Falsifying Anthropics

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(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...

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

How to (not) use Anthropic Reasoning

- the upshot:

  2 conditions for anthropic reasoning in science

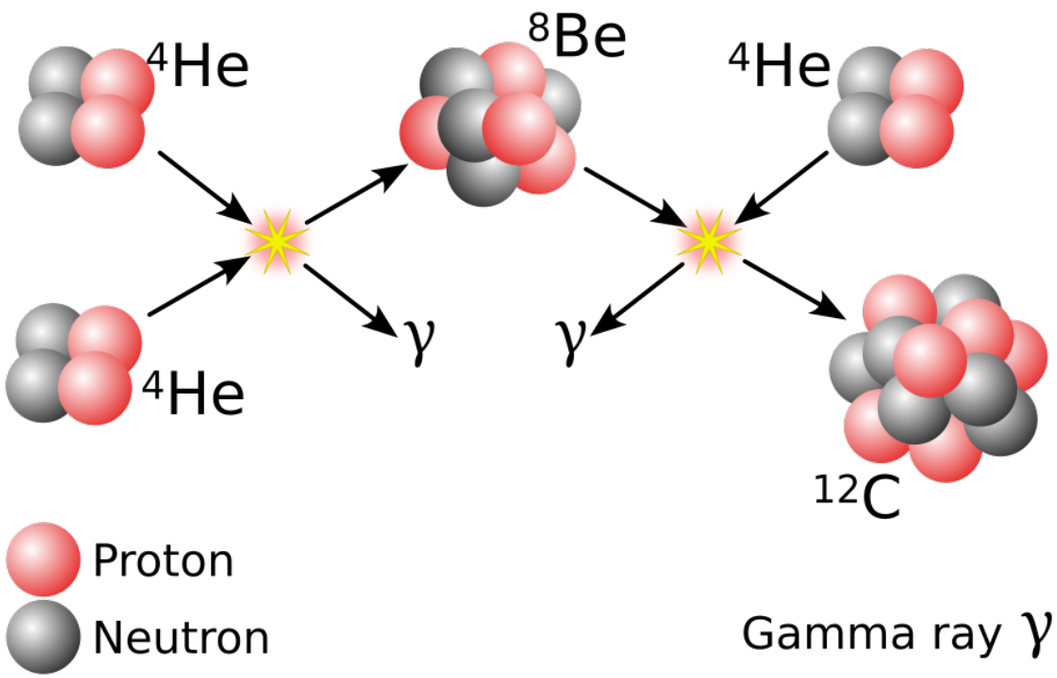
  (i) a physical parameter with a narrow range of values required by life-compatible universe

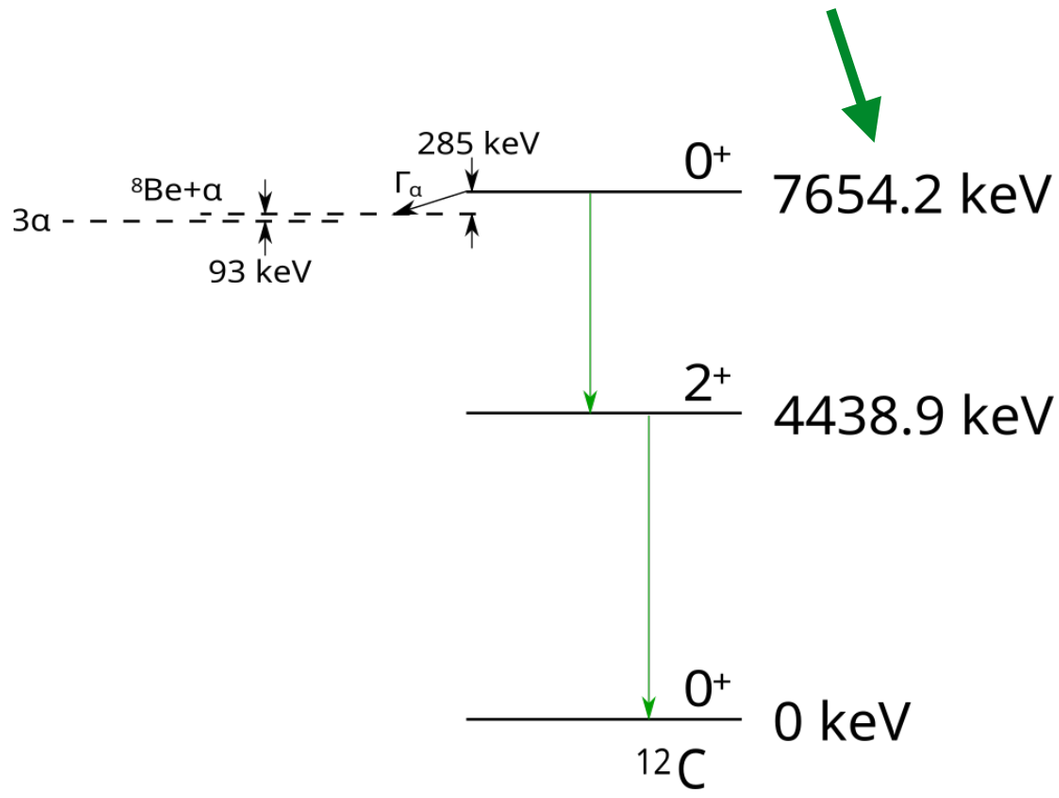
  (ii) a physical mechanism realizing a very large set of values of this parameter on a wide value range in separated regions:

