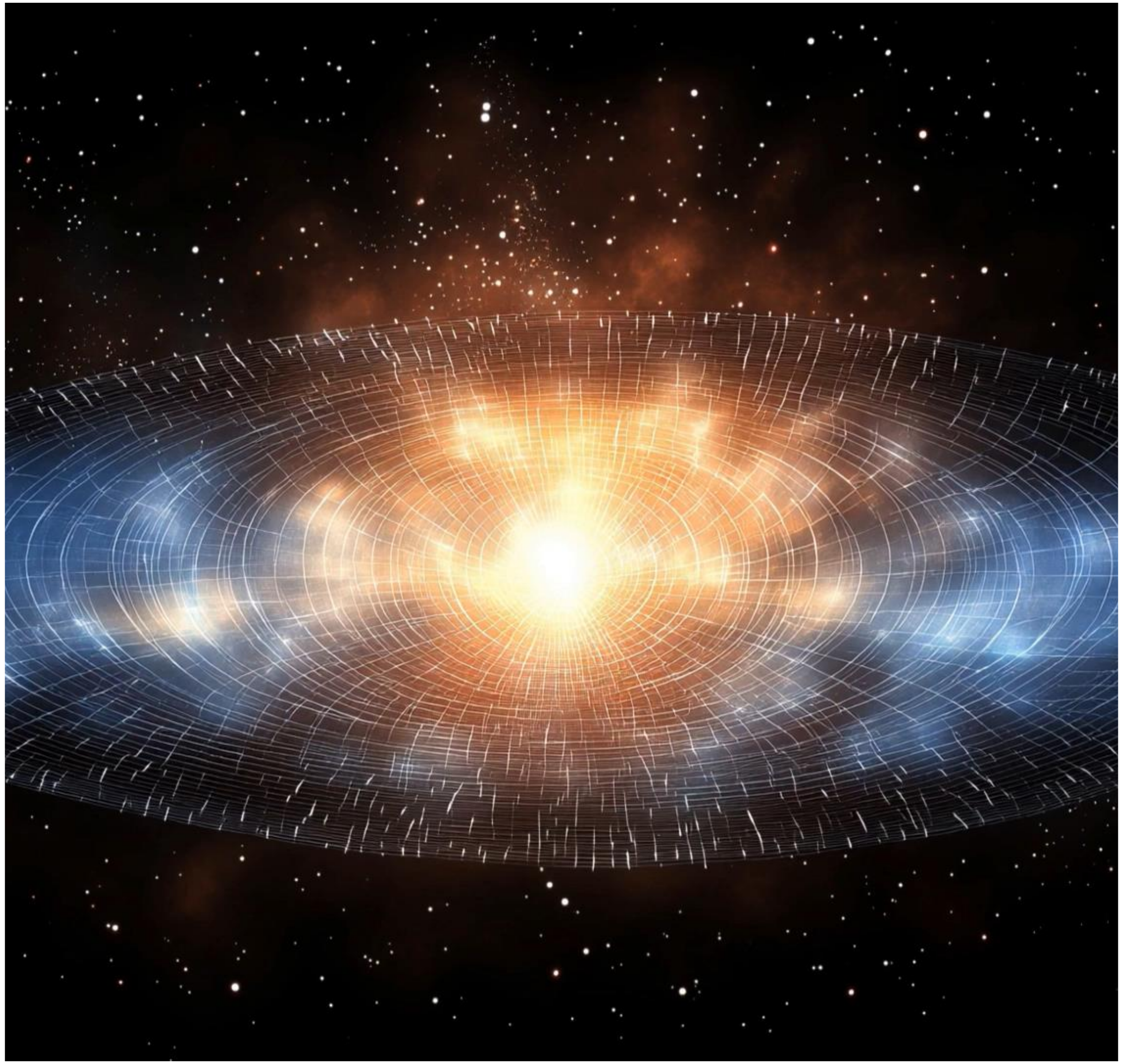
THE SCALAR WEAK GRAVITY CONJECTURE

- Every scalar interaction is stronger than the gravitational interaction:

$$\frac{1}{M_{\mathrm{P}}^2}\left(\frac{\mathrm{d}^2 V}{\mathrm{d}\phi^2}\right)^2 \leq 2\left(\frac{\mathrm{d}^3 V}{\mathrm{d}\phi^3}\right)^2 - \frac{\mathrm{d}^2 V}{\mathrm{d}\phi^2}\frac{\mathrm{d}^4 V}{\mathrm{d}\phi^4}$$

INFLATION AND THE WGC

Large-field inflation is in tension with the Weak Gravity Conjecture



DISTANCE CONJECTURE

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such that the geodesic distance $d(\phi,\phi_{\mathrm{b}})$ between ϕ_{b} on the boundary and ϕ in the bulk is infinite, and that there is an infinite tower of states with an associated mass scale m, where

