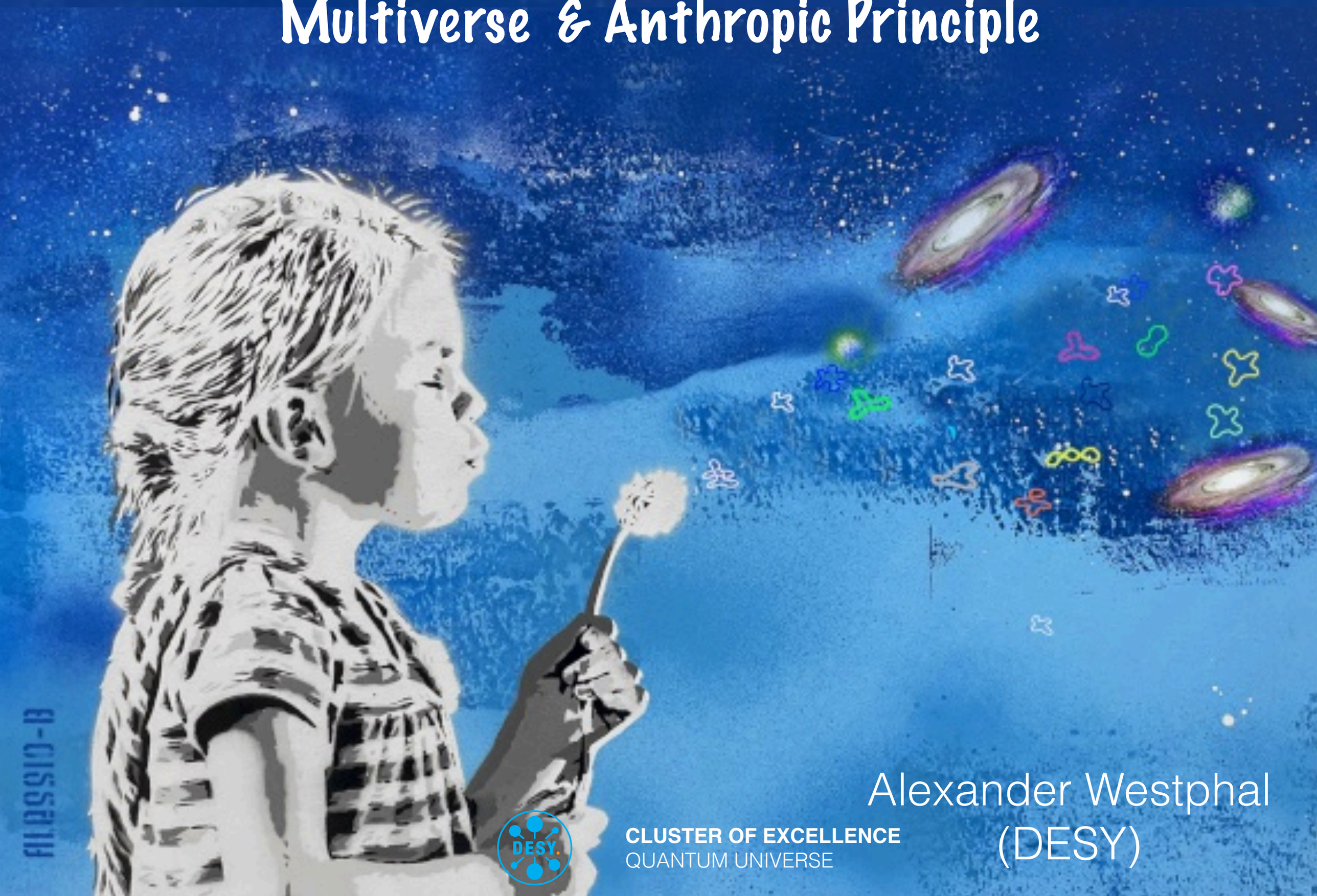
String Axions between Multiverse & Anthropic Principle



Alexander Westphal
(DESY)

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DISCLAIMER

Attributed to S. Weinberg:

A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you're against it, some people will think you're a little too interested...

it is the questions ... that drive us mad

radiation: $\rho \sim \frac{1}{a^4}$

matter: $\rho \sim \frac{1}{a^3}$

curvature: $\rho \sim \frac{1}{a^2}$

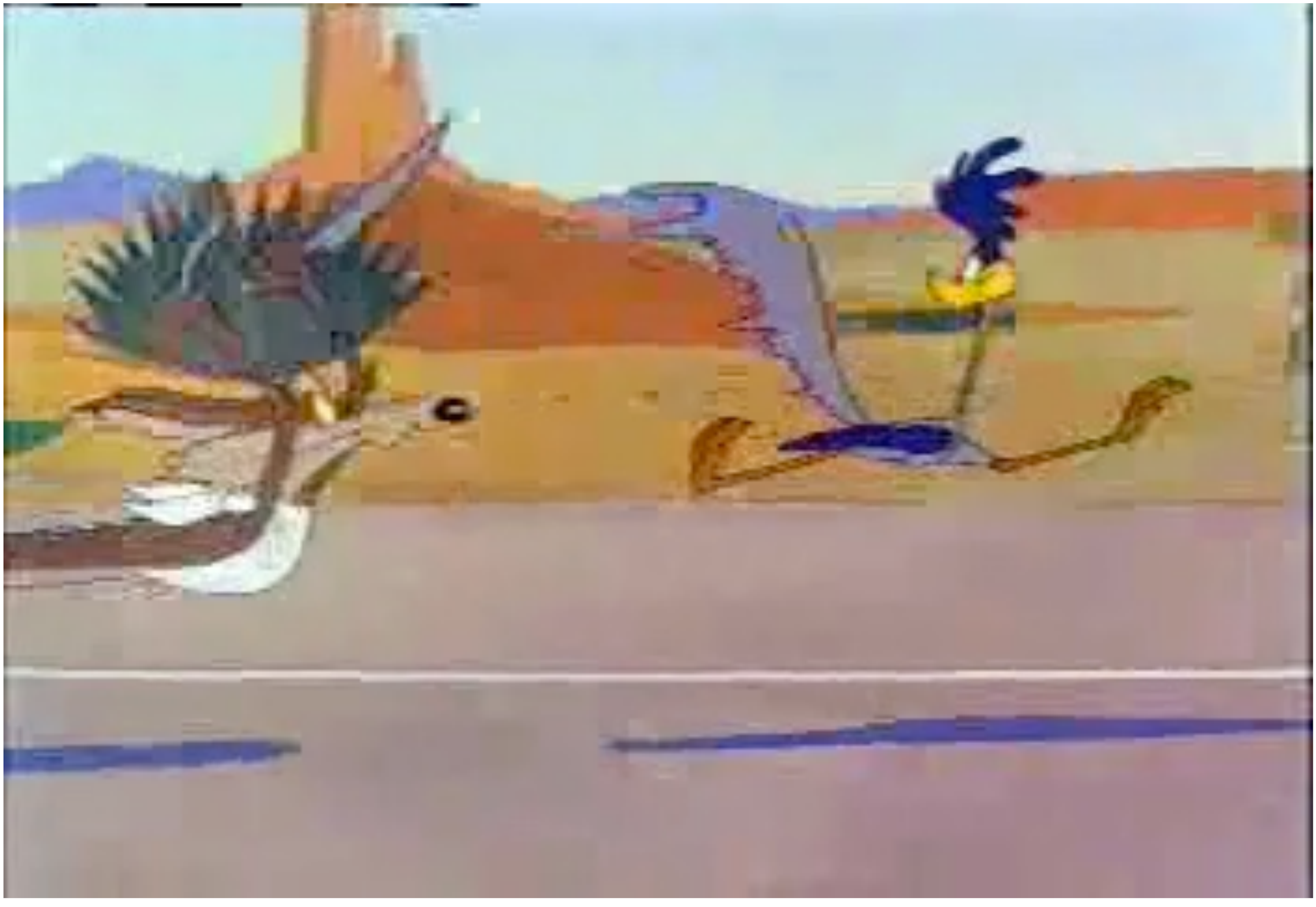
curvature growing
but < 1% today!

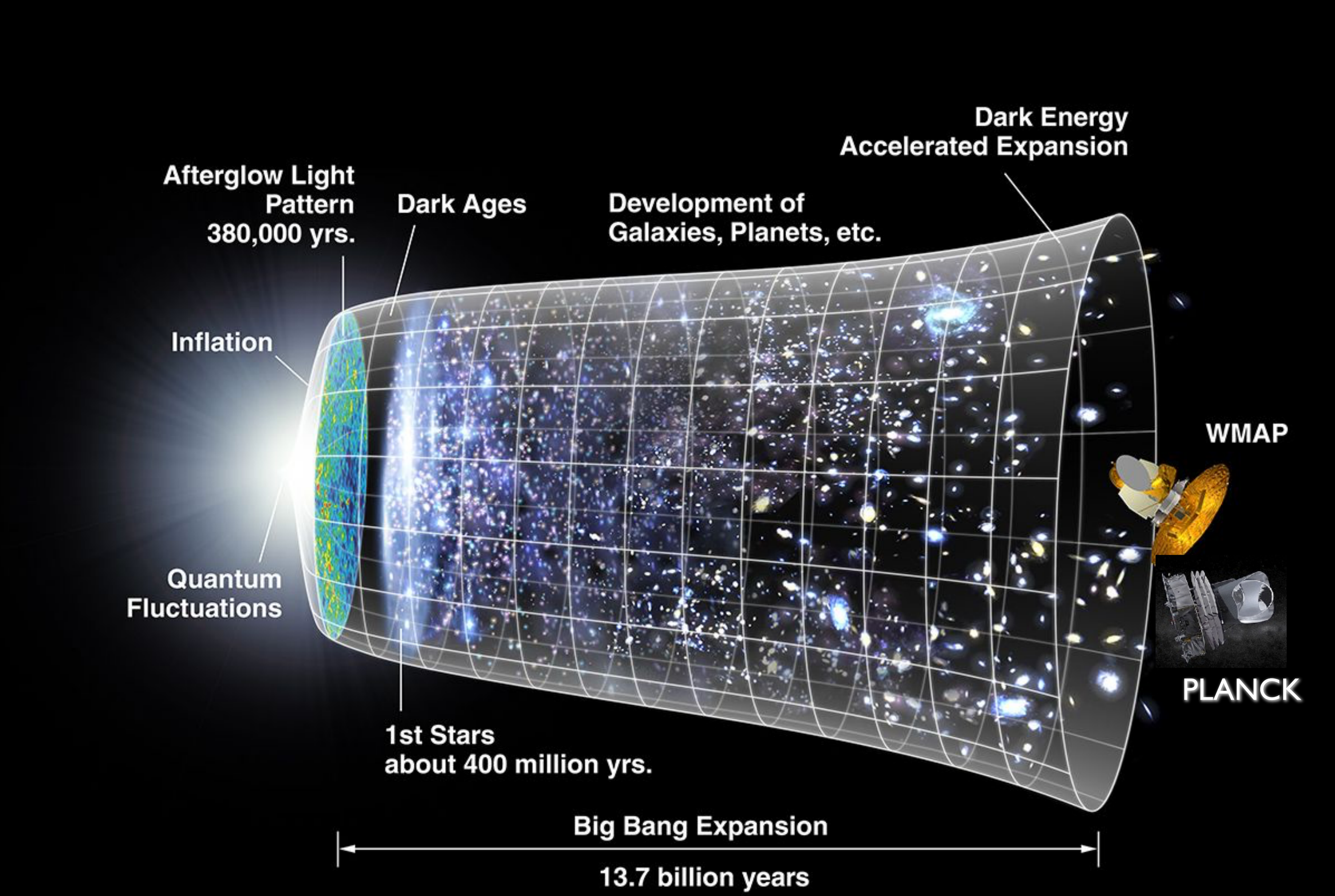
How does cosmological inflation work?

What is Dark Matter made of?

Why is today's CC so small? $\rho_{CC} \simeq const. \simeq 10^{-122} M_{\rm P}^4$

it is the questions ... that drive us mad





NASA/WMAP Science Team

The Anthropic Principle

[Carter '73]

- also known as "observation selection effect"

  The range of possible observations in our universe is constrained by observers necessarily existing in a universe suitable for the formation of observers.

  - first called "Anthropic Principle" by Brandon Carter in 1973

Weak vs Strong

[Barrow & Tipler '86]

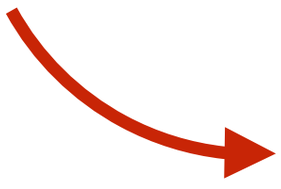
- cosmological formulation by Barrow & Tipler … since then up to 30 variants — mainly cluster into two forms

- Weak Anthropic Principle:

"The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirements that the universe be old enough for it to have already done so."

- Strong Anthropic Principle:

"The Universe must have those properties which allow life to develop within it at some stage in its history."



can be quickly abused to "argue" for creation/intelligent design and/or simulation hypothesis

… don't go down that road — only weak form useful for science

Example 1 - Earth's Orbit

- Before 1992

  - in solar system, Earth has right orbit (distance from the sun) to support liquid surface water (precondition for carbon life)

  - early attempts (e.g. Kepler) to explain why Earth has to have this orbit failed:

    Newtonian mechanics & gravity
    laws explain dynamics, but allow for
    continuum of possible orbits

  - but — selection effect (anthropic statement) :
as water-based carbon life we necessarily find ourselves on (an) Earth

Example 1 - Earth's Orbit

- Since 1992/1995 (first exoplanet discoveries):

  # stars/galaxy # galaxies

  [Wolszczan & Frail '92]
  [Queloz & Mayor '95]

  - there are > 10^{11} x 10^{11} = 10^{22} stars in the visible universe, most of them with planets

  - physical mechanism to realize a very large set of possible orbits

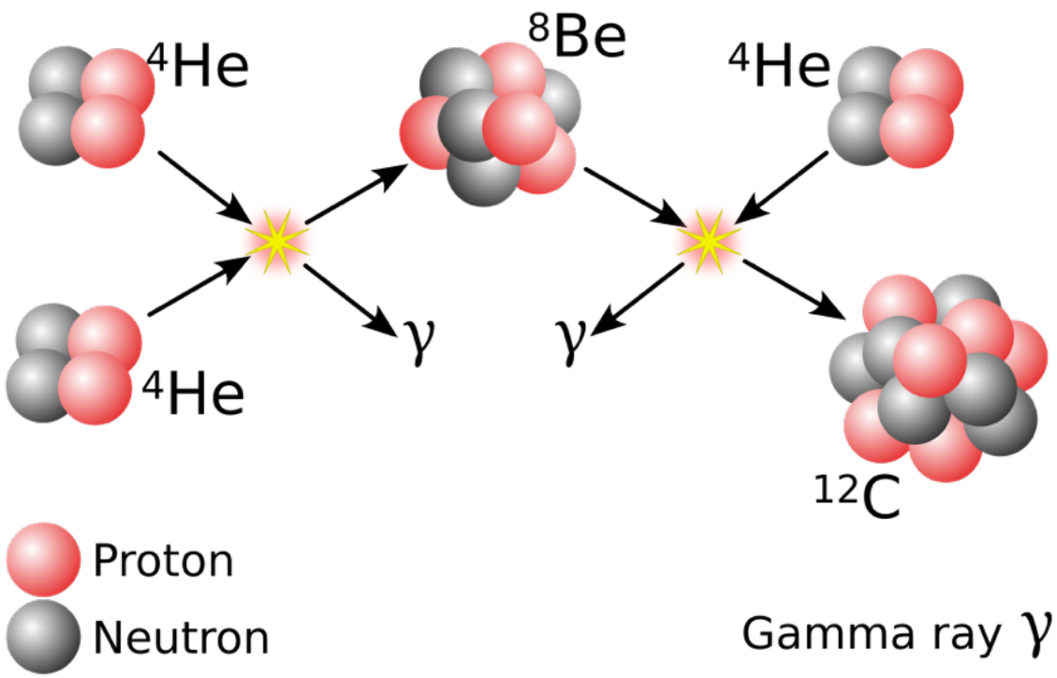
  - now by necessity we find ourselves in an Earth-like orbit, because some of the realized orbits will be Earth-like !