- without (ii) anthropics is mere tautology !

Example - Stellar Nucleosynthesis & Hoyle State

[Hoyle '54]





- for stars to fuse enough carbon from hydrogen via helium

  - need $\Delta\alpha_{\rm EM} < 4\%$

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

[Hollowell, Weiss & Truran '89]

... anthropic constraint Standard Model coupling constants !

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:

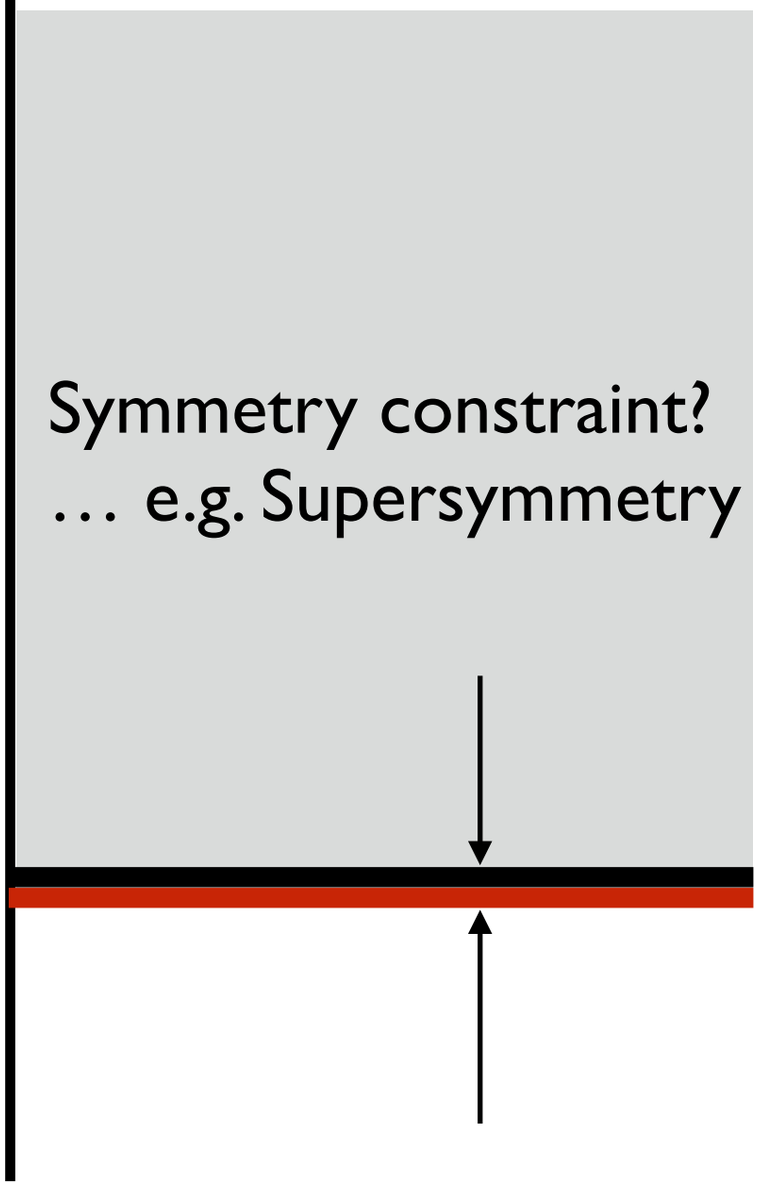
  Do we have mechanism for a multiverse ?