$$m(\phi) \sim m(\phi_0) \exp(-\alpha d(\phi,\phi_0)),$$

where ϕ_0 is sufficiently far away from ϕ and $\alpha \sim \mathcal{O}(1)$

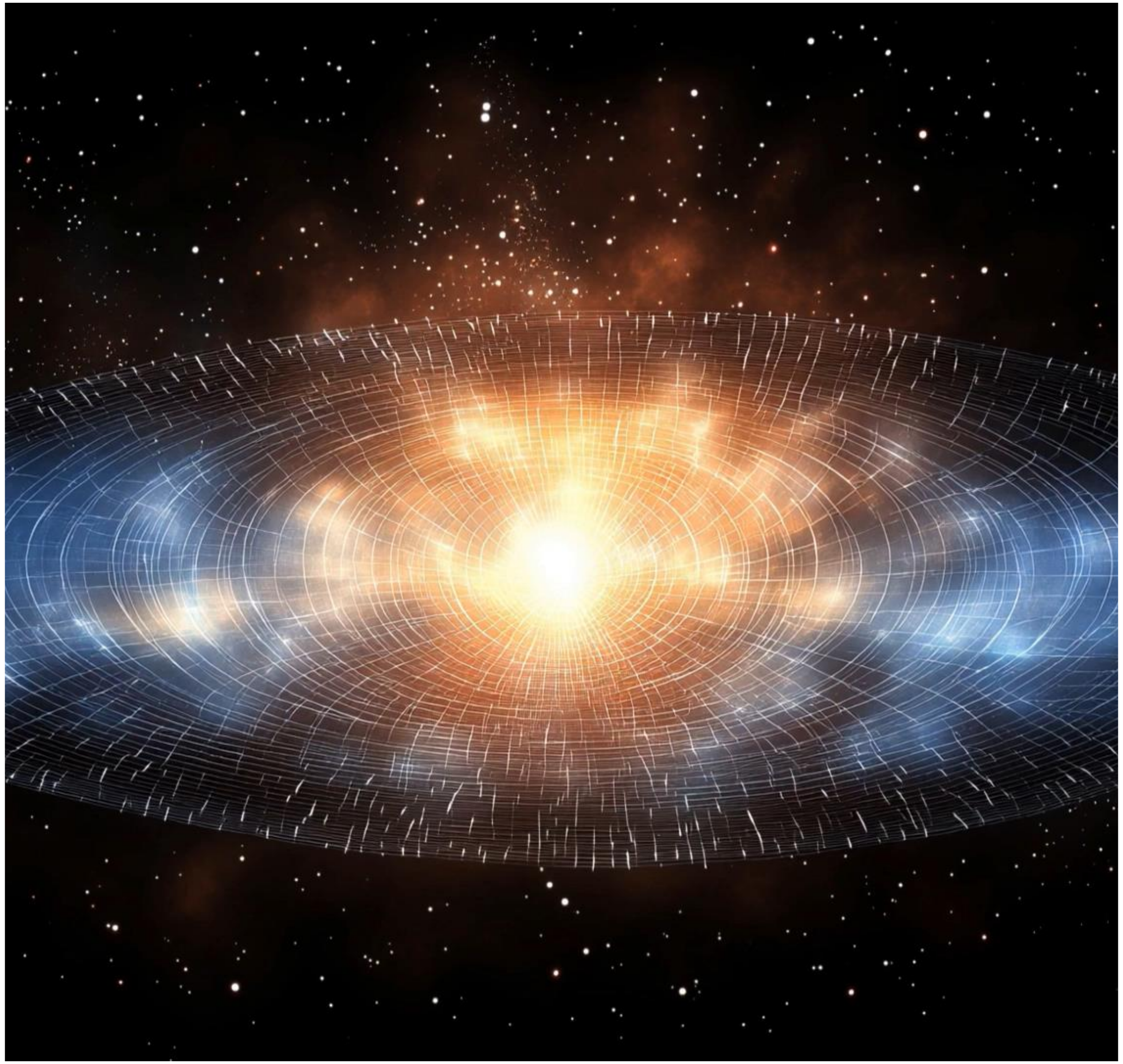
APPLICATION OF DISTANCE CONJECTURE

$$\frac{\Delta\phi}{M_{\mathsf{P}}} \lesssim \mathcal{O}(1)$$

INFLATION AND THE DISTANCE CONJECTURE

The inflaton field range is limited, i.e. large-field inflation models are challenged.

Eternal inflation is incompatible with the DC.

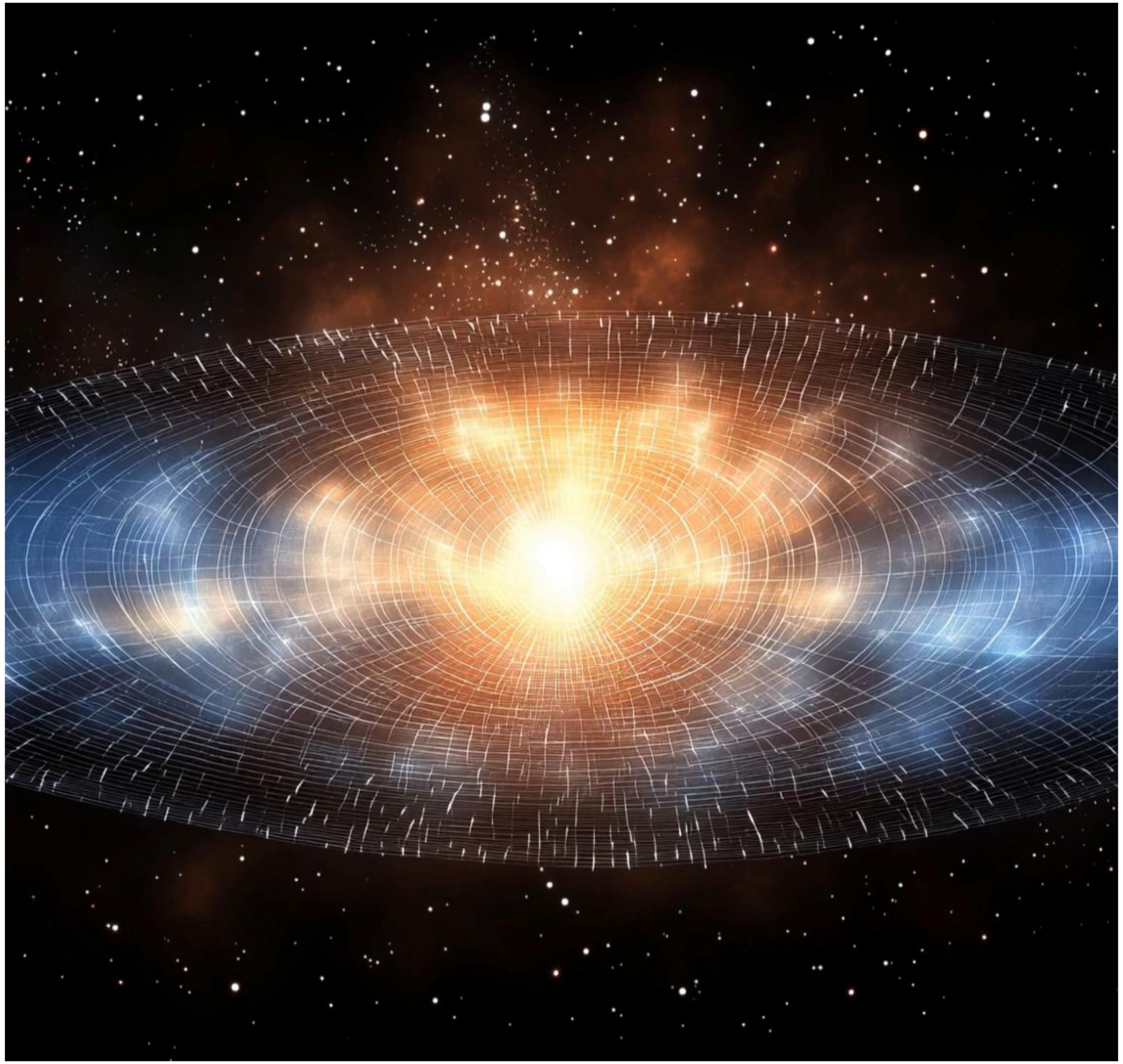


UNIQUE GEODESIC CONJECTURE

- A *marked* moduli space has at most one geodesic between any two points and exactly one shortest path, which is piece-wise geodesic, between any pair of points that are separated by a finite distance.
- This implies that a marked moduli space is contractible, and that there is at most one geodesic between each pair of points at asymptotically infinite distance, i.e. if there is a geodesic between two points, this geodesic is unique.

INFLATION AND THE UGC

Eternal inflation requires non-trivial cycles through moduli space, which is incompatible with a non-contractible space with unique geodesics.



FINITE NUMBER OF MASSLESS FIELDS CONJECTURE

The number of massless fields that appear in a d-dimensional EFT, which is coupled to (Einstein) gravity, is finite.

A strict reading implies a finite volume for moduli space

- Finite action
- Finite lifetime & spatial compactness

- Number of inflaton fields is finite
- Finiteness of action rules out:
  - Eternal inflation
  - Ekpyrotic Scenario
  - Cyclic Models
  - Bounce Cosmologies

DE SITTER CONJECTURE

There are no (meta-)stable de Sitter vacua in string theory.

Eq. (1) rules out local maxima and saddle points and is violated by the Higgs field.