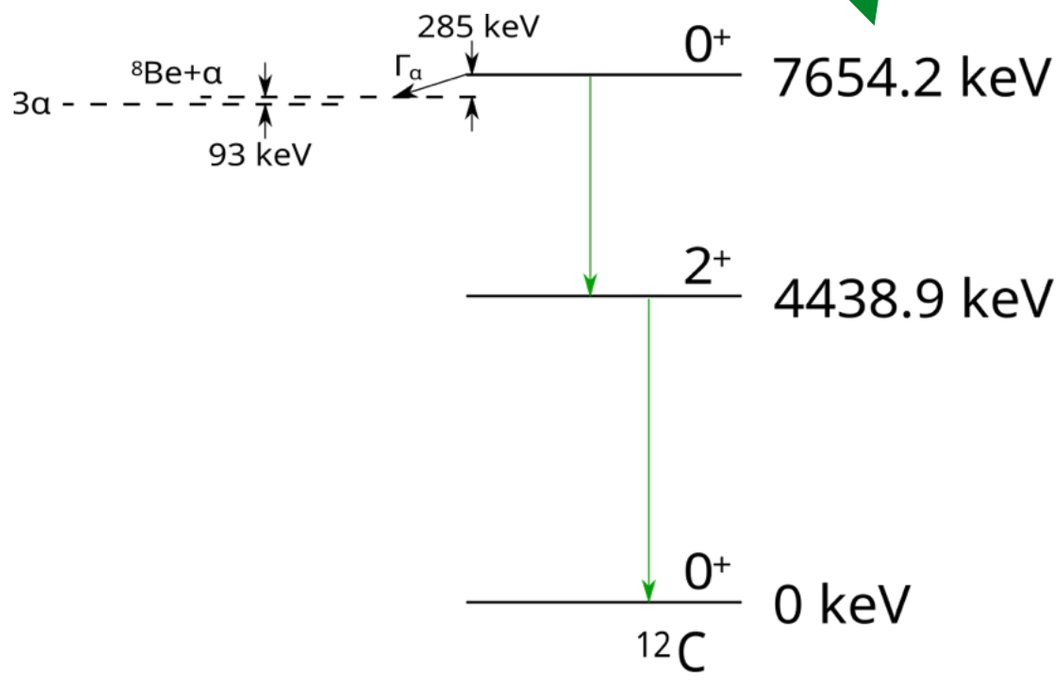
Note the difference:

- Before 1992 — anthropic statement was a tautology

- After 1992 — it becomes half science, as now there is a mechanism to realize many different orbits, with some in the right range

Example 2 - Stellar Nucleosynthesis & Hoyle State [Hoyle '54]





- for stars to fuse enough carbon from hydrogen via helium

  - need $\Delta\alpha_{\rm EM} < 4\%$ [Hollowell, Weiss & Truran '89]

  - need $\Delta\alpha_{\rm strong} < 0.5\%$

... anthropic constraint on Standard Model coupling constants !

How to (not) use Anthropic Reasoning

- the upshot:

  2 conditions for anthropic reasoning in science

  (i) a physical parameter with a narrow range of values required by life-compatible universe

  (ii) a physical mechanism realizing a very large set of values of this parameter on a wide value range in separated regions:

- without (ii) anthropics is mere tautology !

How to (not) use Anthropic Reasoning

- implications of (ii)

  what are the separated regions:

varying planetary orbits:

separated regions = different stellar systems

varying coupling constants:

separated regions = different universes !

A Multiverse !

How to (not) use Anthropic Reasoning

- outcomes:

  - anthropics in cosmology often requires a multiverse

  - anthropics usually explains = postdicts an existing observation / parameter value

- leaves us with 2 questions:

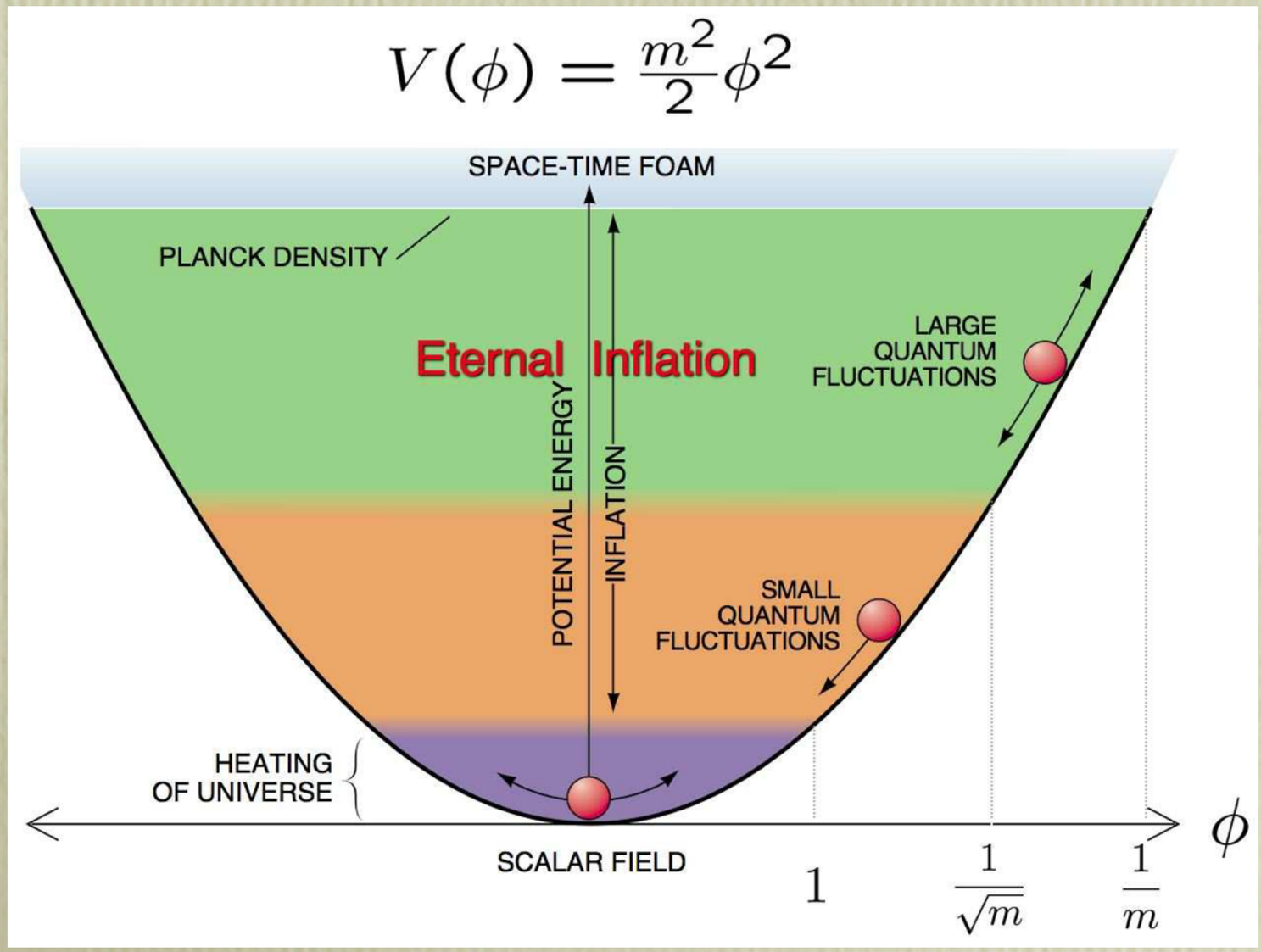
  Do we have a mechanism for a multiverse ?

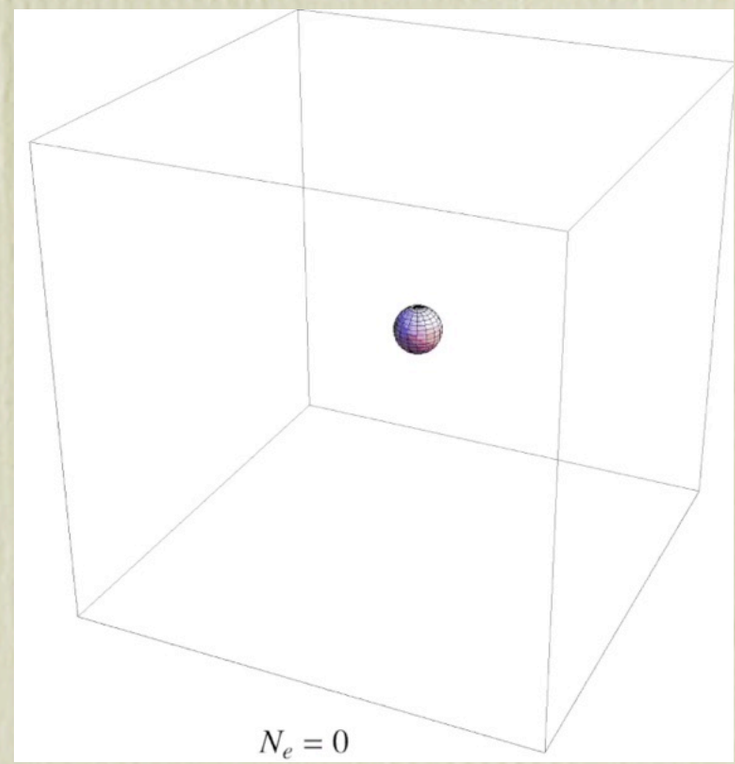
  Can we get a falsifiable prediction from anthropics ?

slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]

$$\ddot{\phi} + 3H\dot{\phi} = -\partial_\phi V \equiv -V' \quad , \quad \frac{\dot{a}^2}{a^2} = H^2 = \frac{1}{3}(\dot{\phi}^2 + V)$$





[picture from lecture notes: Linde '07]

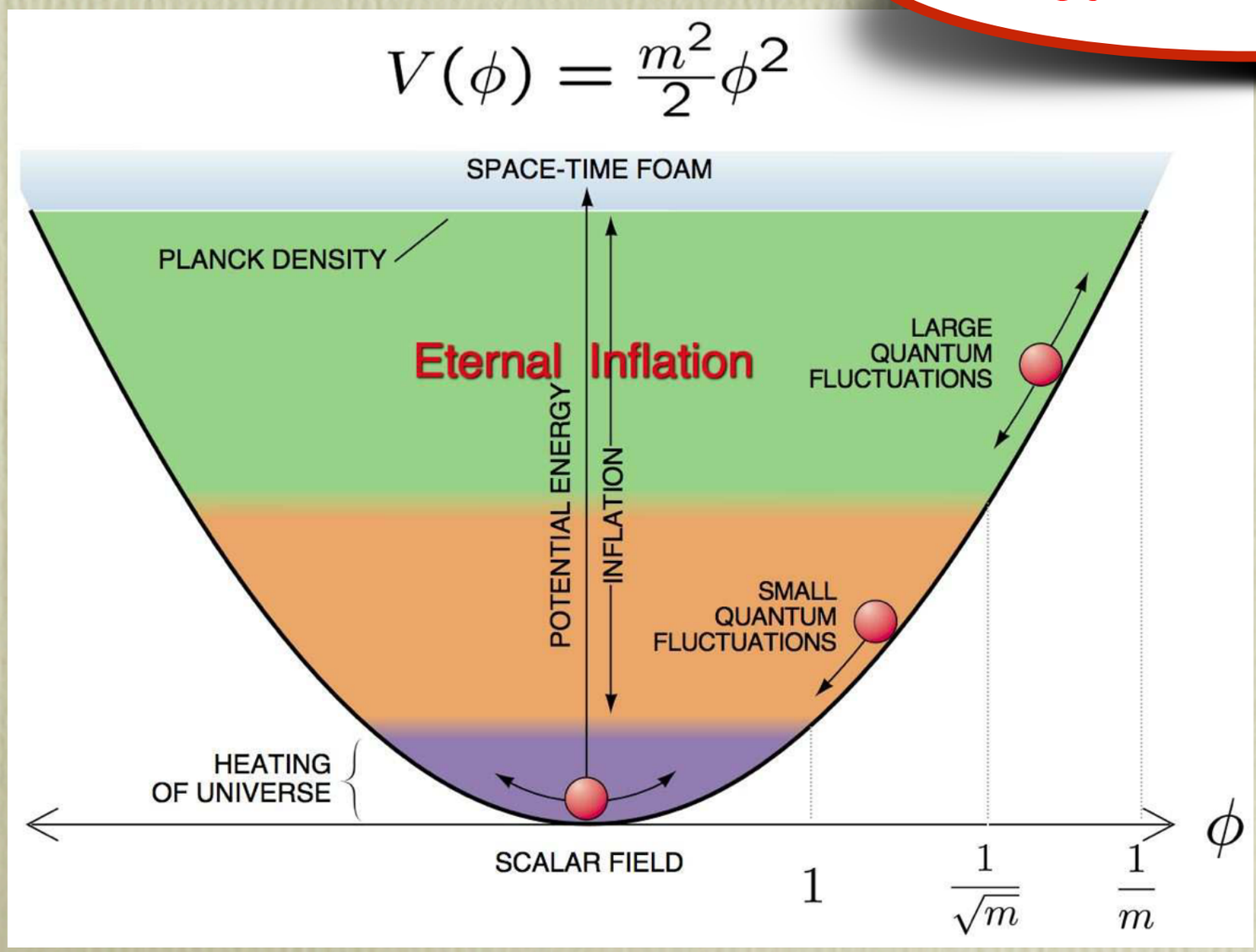
slow-roll inflation ...