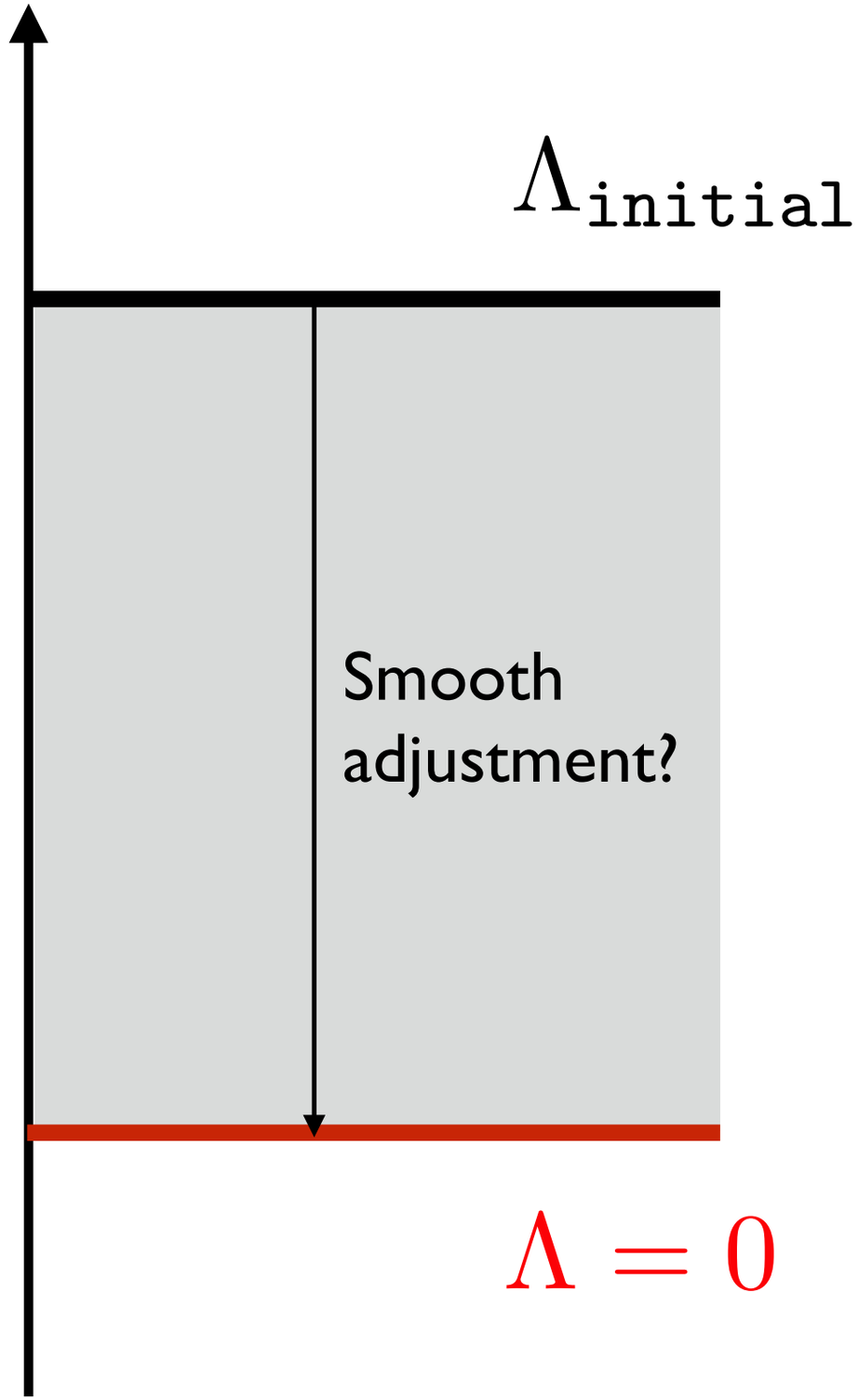
  Can we get a falsifiable prediction from anthropics ?