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_{\mathrm{P}}} \qquad (1)$$

$$\frac{\min\left(\nabla_i \nabla_j V\right)}{V} \leq -\frac{c'}{M_{\mathrm{P}}^2} \qquad (2)$$

INFLATION AND THE DE SITTER CONJECTURE

Eternal inflation violates the dSC.

$$\langle \delta\phi \rangle_{\mathrm{q}} \approx \frac{H}{2\pi}$$

$$\langle \delta\phi \rangle_{\mathrm{c}} \approx \frac{|\dot{\phi}|}{H}$$

$$\frac{\langle \delta\phi \rangle_{\mathrm{q}}}{\langle \delta\phi \rangle_{\mathrm{c}}} = \frac{H^2}{2\pi|\dot{\phi}|} \gtrsim 1$$

$$\Leftrightarrow \frac{H}{M_{\mathrm{P}}} \gtrsim 2\pi\sqrt{2\epsilon_V}$$

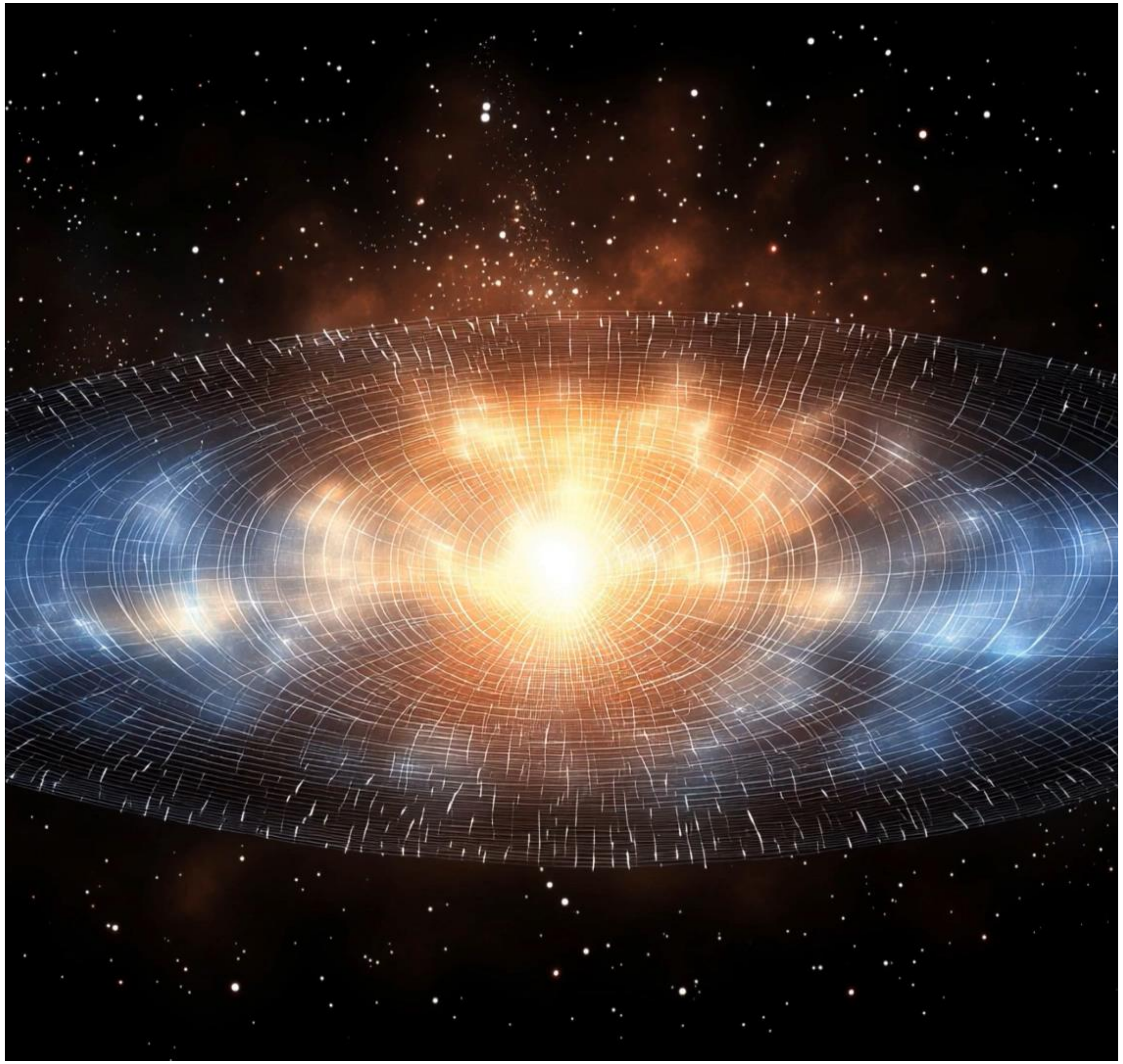
INFLATION AND THE DE SITTER CONJECTURE

$$\epsilon_V := \frac{(\nabla V)^2}{V^2} \geq c^2$$

$$\eta_V \sim \frac{\nabla^2 V}{V} \lesssim -c'$$

$$\epsilon_H = -\frac{\dot{H}}{H^2}$$

$$\eta_H = \frac{\dot{\epsilon}_H}{H \epsilon_H}$$



THE TRANS-PLANCKIAN CENSORSHIP CONJECTURE

- The trans-Planckian Censorship Conjecture forbids trans-Planckian quantum fluctuations to classicalise by expanding. What is quantum remains quantum.

- $\frac{a_\mathrm{f}}{a_\mathrm{i}} < \frac{M_\mathrm{P}}{H_\mathrm{f}}$
- This constrains scalar field potentials in the asymptotic limit of moduli space:

$$\frac{|\nabla V|}{V}\bigg|_{\mathrm{asympt}} \geq \frac{2}{\sqrt{(d-1)(d-2)}}.$$