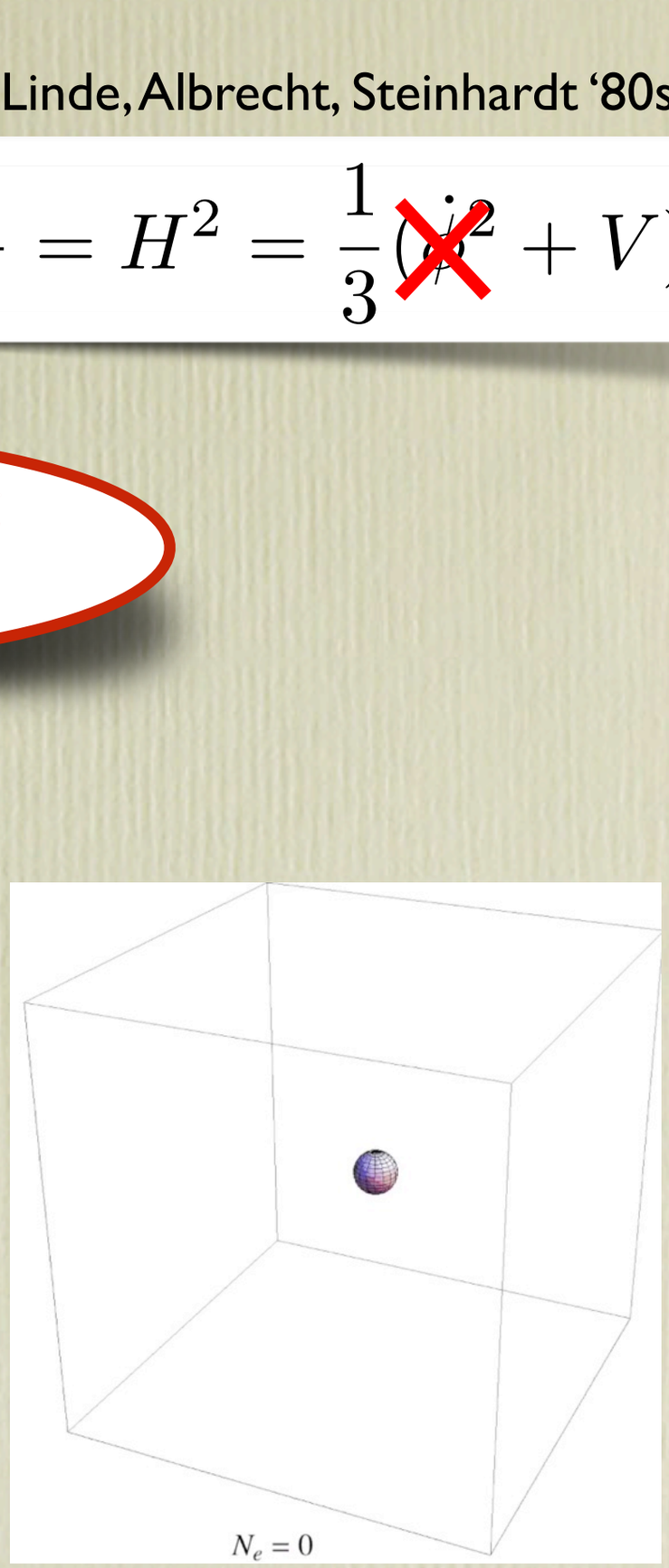
[Guth, Linde, Albrecht, Steinhardt '80s]

$$\cancel{\ddot{\phi}} + 3H\dot{\phi} = -\partial_\phi V \equiv -V' \quad , \quad \frac{\dot{a}^2}{a^2} = H^2 = \frac{1}{3}(\cancel{\dot{\phi}^2} + V)$$

$$a \sim e^{Ht}$$

$$V(\phi) = \tfrac{m^2}{2}\phi^2$$



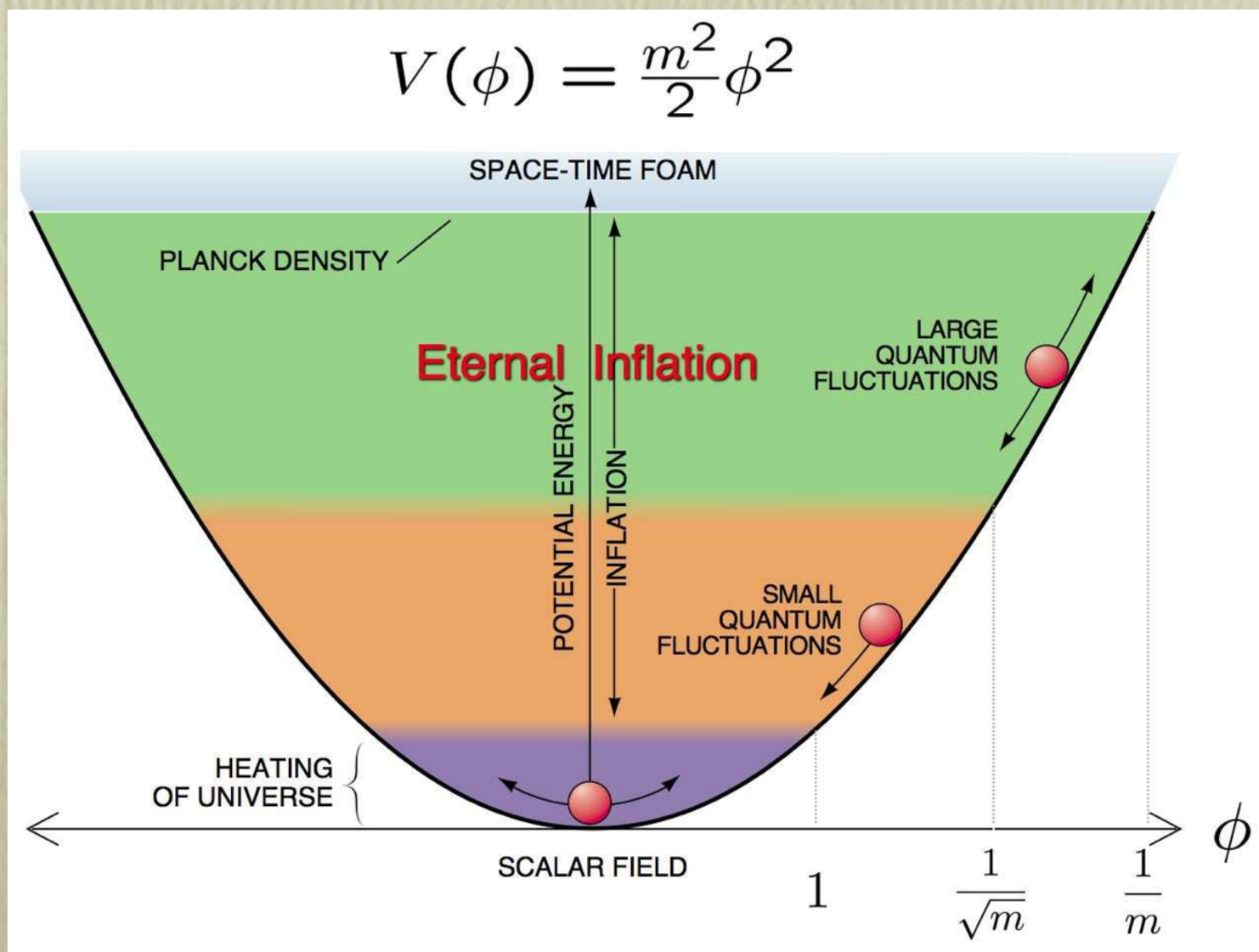


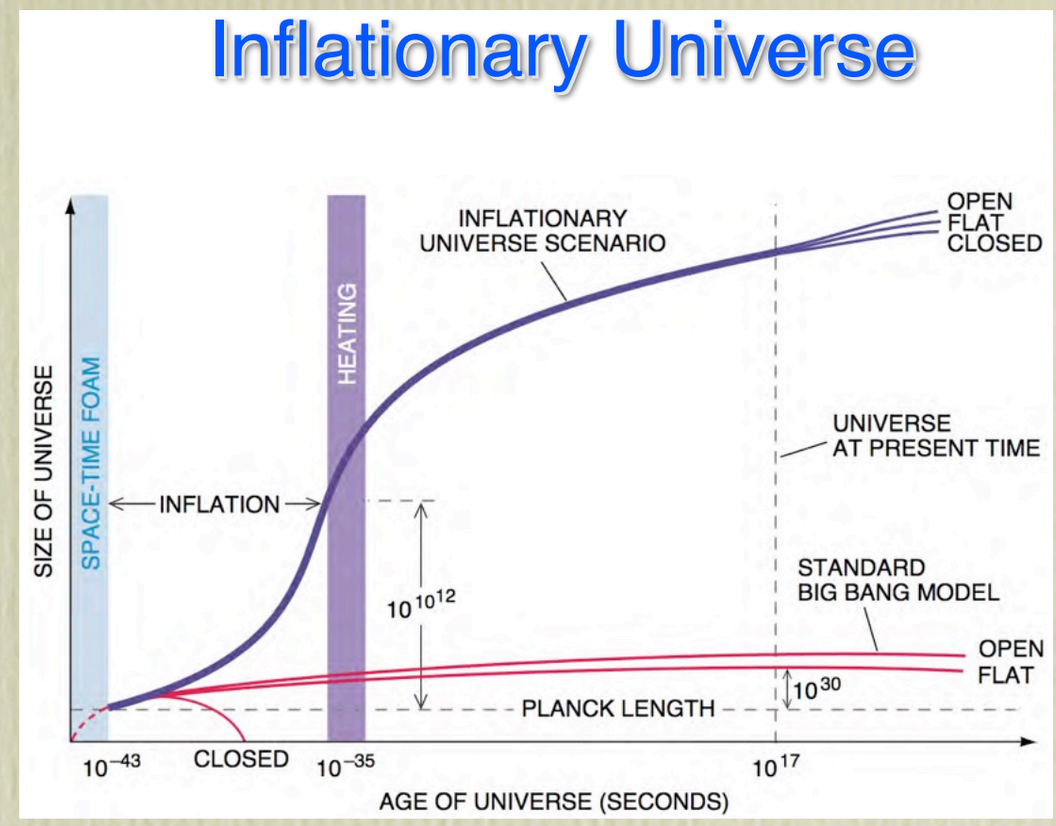
[picture from lecture notes: Linde '07]

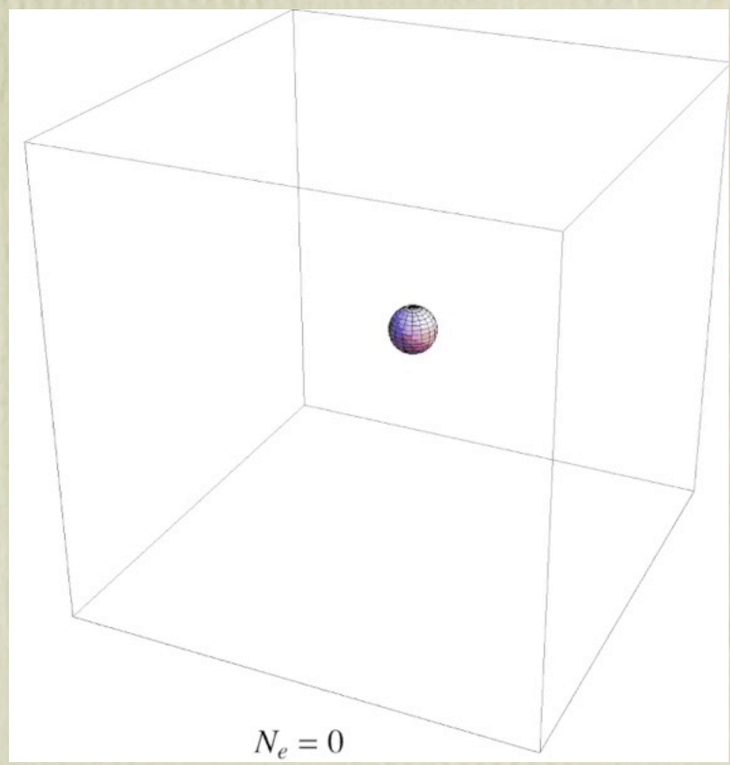
slow-roll inflation ...

$$3H\dot{\phi} \simeq -V' \ , \ H^2 \simeq \frac{1}{3}V$$

$$V(\phi) = \frac{m^2}{2}\phi^2$$

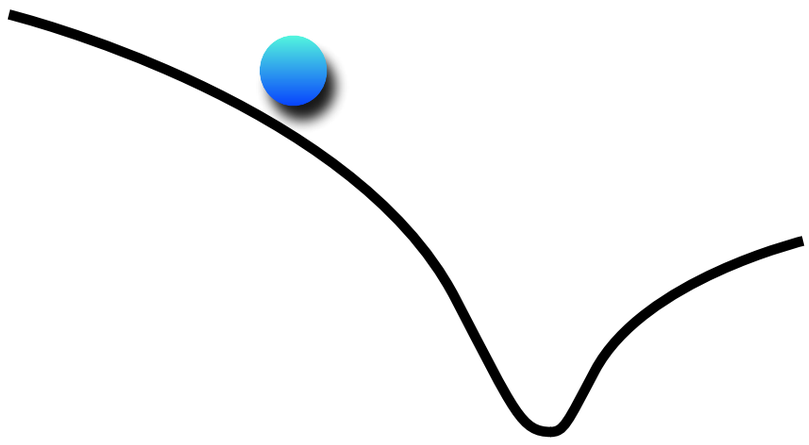






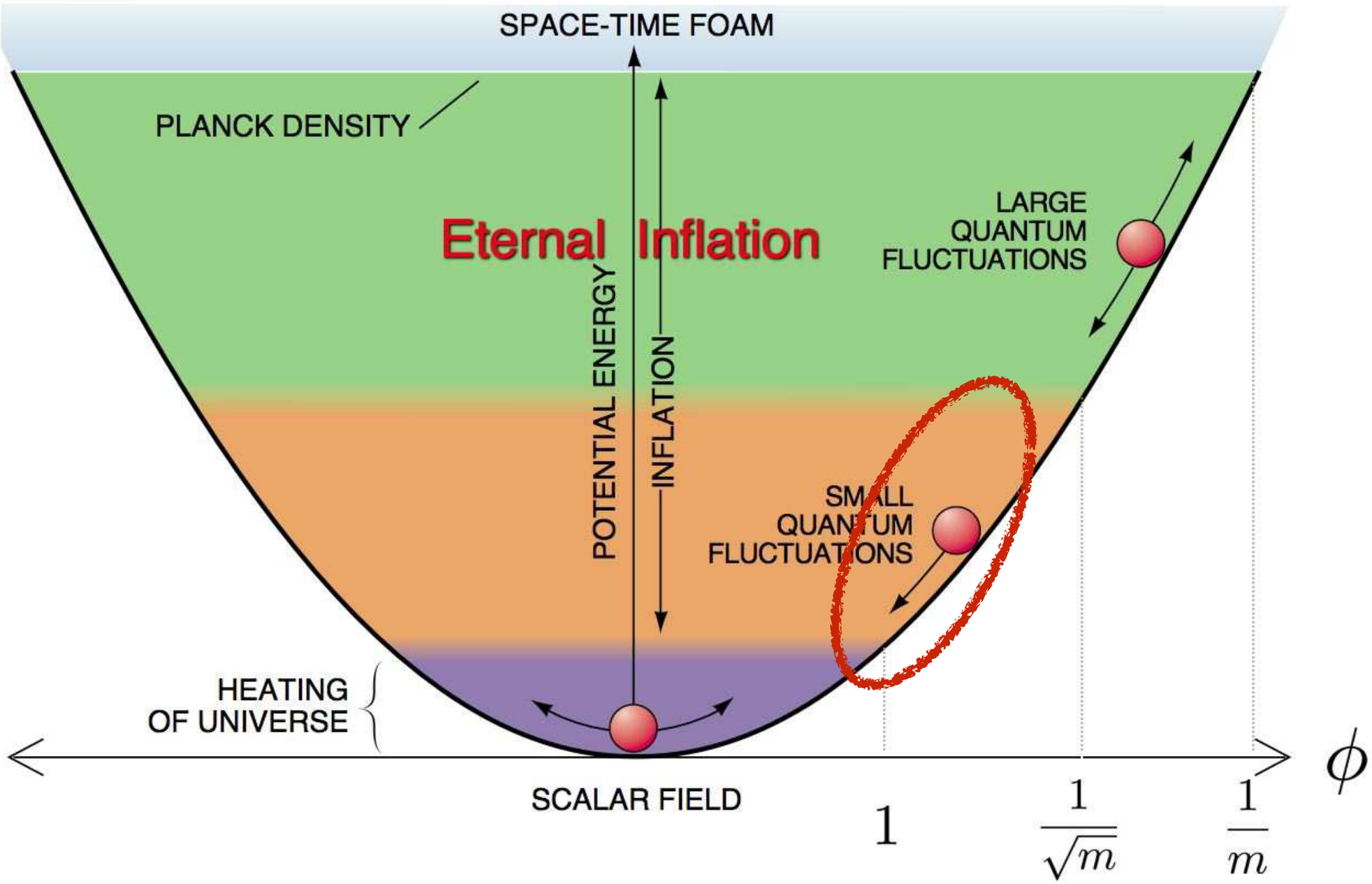
[picture from lecture notes: Linde '07]