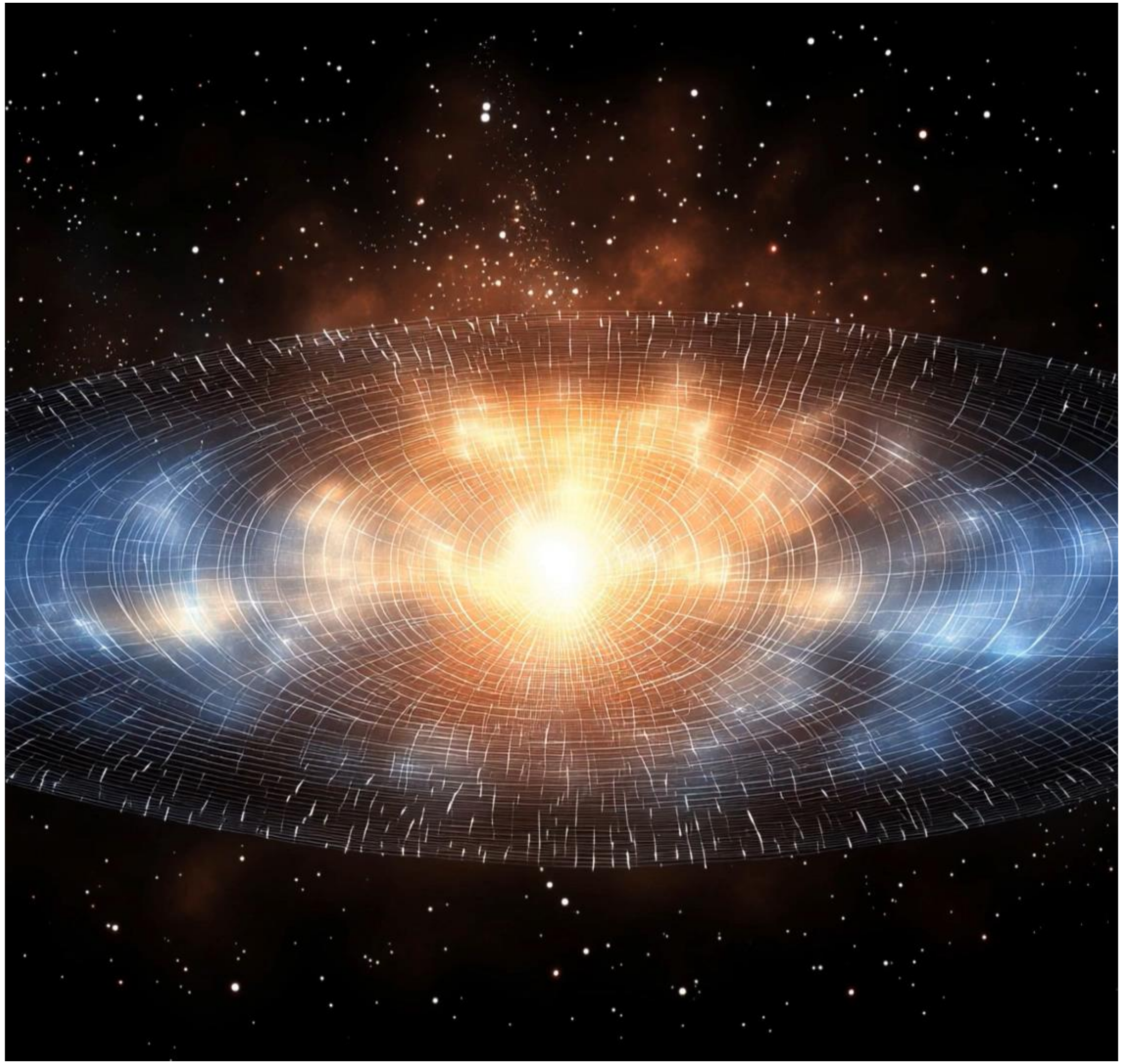
INFLATION AND THE TCC

Instant reheating and constant Hubble parameter during inflation:

- $V^{1/4} < 10^9$ GeV
- $r_{ts} < 10^{-31}$

Giving reheating some time and a dynamical Hubble parameter:

- $V^{1/4} < 10^{14}$ GeV
- $r_{ts} < 10^{-8}$



WHAT KIND OF INFLATION WORKS?

Kinetic Inflation

Warm Inflation

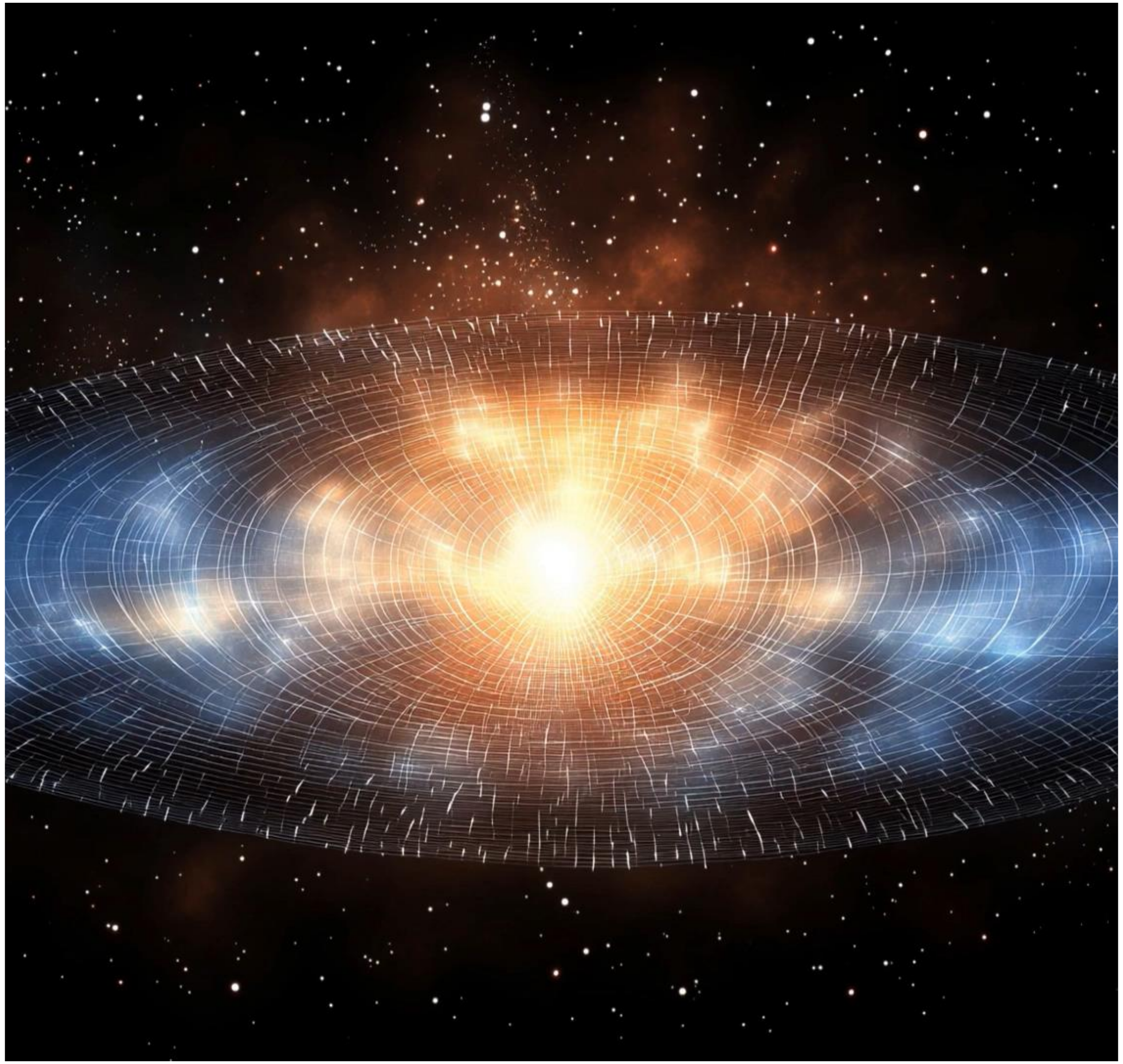
Multi-field inflation

Braneworlds

Modified Gravity

String Gas Cosmology

…



INFLATION AND THE SWAMPLAND

CONJECTURES

- de Sitter Conjecture
  - dS is unstable
- Distance Conjecture
  - Field ranges are sub-Planckian
- Weak Gravity Conjecture
- Unique Geodesic Conjecture
- Finite Number of Massless Fields Conjecture
- Trans-Planckian Censorship Conjecture
  - What is quantum, remains quantum

IMPLICATIONS

- No large single-field slow-roll inflation
- No eternal inflation
- Potentials and field ranges constrained

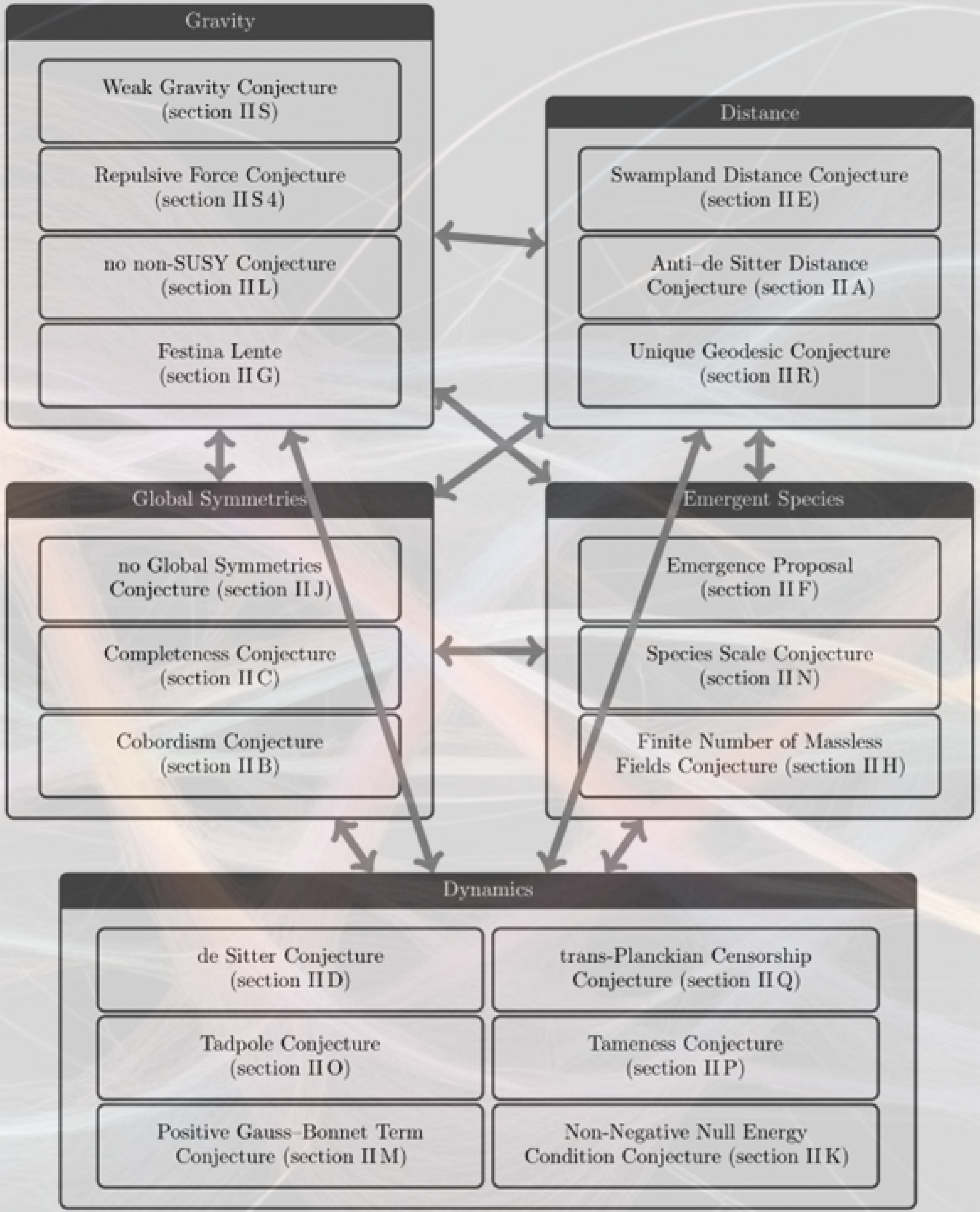
DISCLAIMER

Swampland Conjectures: Infinite boundary of moduli space

Cosmology: Deep in the bulk!

THANK YOU!

- I am thankful for
  - Your attention
  - The opportunity to present here
  - the support by
    - The Friedrich Naumann Foundation for Freedom and the Bundesministerium für Forschung, Technologie und Raumfahrt
    - John and Pat Hume
    - The Swiss Study Foundation



Gravity
Weak Gravity Conjecture (section II S)
Repulsive Force Conjecture (section II S 4)
no non-SUSY Conjecture (section II L)
Festina Lente (section II G)
Distance
Swampland Distance Conjecture (section II E)
Anti–de Sitter Distance Conjecture (section II A)
Unique Geodesic Conjecture (section II R)
Global Symmetries
no Global Symmetries Conjecture (section II J)
Completeness Conjecture (section II C)
Cobordism Conjecture (section II B)
Emergent Species
Emergence Proposal (section II F)
Species Scale Conjecture (section II N)
Finite Number of Massless Fields Conjecture (section II H)
Dynamics
de Sitter Conjecture (section II D)
trans-Planckian Censorship Conjecture (section II Q)
Tadpole Conjecture (section II O)
Tameness Conjecture (section II P)
Positive Gauss–Bonnet Term Conjecture (section II M)
Non-Negative Null Energy Condition Conjecture (section II K)

FURTHER REMARKS ON THE DE SITTER CONJECTURE

DE SITTER CONJECTURE

There are no (meta-)stable de Sitter vacua in string theory.

Eq. (1) rules out local maxima and saddle points and is violated by the Higgs field.

Eq. (3) combines the constraints into one inequality.

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_{\mathrm{P}}} \qquad (1)$$

$$\frac{\min(\nabla_i \nabla_j V)}{V} \leq -\frac{c'}{M_{\mathrm{P}}^2} \qquad (2)$$

$$\left(M_{\mathrm{P}} \frac{|\nabla V|}{V}\right)^{\alpha} - k M_{\mathrm{P}}^2 \frac{\min(\nabla_i \nabla_j V)}{V} \geq b \qquad (3)$$