observable inflation: small quantum fluctuations



observable inflation: small quantum fluctuations

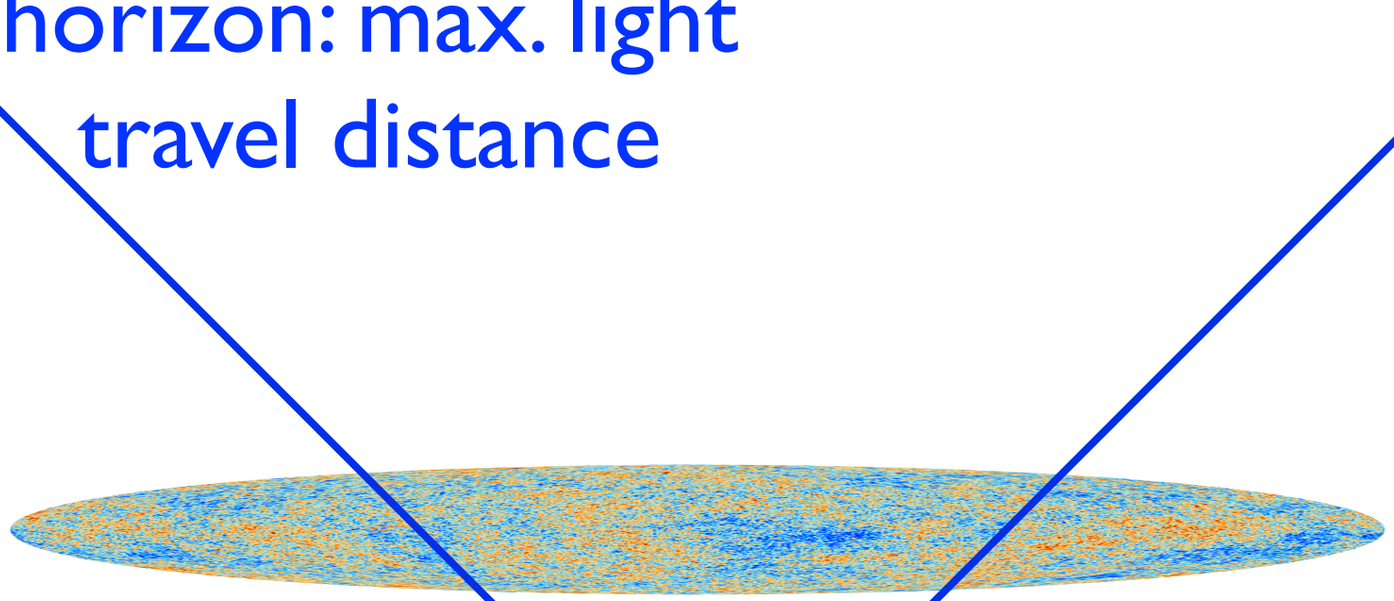
$$V(\phi) = \frac{m^2}{2}\phi^2$$



inflation amplifies & stretches quantum fluctuations — origin of all structure

time *t*

horizon: max. light travel distance

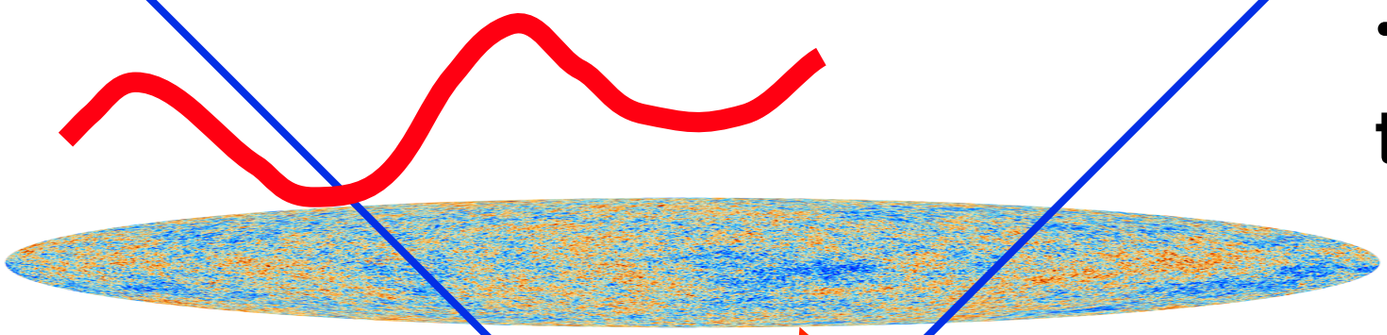


quantum fluctuations during inflation

inflation amplifies & stretches quantum fluctuations — origin of all structure

time *t*

horizon: max. light travel distance

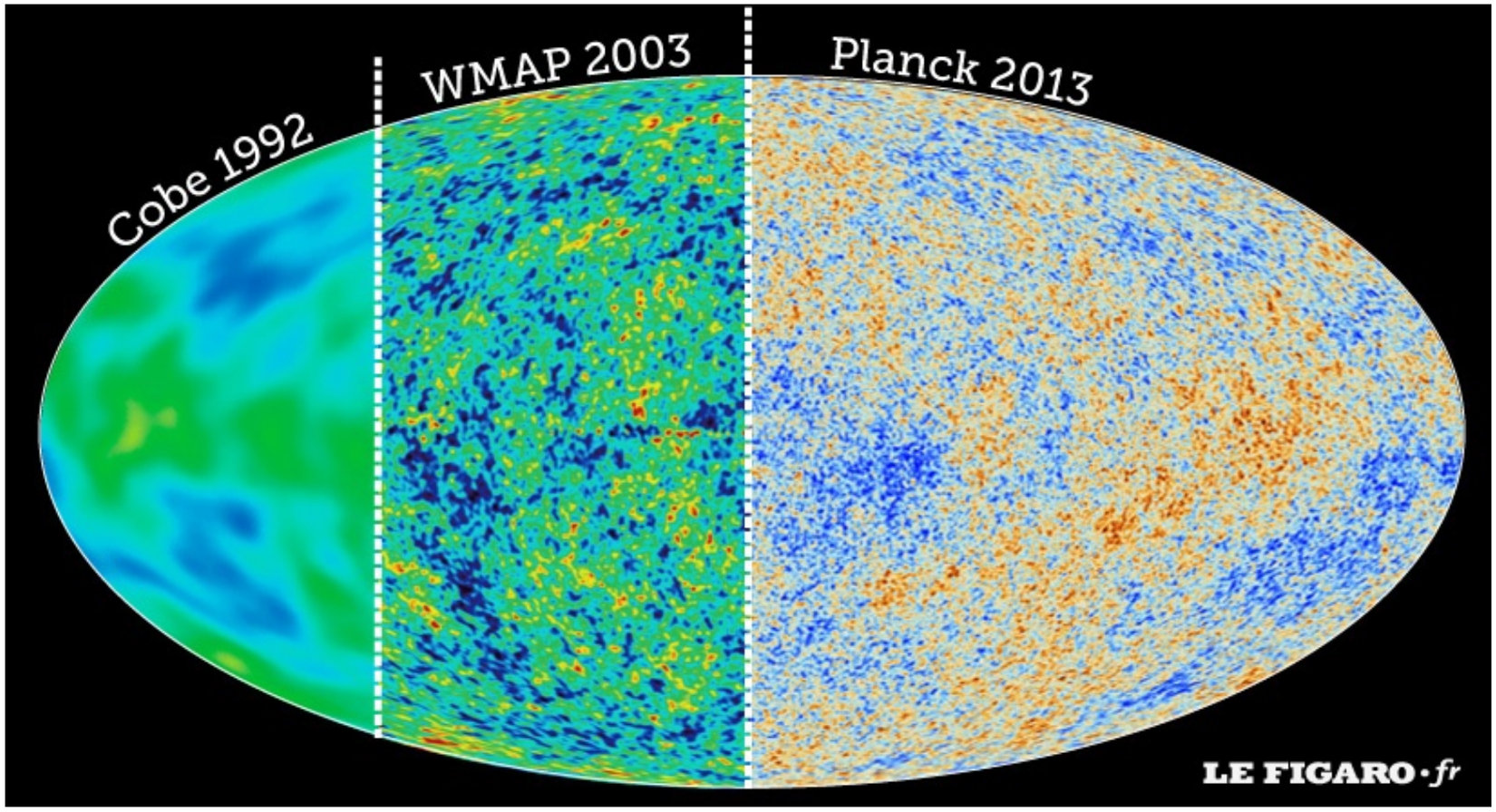


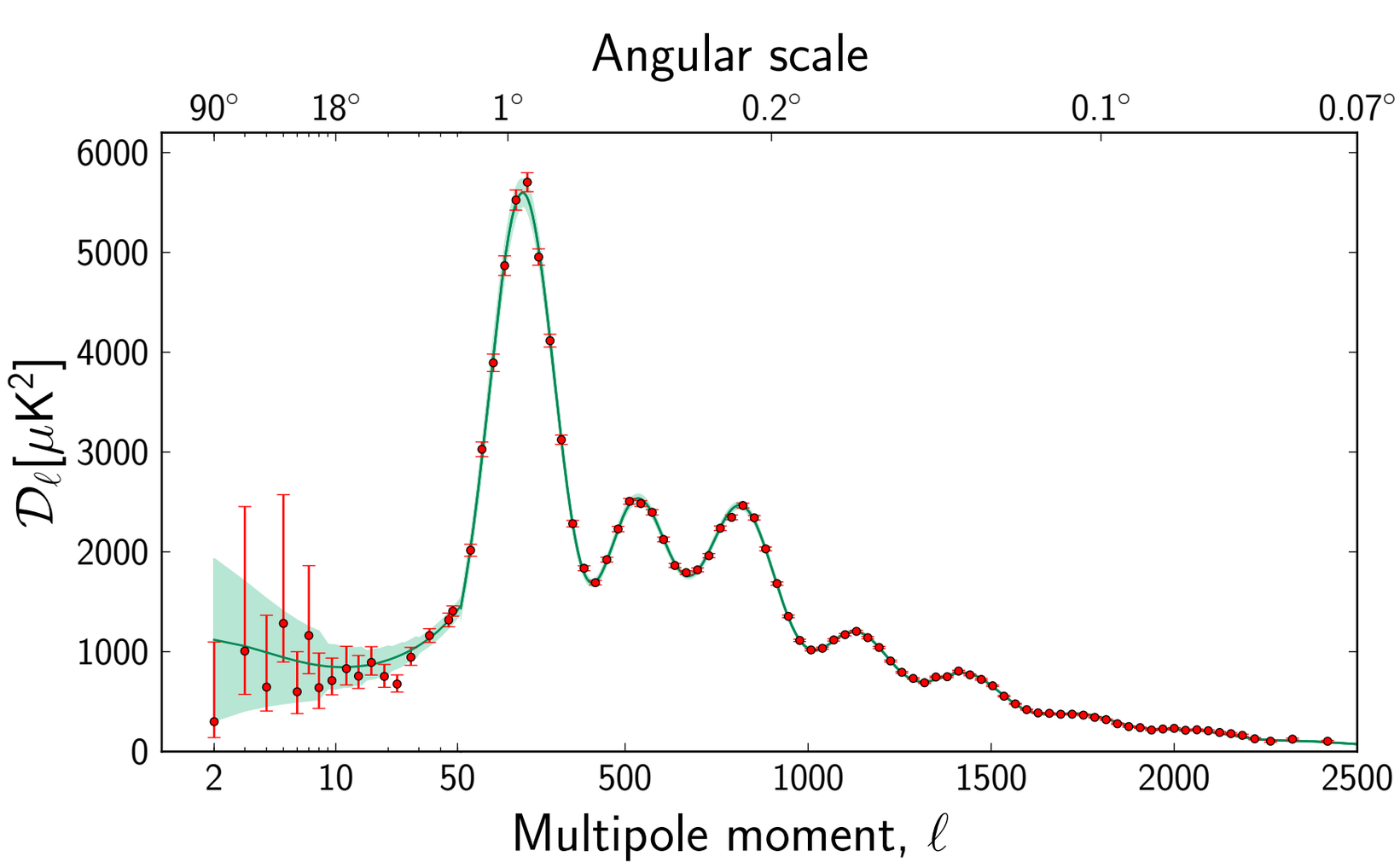
quantum fluctuations during inflation

➜ horizon grows faster than fluctuation scale

➜ energy density fluctuations generate plasma sound waves — frequency: 10^{-13} Hz

➜ quantum fluctuations stretch & generate temperature variations of CMB





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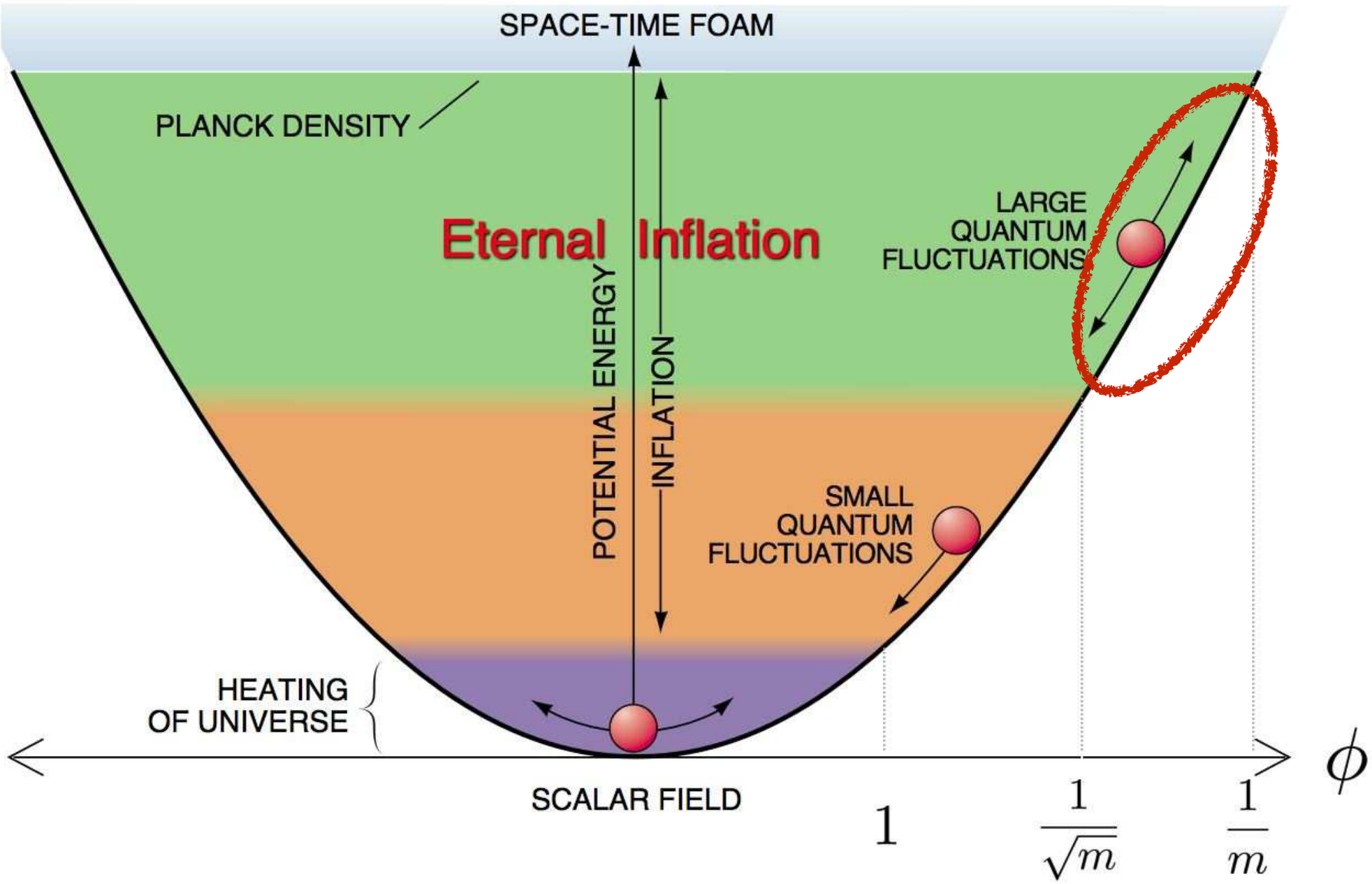
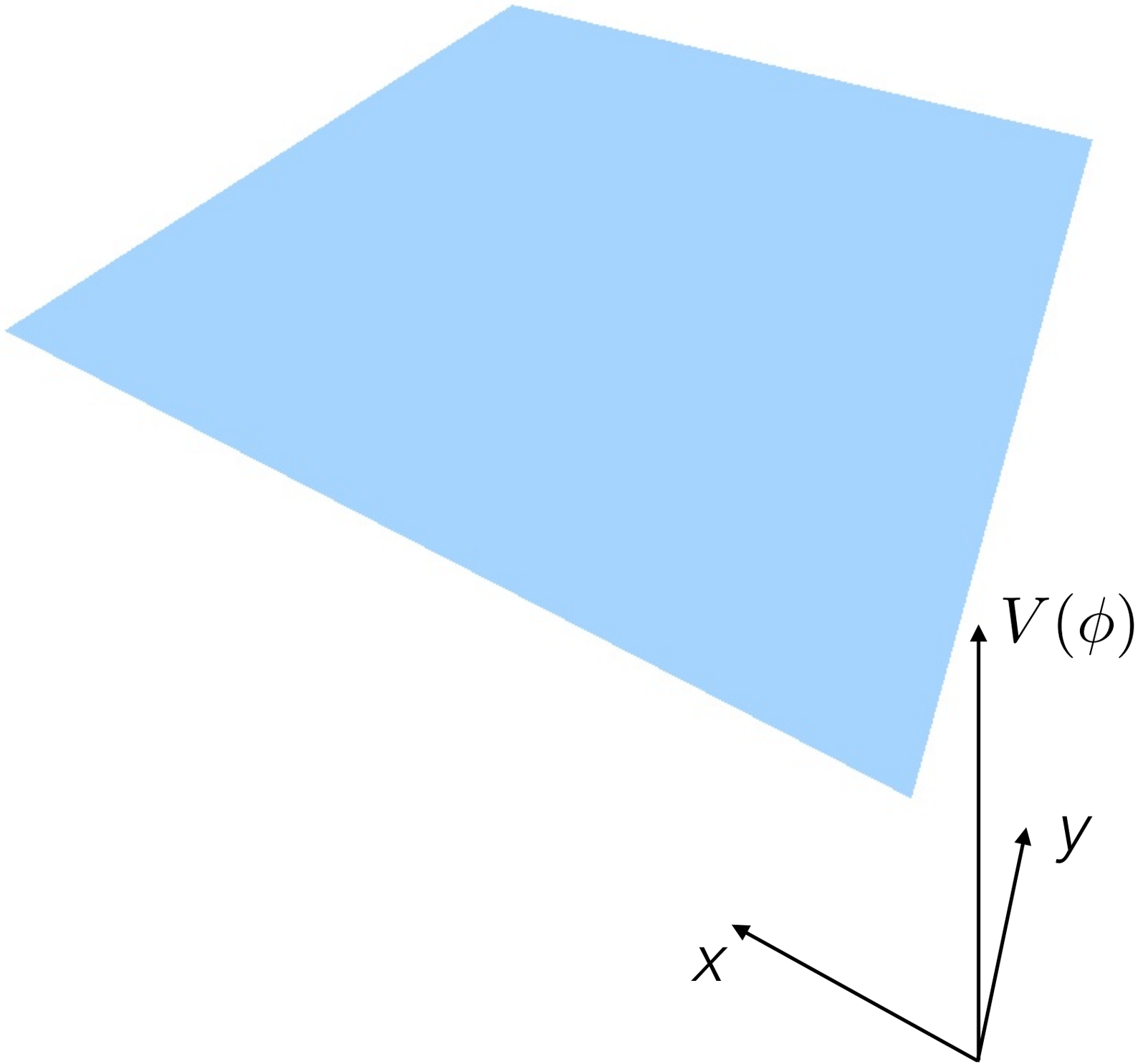
eternal inflation
large quantum fluctuations generate Multiverse

$$V(\phi) = \frac{m^2}{2}\phi^2$$

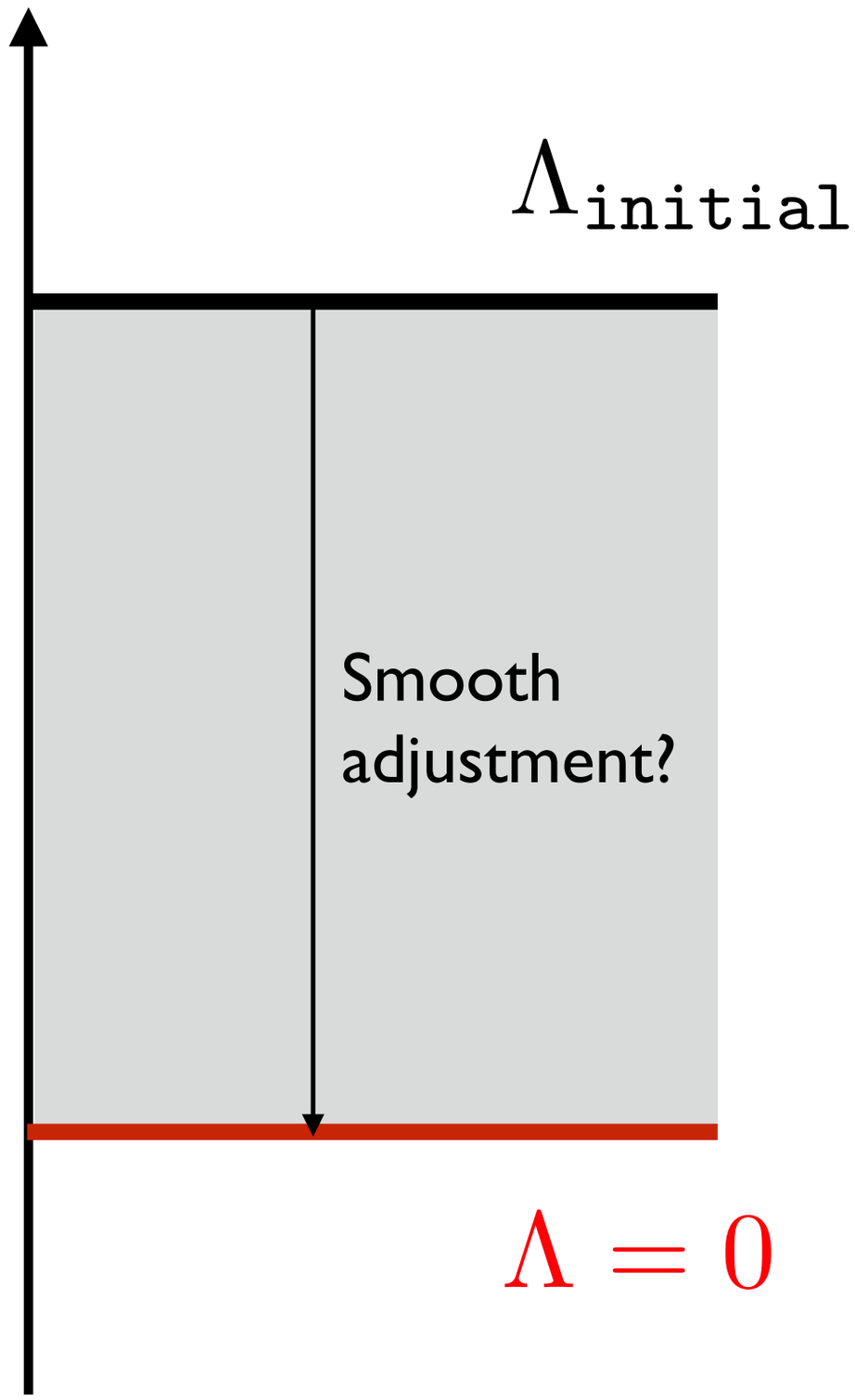


eternal inflation
large quantum fluctuations generate Multiverse



Cosmological Constant Problem

those same vacuum fluctuations
give huge CC = create ultra-rapid inflation!

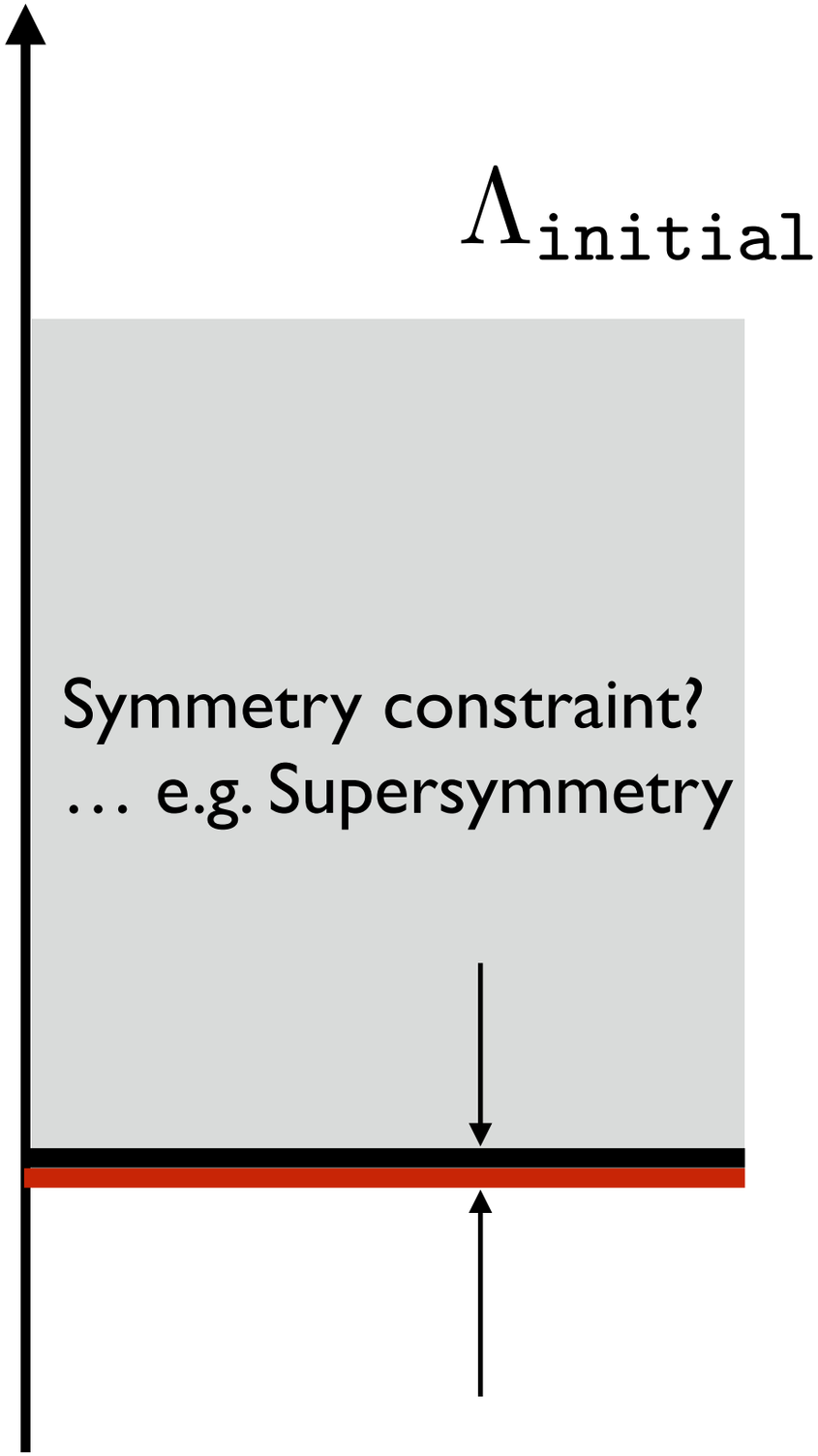


[Weinberg '89]

NO!

Cosmological Constant Problem

those same vacuum fluctuations
give huge CC = create ultra-rapid inflation!



[Weinberg '89]

NO!

Cosmological Constant Problem

those same vacuum fluctuations
give huge CC = create ultra-rapid inflation!