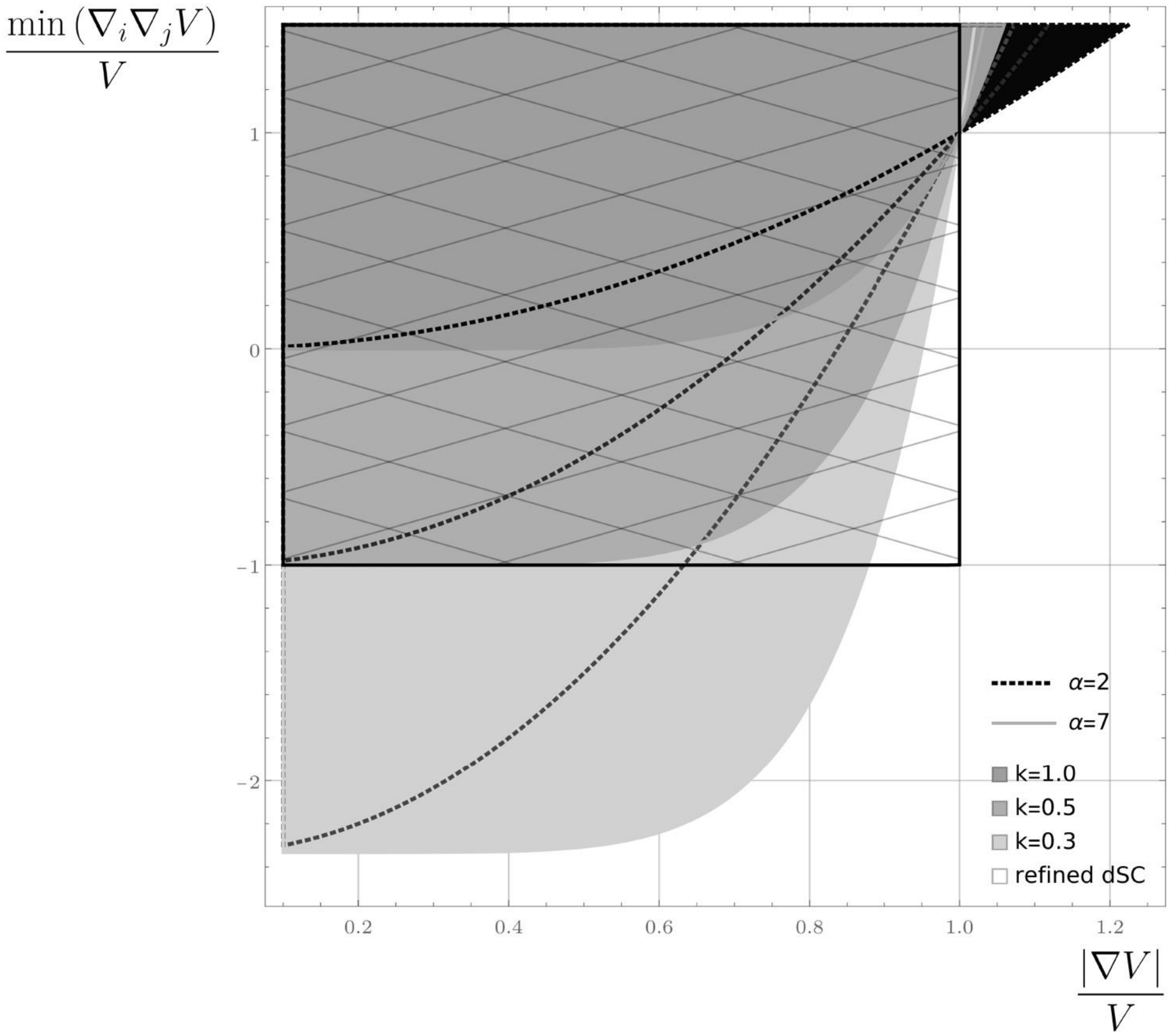
THE COMBINED DSC

$$c \sim \mathcal{O}(1)$$
$$c' \sim \mathcal{O}(1)$$
$$\alpha > 2$$
$$k > 0$$
$$b > 0$$
$$k + b = 1$$
$$c^{\alpha} + k\,(1 + c') > 1$$

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_{\mathrm{P}}} \qquad (1)$$

$$\frac{\min\left(\nabla_i \nabla_j V\right)}{V} \leq -\frac{c'}{M_{\mathrm{P}}^2} \qquad (2)$$

$$\left(M_{\mathrm{P}} \frac{|\nabla V|}{V}\right)^{\alpha} - k M_{\mathrm{P}}^2 \frac{\min\left(\nabla_i \nabla_j V\right)}{V} \geq b \qquad (3)$$



DE SITTER CONJECTURE

- No rigorous proofs
- No undisputed counterexamples
- Arguments that it might not apply to 4d

WHICH OBSERVABLES WOULD INDICATE AN UNSTABLE DE SITTER SPACE?

- Exactly stable dS space does not allow for precisely measurable observables.
- The (1σ) signature of a cascade of dS decays is claimed to be found in the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) data set for the following model:
  - The lifetime of inflation is limited by the TCC to int H dt < log (MP/H).
  - The lifetime of dS space during inflation is limited by the TCC to $\Delta t < 1/H * \log (MP/H)$.
  - A cascade of first-order phase transitions produces gravitational waves at different frequencies, which are subsequently redshifted by the dS expansions of the following short-lived phases of inflation of the cascade. This leads to a stochastic gravitational wave background with a red-tilt, which is compatible with the NANOGrav results at the 1σ level.

VALUES OF C AND C'

c

- DESI indicates $c \gtrsim \mathcal{O}(1)$
- $\frac{\|\nabla V\|}{V} \geq \frac{2}{\sqrt{d-2}}$ holds in the asymptotic limit of every known string theory
- $c \geq 2/\sqrt{(d-1)(d-2)}$ from the TCC and Hodge theory

c'

- ${c'}^2 = -V''/V \gtrsim \mathcal{O}(1)$ is required to have a concave potential with a lower bound on the curvature.
- $c' \sim \mathcal{O}(1)$ because of DC:

$$M_{\mathrm{P}}^2 \frac{\nabla_j \nabla_j V}{V} \sim -\frac{M_{\mathrm{P}}^2}{(\Delta\phi)^2} \leq -\mathcal{O}(1).$$

FURTHER REMARKS ON
THE DISTANCE CONJECTURE

DISTANCE CONJECTURE

In a theory that couples to gravity, with a moduli space $\mathcal{M}$ parametrised by the expectation values of a scalar field $\phi \in \mathcal{M}$ with no potential,

$$\forall \phi \in \mathcal{M} \; \exists \; \phi_{\mathrm{b}} \in \partial\mathcal{M}$$

such that the geodesic distance $d(\phi, \phi_{\mathrm{b}})$ between ϕ_{b} on the boundary and ϕ in the bulk is infinite, and that there is an infinite tower of states with an associated mass scale m, where

$$m(\phi) \sim m(\phi_0) \exp(-\alpha d(\phi, \phi_0)),$$

where ϕ_0 is sufficiently far away from ϕ and $\alpha \sim \mathcal{O}(1)$

APPLICATION OF DISTANCE CONJECTURE

$$\frac{\Delta\phi}{M_{\mathsf{P}}} \lesssim \mathcal{O}(1)$$

WHAT DOES IT MEAN TO *INTEGRATE OUT* A STATE?

$$L \sim \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\varphi)^2 + m^2(\phi)\varphi^2$$

$$\phi = \langle\phi\rangle + \delta\phi$$

$$\frac{1}{2}m^2(\phi)\varphi^2 = \frac{1}{2}m^2(\langle\phi\rangle)\varphi^2 + (m\partial_\phi m)|_{\langle\phi\rangle}\delta\phi\varphi^2 + \dots$$

$$m(\phi)\bar{\Psi}\Psi = m(\langle\phi\rangle)\bar{\Psi}\Psi + \partial_\phi m|_{\langle\phi\rangle}\delta\phi\bar{\Psi}\Psi$$

$$S = \int L \sim \int L_0 + \delta\phi^2$$

$$L = L_{\text{EFT}} + \sum_n \frac{\mathcal{O}_{n+4}}{\Lambda_{\text{S}}^{n-4}}$$

HOW IS DISTANCE MEASURED?

$$d(\phi,\phi_0) := \int_\gamma \sqrt{g_{ij}\frac{\partial\phi^i}{\partial s}\frac{\partial\phi^j}{\partial s}}\,\mathrm{d}s$$

The measure can also be

- Information metric
- Number of microstates in a BH
- Physical spacetime distance between two moving BPS objects
- de Witt distance (distance between EFTs in moduli space)
- Entropy

FURTHER REMARKS ON THE WEAK GRAVITY CONJECTURE

STABLE REMNANTS ARE PROBLEMATIC

- Mean energy density diverges, as remnants contribute $\rho(m,g)\,\exp{(-m/T)}$
- Covariant Entropy Bound is violated
- (weak) Cosmic Censorship Conjecture is violated
- If PBHs formed after Inflation and before BBN, stable remnants overclose universe $\Rightarrow \omega = 0$
- Stable remnants correspond to global charges

➡ Since stable remnants are problematic, something must forbid them.