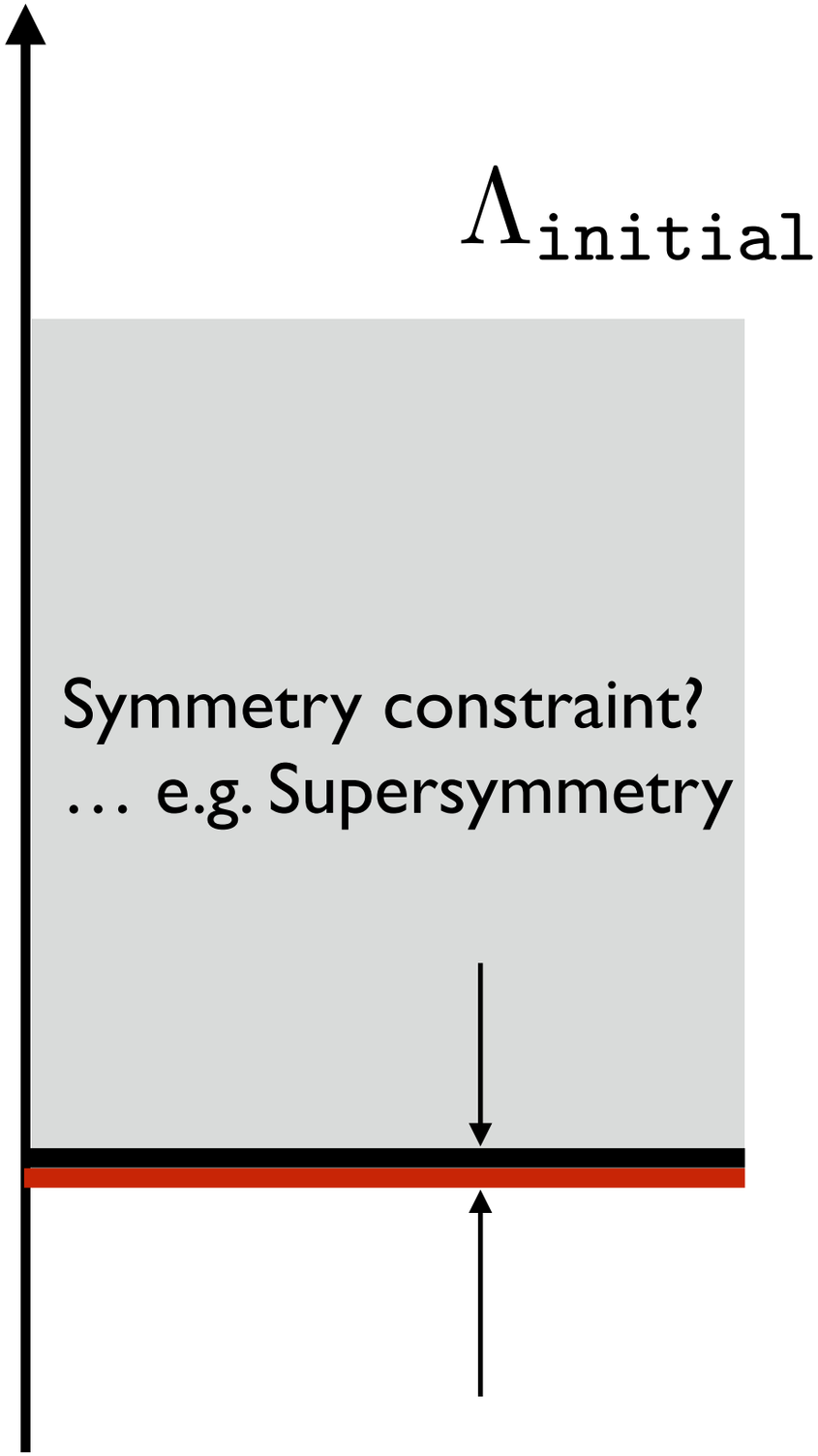
[Weinberg '89] **no cosmic structure if:**

$$\rho_{CC} \gtrsim 10^{-121} M_{\rm P}^4 = 10 \rho_{CC,0}$$

anthropic explanation of small CC

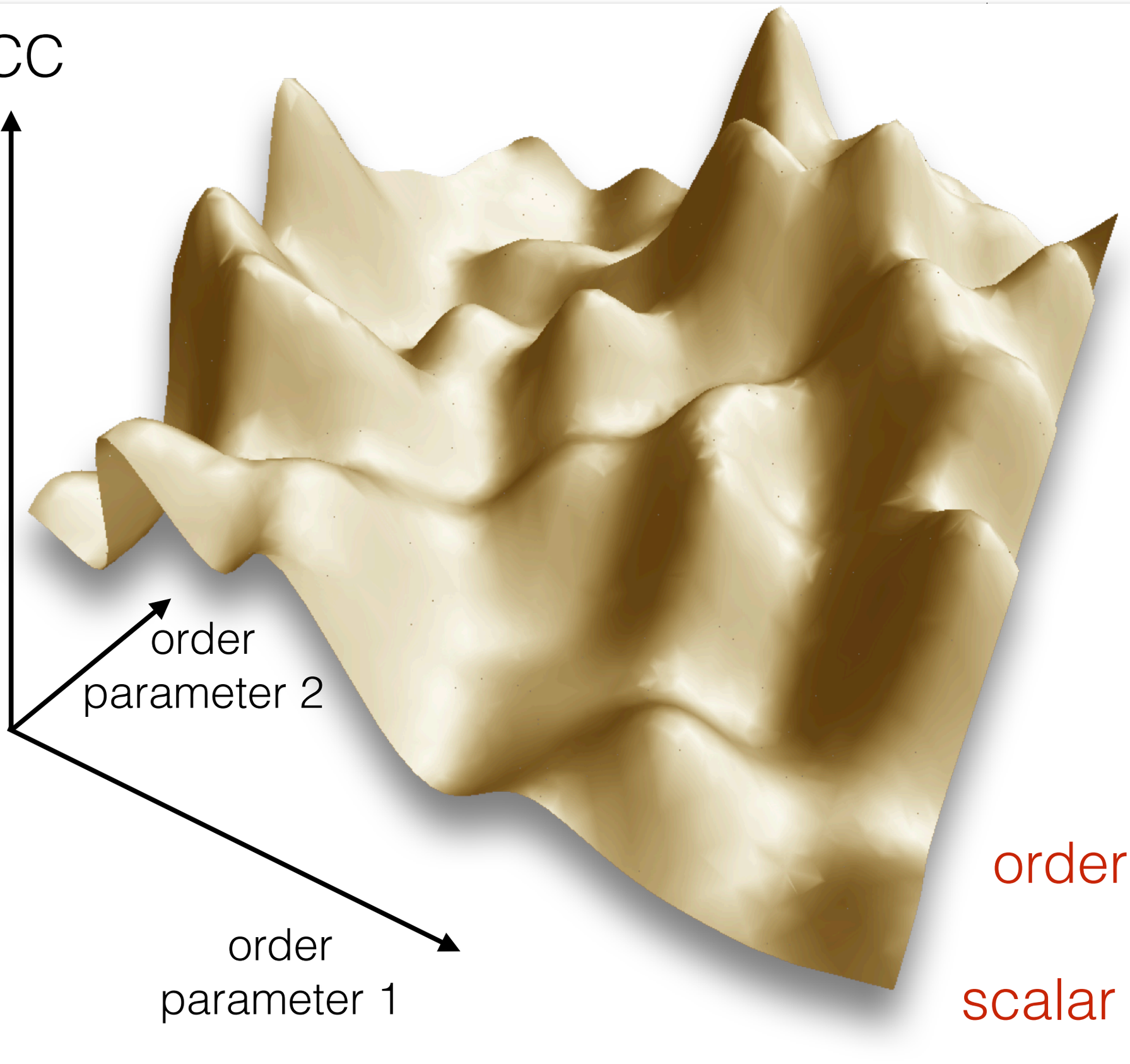
IF

… there is huge landscape of CCs !



[Weinberg '89] **NO!**

Cosmological Constant Problem



origin ?

string theory
solutions:

$\# > 10^{500}$

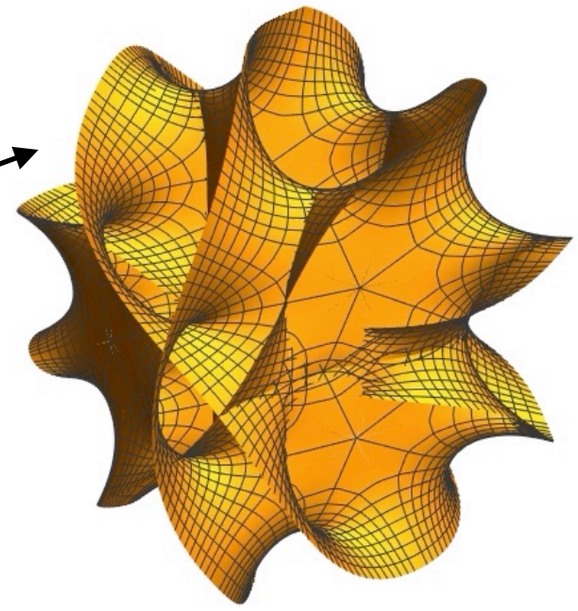
order parameters?

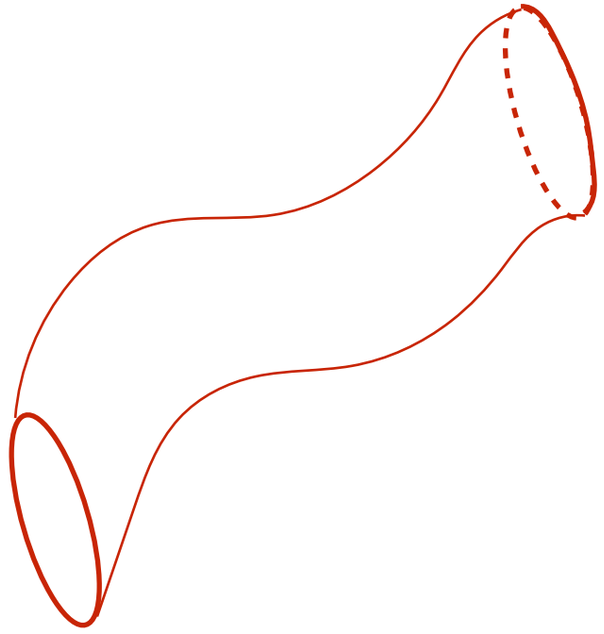
scalar fields (moduli)

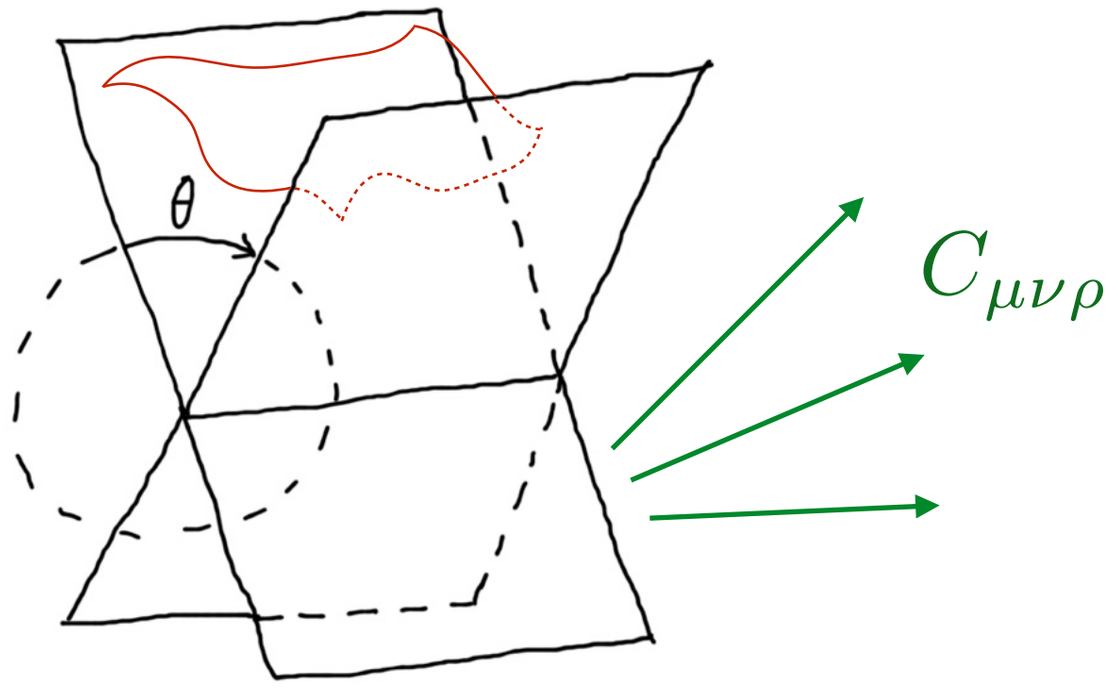
strings ...

deformations:
moduli - scalar fields

- string theory:
  - gravity + extra dimensions
  - higher-dimensional gauge fields
  - branes (SM fields)







strings ...

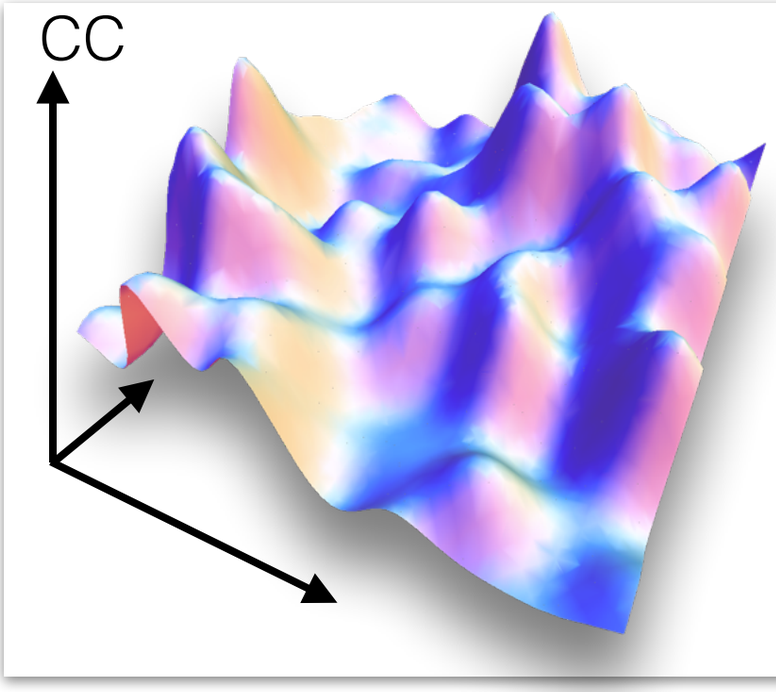
[Dasgupta, Rajesh & Sethi '99]

[Giddings, Kachru & Polchinski '01]

moduli stabilization:
field strengths (fluxes) produce
masses for moduli scalars

$$S = M_S^8 \int \mathrm{d}^{10}x\sqrt{-g}\left[e^{-2\phi}\left(R + (\partial_M\phi)^2 + |H_3|^2\right) + |F_p|^2\right]$$

$+$ branes : matter, gauge fields



landscape of CCs

[Kachru, Kallosh, Linde & Trivedi '03]

[Susskind '03]

… many more since then …

$\partial_{[M}B_{NP]}$

$\partial_{[M}C_{NP\ldots Q]}$

like Maxwell, but more indices

string landscape ... borders the swamp

[Kachru, Kallosh, Linde & Trivedi '03]

[Susskind '03]

- # of discrete solutions (`vacua') very large:

  - $\sim \#(\text{fluxes})^{\#(\text{cycles})} \gg 10^{100}$ **the landscape**

  - many different matter & gauge field spectra

string landscape ... borders the swamp

[Kachru, Kallosh, Linde & Trivedi '03]

[Susskind '03]

- # of discrete solutions (`vacua') very large:

  - $\sim \#(\text{fluxes})^{\#(\text{cycles})} \gg 10^{100}$ **the landscape**

  - many different matter & gauge field spectra

- anything goes? — No!

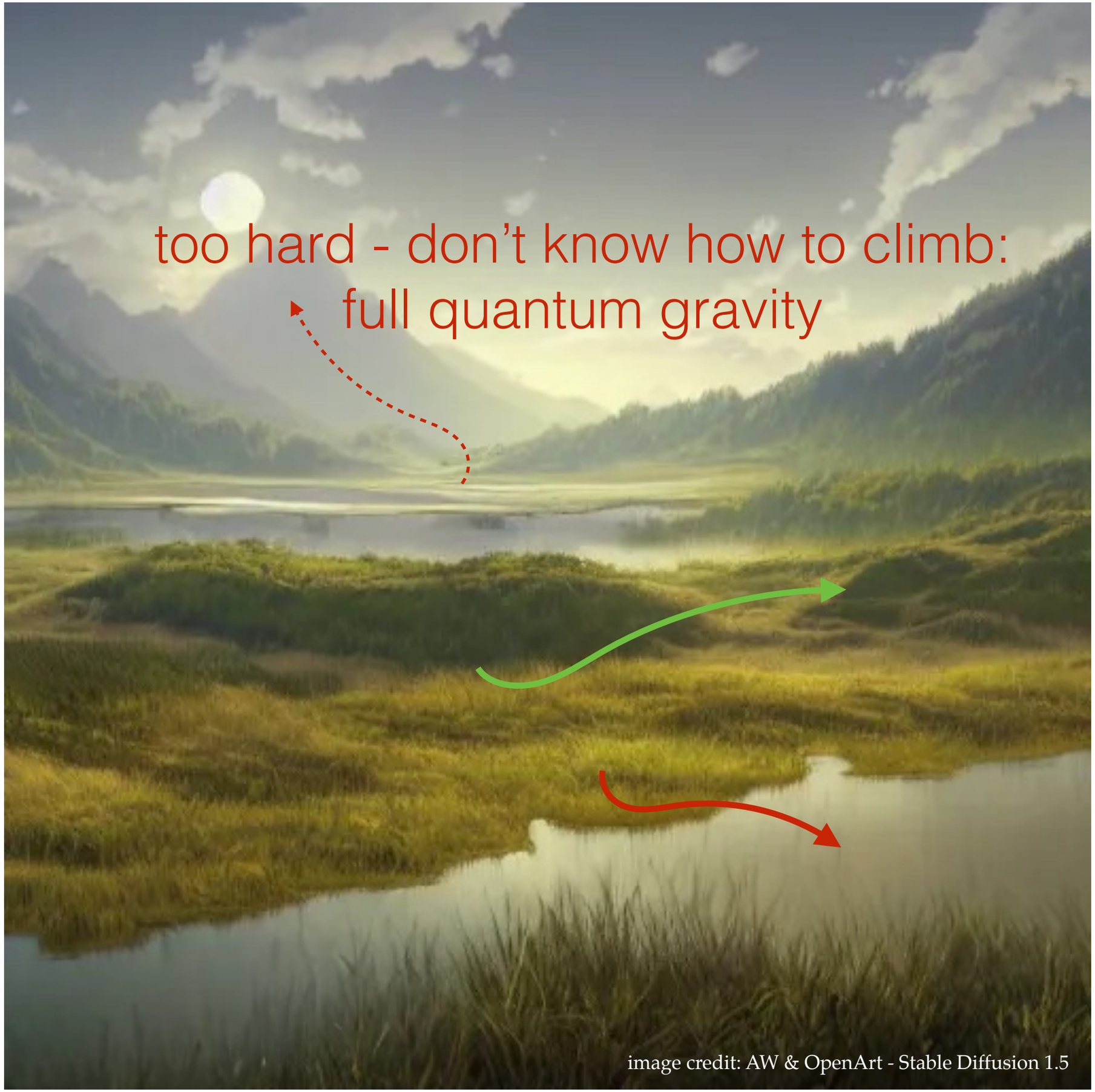
- Swampland observation:

[Vafa '05] [Ooguri & Vafa '06]

[Arkani-Hamed, Motl, Nicolis & Vafa '06]

[many works since '15 including from IFT]

some consistent QFT's don't mesh well with string theory or semi-classical gravity …
… on-going research program **the swamp**

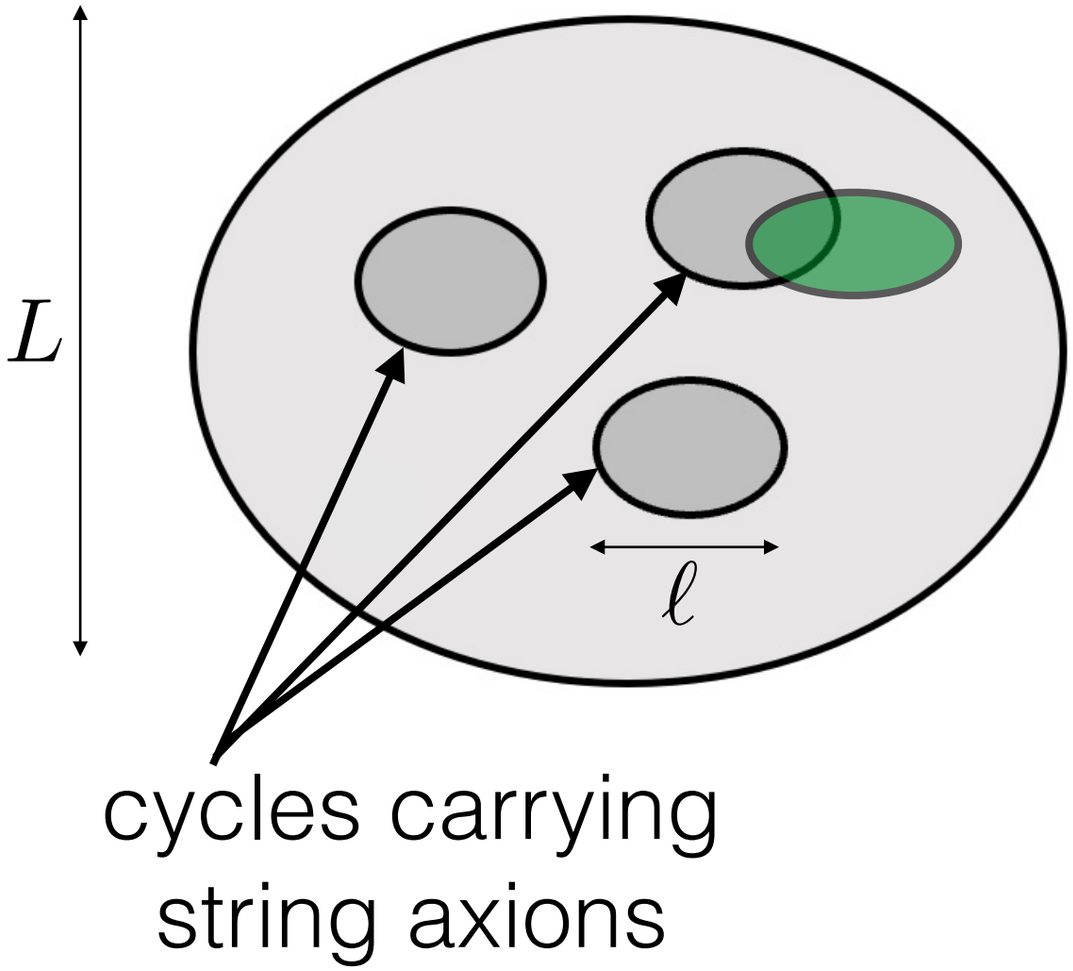


walkable landscape

avoid obvious swamp!

axions from string theory

[Peccei & Quinn '77]
[Weinberg '78]
[Wilczek '78]



cycles carrying
string axions

$$\mathcal{L} = f^2(\partial_\mu a)^2$$

$$-m_a^2 \cdot f^2 \cos(a)$$

[Gendler, Marsh, McAllister & Moritz '23]
[Berg, Marsh, McAllister & Pajer '10]
[Hebecker, Jaeckel & Kuespert '23]

axions from string theory

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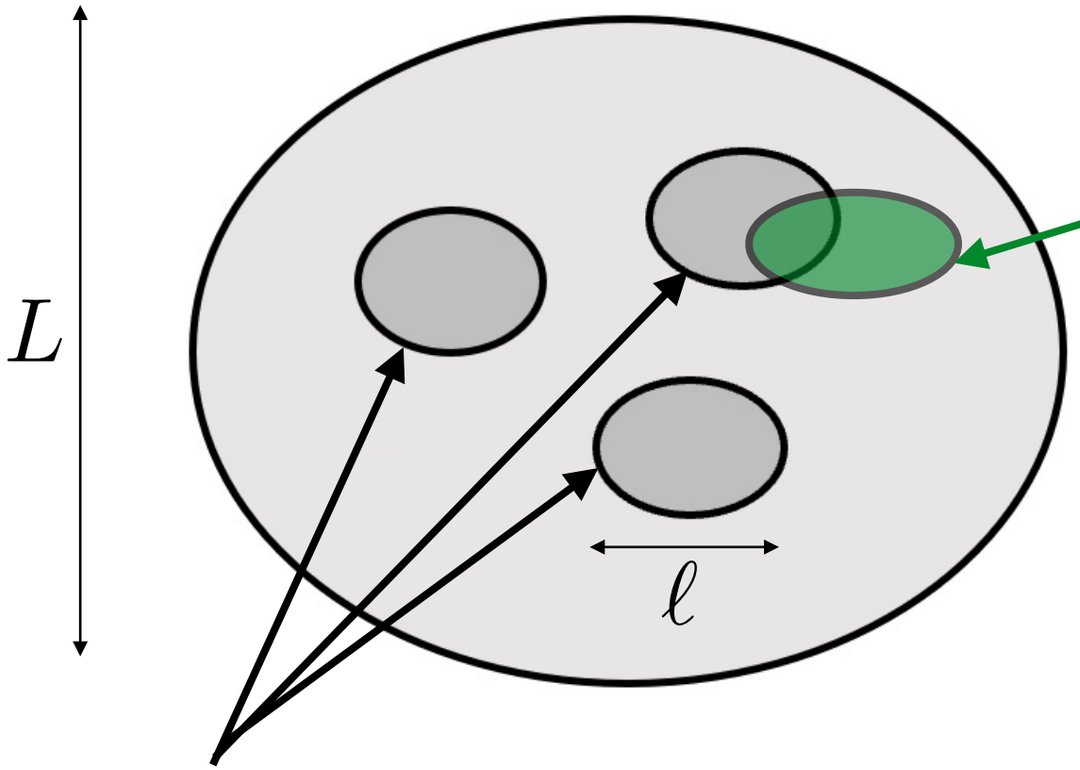

cycle carrying branes with SM

cycles carrying string axions

$$\int_{p-dim.\ cycle} C_p = a$$

fixes strong CP

$$\mathcal{L} = f^2(\partial_\mu a)^2 \quad -a\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma}$$

$$-m_a^2 \cdot f^2 \cos(a)$$

[Gendler, Marsh, McAllister & Moritz '23]
[Berg, Marsh, McAllister & Pajer '10]
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axions from string theory

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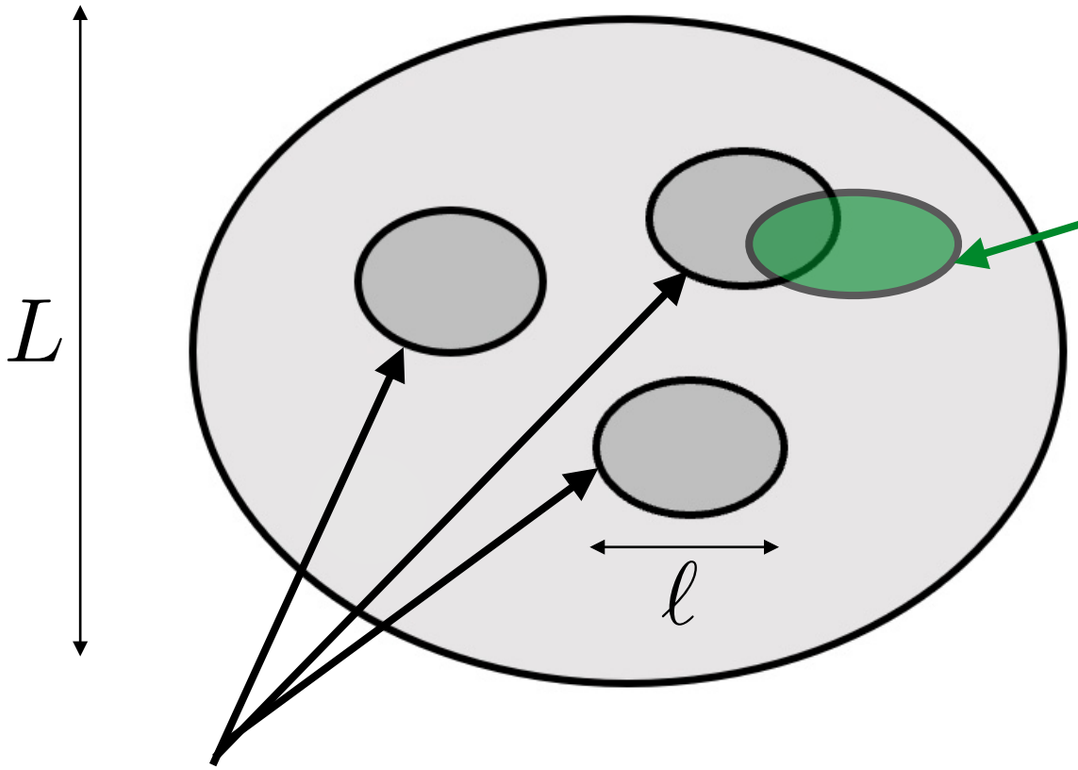


cycle carrying branes with SM

cycles carrying string axions

$$\int_{p-dim.\ cycle} C_p = a$$

$$\mathcal{L} = f^2 (\partial_\mu a)^2$$

$$f \sim \frac{M_{\rm P}}{\ell^d}$$

$$-m_a^2 \cdot f^2 \cos(a)$$

$$m_a^2 \sim M_{\rm P}^2 \, e^{-\ell^d}$$

… most axions are dark!

… instanton effects

[Gendler, Marsh, McAllister & Moritz '23]
[Berg, Marsh, McAllister & Pajer '10]
[Hebecker, Jaeckel & Kuespert '23]

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09]
[Cicoli, Goodsell & Ringwald '12] , many many more …

- consequence of string extra dimensions:
  a p-form & many (p or p-1-dim) cycles
  — *O*(100) axions and "photons" !!

★ string theory generically contains **many axions**

★ **decay constants** are **high** => **universal !!**
… **power-law** in extra-dim. size

★ **masses** distribute **exponentially wide** => **for type IIB strings yes**
… **exponential** in extra-dim. size **… but for heterotic strings ?**

★ couplings to SM: mostly no …
… exceptions highly model-dependent (e.g. kinetic mixing)

string theory axiverse & photoverse !

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09] [Coudarchet, Hebecker, Jaeckel & Steiner '25]

string axions ...