OBSERVATIONS TO RULE OUT THE WGC

- detection of a super-light $B - L$ gauge boson in neutron–antineutron scattering experiments
- features that are predicted by inflationary models that were deemed incompatible with the WGC
- The discovery of a very light magnetic monopole (low EFT cutoff)
- Naked Singularities

THE MAGNETIC WGC

- The (electric) WGC says that BHs are able to decay.
- The magnetic counterpart says that the minimally charged magnetic object is not a BH, i.e. the magnetic Coulomb force on the monopole of the smallest magnetic charge acts more strongly than the Newtonian gravitational force:

$$\Lambda_{\mathrm{EFT}} \lesssim g \left(M_{\mathrm{P}}^{d}\right)^{\frac{d-2}{2}}$$

HOW ARE THE *MAGNETIC* AND THE *ELECTRIC* WGC RELATED?

- The mass of the magnetic monopole is constraint by the electric WGC: $m \lesssim g_{\text{mag}} M_{\text{P}} \sim \frac{M_{\text{P}}}{g_{\text{el}}}$
- The monopole field is linearly divergent, i.e. it has a cutoff Λ, and the monopole mass is of the order of the field energy $m \sim \frac{\Lambda}{g_{\text{el}}^2}$
- $\Rightarrow \Lambda \lesssim g_{\text{el}} M_{\text{P}} \qquad \square$

FURTHER REMARKS ON
THE COBORDISM CONJECTURE

HOW ARE GLOBAL CHARGES AND NON-TRIVIAL COBORDISM CLASSES RELATED?

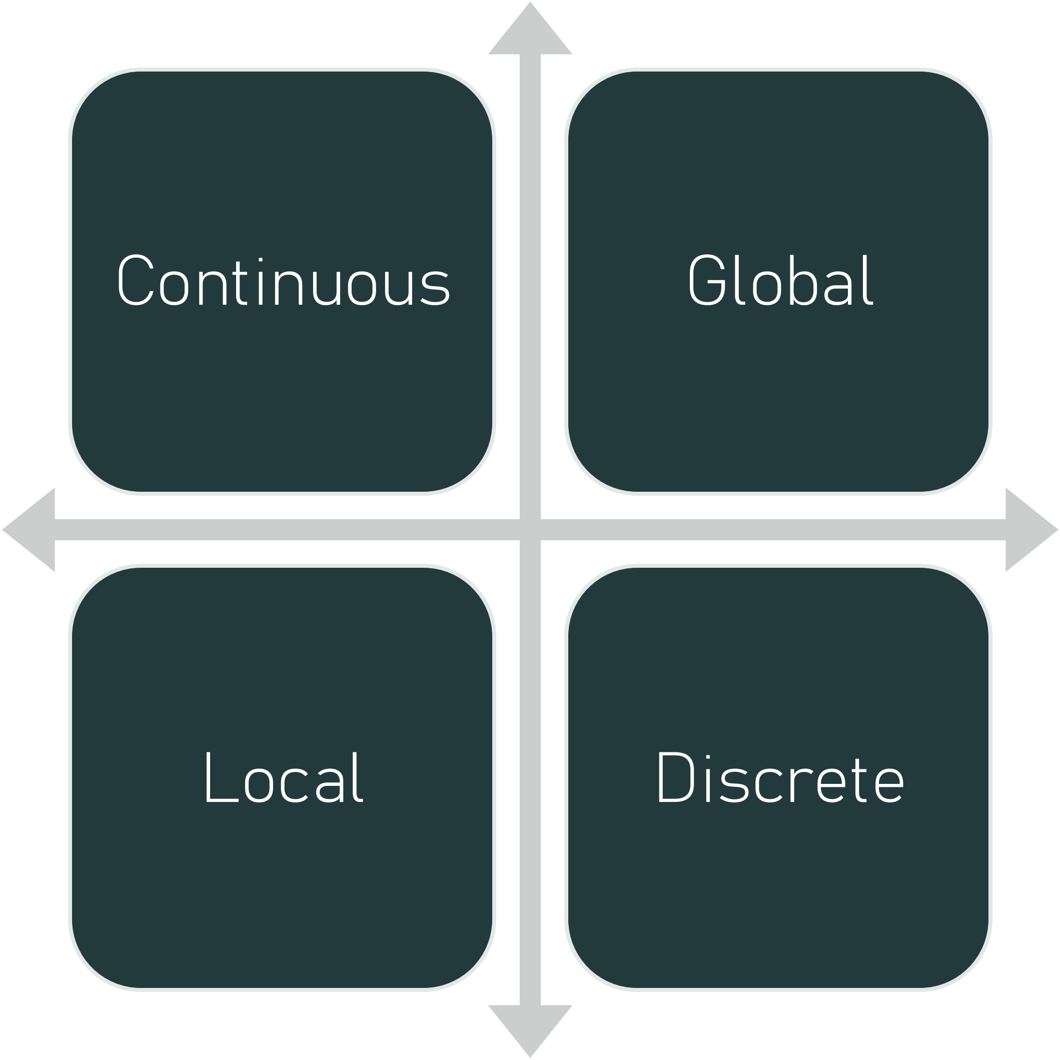
- Start with spacetime X
- Replace submanifold A in X with submanifold B from a different bordism class
- After this change, your new spacetime X` is no longer cobordant to X
- Far away from the change, you don't see the change
    - ➢ not a local defect, cannot be gauged away
- You introduced a global topological charge

FURTHER REMARKS ON SYMMETRIES

WHAT KIND OF SYMMETRIES ARE THERE?

- Global Symmetries
  - Unitary transformations
  - Commute with Hamiltonian
  - Act non-trivially on Hilbert space
- Continuous Symmetries
  - Lead to conserved world sheet current
    - Which serves as vertex operator for gauge boson

$l_P=1/M_P$



FURTHER REMARKS ON TRANS-PLANCKIAN CENSORSHIP

MATHEMATICAL MOTIVATION

- Grönwall's Inequality:
  - if $\int_{t_i}^{t_f} H(s)\,ds < \log\frac{M_P}{H_f}$ and assuming $\frac{\dot{a}}{a} \leq H$,
  - $\frac{a_f}{a_i} < \frac{M_P}{H_f}$ holds.