- heterotic string …

gauge coupling unification & perturbativity:

$$g_{\rm YM}^{-2} \sim \mathcal{V}/g_s^2 \qquad \Rightarrow \mathcal{V} \lesssim 20$$

[Hebecker & Trapletti '04]

[Cicoli, de Alwis & AW '13]

isotropic - extra-dimensions - fibration (anisotropic)

$$\mathcal{V} = \frac{\kappa_{ijk}}{6} v^i v^j v^k$$

$$v^i \simeq v^j \lesssim 3$$

$$\mathcal{V} = \frac{\kappa_{bff}}{2} v^b (v^f)^2$$

$$h^{1,1} = 2$$

$$\Rightarrow \; v^b \simeq 30 \; , \; v^f = \mathcal{O}(1)$$

- type IIB string … [KKLT , LVS , ...]

$$\mathcal{V} > 10^3 \ldots 10^4 \qquad \text{several} \;\; v^i \gtrsim 10$$

axions in the heterotic string

[Leedom, Putti & AW '25]

2 classes of axion spectra:

$$\Lambda^4_{QCD} \ll \Lambda^4_{WS,i} \sim e^{-2\pi v^i}$$

mass (log-scale)

GUT scale

eV

10^{-20} eV

string axions

QCD axion

$$\Lambda^4_{QCD} \ll \Lambda^4_{WS,i} \sim e^{-2\pi v^i}$$

1 large cycle !

$$\Lambda^4_{WS,b} \sim e^{-2\pi v^b} \ll \Lambda^4_{QCD}$$

string axions

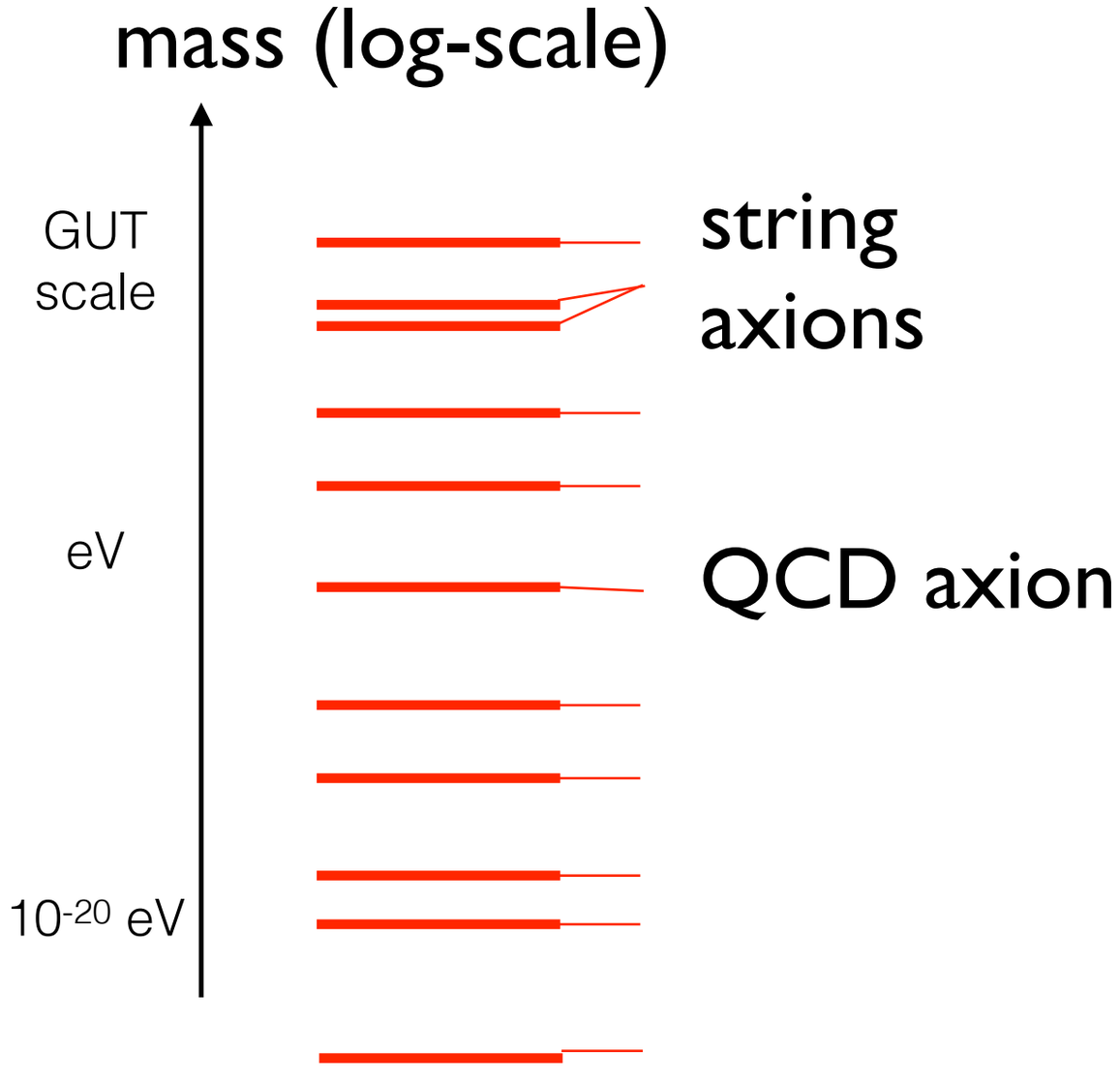
QCD axion

1 fuzzy DM string axion

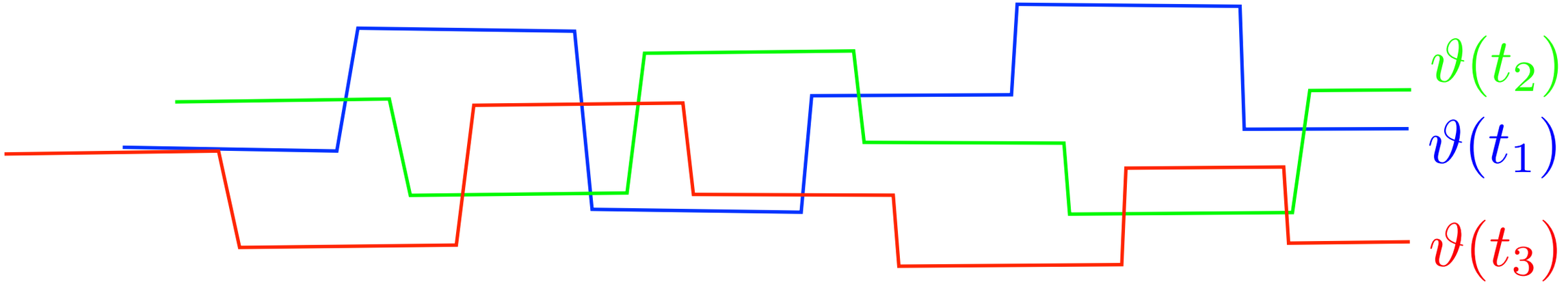
axions in type IIB

[Cicoli, Guidetti, Righi & AW '21]
[Demirtas, Gendler, Long, McAllister & Moritz '21]
[Gendler, Marsh, McAllister & Moritz '23]
[Carta, Gendler, Jain, Marsh, McAllister, Righi, Rogers & Schachner '25]
[Vander Ploeg Fallon, Halverson, McAllister & Zhu '25]

type IIB axion spectra:



- during inflation, all light stuff — including light axions drifts & decays …



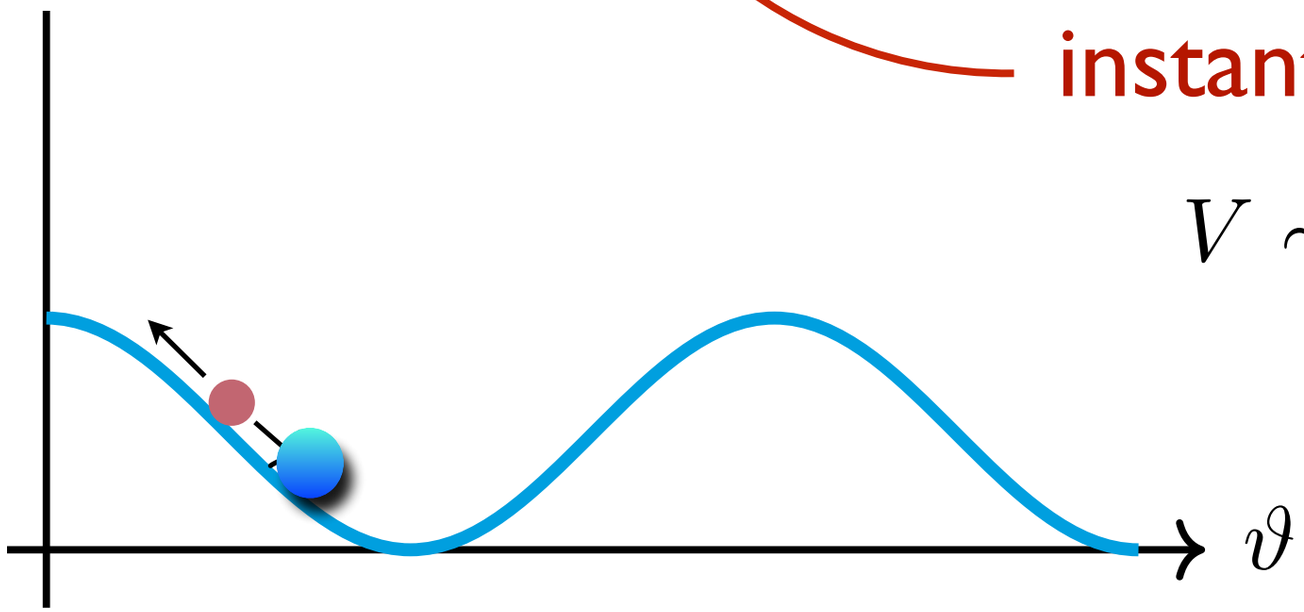
light axion ϑ :

$$f_\vartheta \sim M_{\rm GUT}$$

$$m_\vartheta < H \ , \ V \text{ periodic} \ \Rightarrow \ \langle \vartheta \rangle \sim f_\vartheta$$

instanton effects

$$V \sim \cos\left(\frac{\vartheta}{f_\vartheta}\right)$$



axion is in deep slow-roll = frozen on the slopes

quantum drift from dS fluctuations dominates = it walks up the hill …

- after inflation I …

$m_\vartheta > H$: frozen ϑ melts … ϑ oscillates - it is matter !

- after inflation II …

[Kaloper & AW '24]

$$\text{at } a_\star \quad : \quad \rho_\vartheta = m_\vartheta^2 f_\vartheta^2 \frac{a_{melt}^3}{a_\star^3} = \rho_{rad.} = \frac{T_{reh}^4}{a_\star^4}$$

$$\Rightarrow \text{for } m_\vartheta > 10^{-19}\ \text{eV we have } T_\star > \text{eV}.$$

see also: [Cicoli, Guidetti, Righi & AW '21]

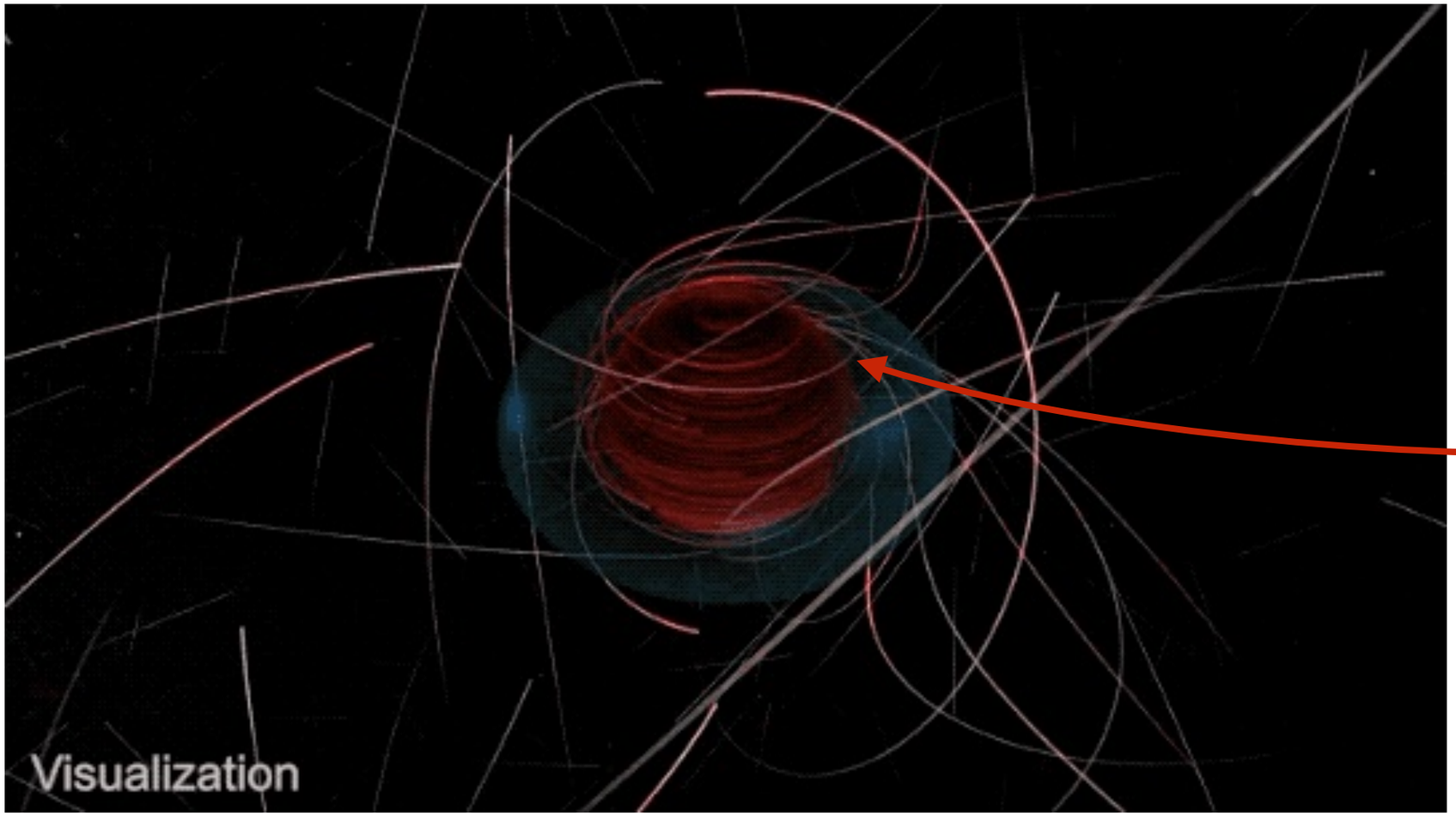
too much DM !

$\Rightarrow$ anthropic cut $\langle\vartheta\rangle_{\text{anthr.}} < f_\vartheta$ so $T_\star = \text{eV}$

black hole superradiance production of axions

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09]

based on:
[Penrose '69 ; Christodoulou '70]



spinning black hole (BH)

Credit: NASA's Goddard Space Flight Center

light axion fed from ergo region of near-extremal rotating BH:

$$\lambda_{\text{de Broglie},\,\vartheta} \sim \frac{1}{m_\vartheta} \quad \overset{!}{\sim} \quad R_{\text{BH}} \sim M_{\text{BH}}$$

$$\Rightarrow \quad m_\vartheta \sim 10^{-20}\,\text{eV}\,\frac{10^8\,M_\odot}{M_{\text{BH}}}$$

- a possible future observational outcome …

[Kaloper & AW '24]

(i) inflation is high-scale (CMB B-mode detection)

(ii) BH superradiance detects an axion ϑ with

$$m_\vartheta > 10^{-19}\,\mathrm{eV} \quad \Rightarrow \quad T_\star > \mathrm{eV}$$

(iii) other experiment determines: DM largely NOT ϑ

consequence: $\langle\vartheta\rangle_{\mathrm{obs.}} \ll \langle\vartheta\rangle_{\mathrm{anthr.}}$

… anthropics has failed !

if (ii) does not happen — evidence for heterotic ?

summary

- weak anthropic reasoning can be useful to understand features of our universe — IF used correctly (conditions (i) AND (ii)) !!

- use it only as a last resort !

  The feature it explains may yet have a better explanation by a new mechanism !

- it is falsifiable (in at least one future observational situation), and thus in its restricted form part of science.

  Should there be used AND tested as all science — without any metaphysical whiff or 'holy fear' …

- if no mis-anthropic axion is found … evidence towards heterotic strings ?

Webb's first Deep Field — NASA, ESA, CSA, and STScI