BOUND ON SCALAR FIELDS

- TCC: $\int_{\phi_\mathrm{i}}^{\phi_\mathrm{f}} \frac{H}{\dot\phi}\,\mathrm{d}\phi = \int_{t_\mathrm{i}}^{t_\mathrm{f}} H(t)\,\mathrm{d}t < \log \frac{M_\mathrm{P}}{H_\mathrm{f}}$
- Friedmann equation $\frac{(d-1)(d-2)}{2} H^2 = \frac{\dot\phi^2}{2} + V(\phi)$

$$\frac{H}{|\dot\phi|} > \frac{1}{\sqrt{(d-1)\,(d-2)}}$$

$$\Rightarrow \frac{|\phi_\mathrm{f} - \phi_\mathrm{i}|}{\sqrt{(d-1)\,(d-2)}} < -\log H_\mathrm{f}$$

$$\Rightarrow H_\mathrm{f} < e^{-\frac{|\phi_\mathrm{f} - \phi_\mathrm{i}|}{\sqrt{(d-1)(d-2)}}}$$

$$\Rightarrow V(\phi) < \frac{(d-1)\,(d-2)}{2} e^{-\frac{2|\phi - \phi_\mathrm{i}|}{\sqrt{(d-1)(d-2)}}}$$

BOUNDS ON INFLATION

$$\frac{1}{H_\mathrm{i}} e^{N_e} \frac{a_\mathrm{r}}{a_\mathrm{f}} \frac{T_\mathrm{r} g_*(T_\mathrm{r})^{1/3}}{T_0 g_*(T_0)^{1/3}} \simeq \frac{1}{H_0}$$

- Initially, we start with the Hubble radius $1/H_\mathrm{i}$.

BOUNDS ON INFLATION

$$\frac{1}{H_{\mathrm{i}}} e^{N_e} \frac{a_{\mathrm{r}}}{a_{\mathrm{f}}} \frac{T_{\mathrm{r}} g_*(T_{\mathrm{r}})^{1/3}}{T_0 g_*(T_0)^{1/3}} \simeq \frac{1}{H_0}$$

$$\frac{\sqrt{3} M_{\mathrm{P}}}{\sqrt{V}} e^{N_e} \frac{V^{1/4}}{T_0} \simeq \frac{\sqrt{3} M_{\mathrm{P}}}{\sqrt{T_0^4 \frac{T_{\mathrm{eq}}}{T_0} \frac{1}{\Omega_{\mathrm{m}}}}}$$

$$\Rightarrow e^{N_e} \simeq \frac{V^{1/4}}{\sqrt{T_0 T_{\mathrm{eq}}}} \sqrt{\Omega_{\mathrm{m}}}$$

- For the inflaton potential, we know that $H = \sqrt{V}/\sqrt{3} M_{\mathrm{P}}$.
- If we assume that reheating takes place rapidly enough, $a_{\mathrm{r}}/a_{\mathrm{f}} \sim 1$ holds.
- Assuming that reheating lasts less than a Hubble time, $T_{\mathrm{r}} \approx V^{1/4}$ holds.
- To get an order of magnitude estimate, we can also assume that $g_*(T_{\mathrm{r}})^{1/3} \sim g_*(T_0)^{1/3}$.
- The Friedmann equation informs us that the Hubble scale is given by the current energy density: $1/H_0 = \sqrt{3} M_{\mathrm{P}}/\sqrt{\rho_0}$.
- The energy density today corresponds roughly to the following expression: $\rho_0 \approx T_0^4 \frac{T_{\mathrm{eq}}}{T_0} \frac{1}{\Omega_{\mathrm{m}}}$, with T_{eq} the temperature during radiation–matter equality, and Ω_{m} today's relative matter density.

BOUNDS ON INFLATION

$$e^{N_e} \simeq \frac{V^{1/4}}{\sqrt{T_0 T_{\text{eq}}}} \sqrt{\Omega_{\text{m}}}$$

Then, we use $H \simeq \sqrt{V/3M_{\text{P}}^2}$ again, apply the TCC bound $e^{N_e} < M_{\text{P}}/H$, and solve for V to find

$$V^{3/4} < \sqrt{3} M_{\text{P}}^2 \sqrt{T_0 T_{\text{eq}}} \tag{7}$$

$$V^{1/4} < 10^9 \text{ GeV} \sim 10^{-10} M_{\text{P}}. \tag{8}$$

If we express this bound again in terms of H to find $H \lesssim \mathcal{O}(10^{-20}) M_{\text{P}}$, and assume a scale invariant scalar powerspectrum $P_\zeta = H^2/8\pi^2 M_{\text{P}}^2 \epsilon_V c_{\text{s}} \sim 10^{-9}$ we find the bound on the tensor-to-scalar ratio $r_{\text{ts}} = 16\epsilon_V c_{\text{s}} \lesssim 10^{-31}$.

LARGE SINGLE-FIELD SLOW-ROLL INFLATION

Let us write the field range as

$$|\Delta\phi| = \left|\dot{\phi}\Delta t\right|.$$

Then, we use the slow-roll condition $3H\dot{\phi} = -V'$ and the TCC condition $\Delta t \leq H^{-1} \log H^{-1}$ to find

$$|\Delta\phi| \leq \left|\frac{V'}{3H^2} \log H^{-1}\right|.$$

With the slow-roll parameter $\epsilon_V = \left(V'/V\right)^2/2$ and the TCC energy bound on the potential V we find then $|\Delta\phi| \leq 10^{-13} M_{\mathrm{P}}$, which conflicts with large-field inflation.

FURTHER REMARKS ON THE SPECIES SCALE CONJECTURE

SPECIES SCALE CONJECTURE

ENTROPY

If the smallest BH that can be semi-classically described in an EFT has a Schwarzschild radius of r_{minBH}, then there are N_{S} weakly coupled elementary particles with a decay width much less than their mass in the theory, and the following relation holds:

$$r_{\mathrm{minBH}} > l_{\mathrm{S}} := N_{\mathrm{S}}^{1/(d-2)} l_{\mathrm{P};d},$$

with $l_{\mathrm{P};d} = 1/M_{\mathrm{P};d}$ the d-dimensional Planck length and l_{S} the *species scale*.

ENERGY

Given a d-dimensional theory, coupled to gravity with d-dimensional Planck mass defined by $M_{\mathrm{P};d}^{d-2} = \hbar^{d-3} c^{5-d}/8\pi G_{\mathrm{N}}$, there are N_{S} particle states below a cutoff scale

$$\Lambda_{\mathrm{S}} = \frac{M_{\mathrm{P};d}}{N_{\mathrm{S}}^{\frac{1}{d-2}}};$$

after this scale, new gravitational dynamics appear, e.g. in the form of higher-derivative operators.

SSC SCALAR FIELD BOUND

- A potential V is described within an EFT if $V < \Lambda^d$
- $N_S \sim (M_P/m)$
- DC predicts $m \sim \exp(-\alpha \Delta\phi)$

➢ $\Lambda_S \sim \exp(-\lambda_S \Delta\phi)$ with $\lambda_S = \left|\Lambda_S^{`}/\Lambda_S\right|$

➢ $\Delta\phi \leq \frac{1}{\lambda_S} \log \frac{M_P}{\Lambda_S}$

FURTHER REMARKS ON STRING THEORY

WHAT MAKES STRINGS SPECIAL?

- Point particles only have momentum modes.
- Strings on a torus of radius R have
  - momentum modes whose energies are quantized in units of 1/R,
  - winding modes whose energies are quantized in units of R,
  - and a tower of oscillatory modes independent of R.
- Consider a box of strings in thermal equilibrium and compress the radius. The temperature of the gas increases since the energy of the momentum modes (which are the light modes for large values of R) increases.
- At one point, it becomes thermodynamically preferable to excite oscillatory modes, up until the Hagedorn temperature T_H, which is the maximal temperature of a gas of strings.
- When R decreases below the string scale, the energy will flow into the winding modes (which are now the light modes), and the temperature will decrease.
  - -> No temperature singularity in a stringy early universe cosmology!