Cosmological Constant Problem

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

Symmetry constraint?
… e.g. Supersymmetry





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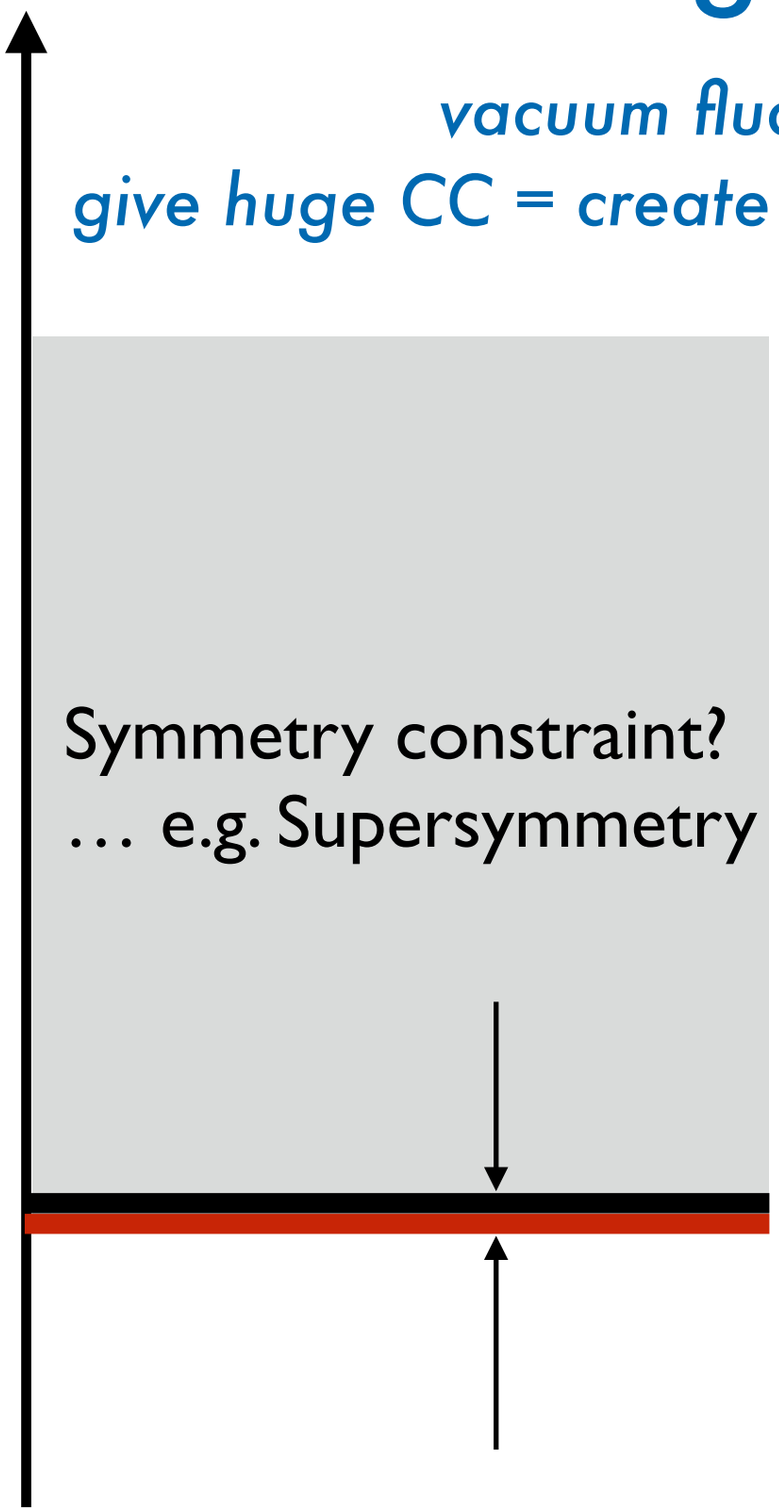
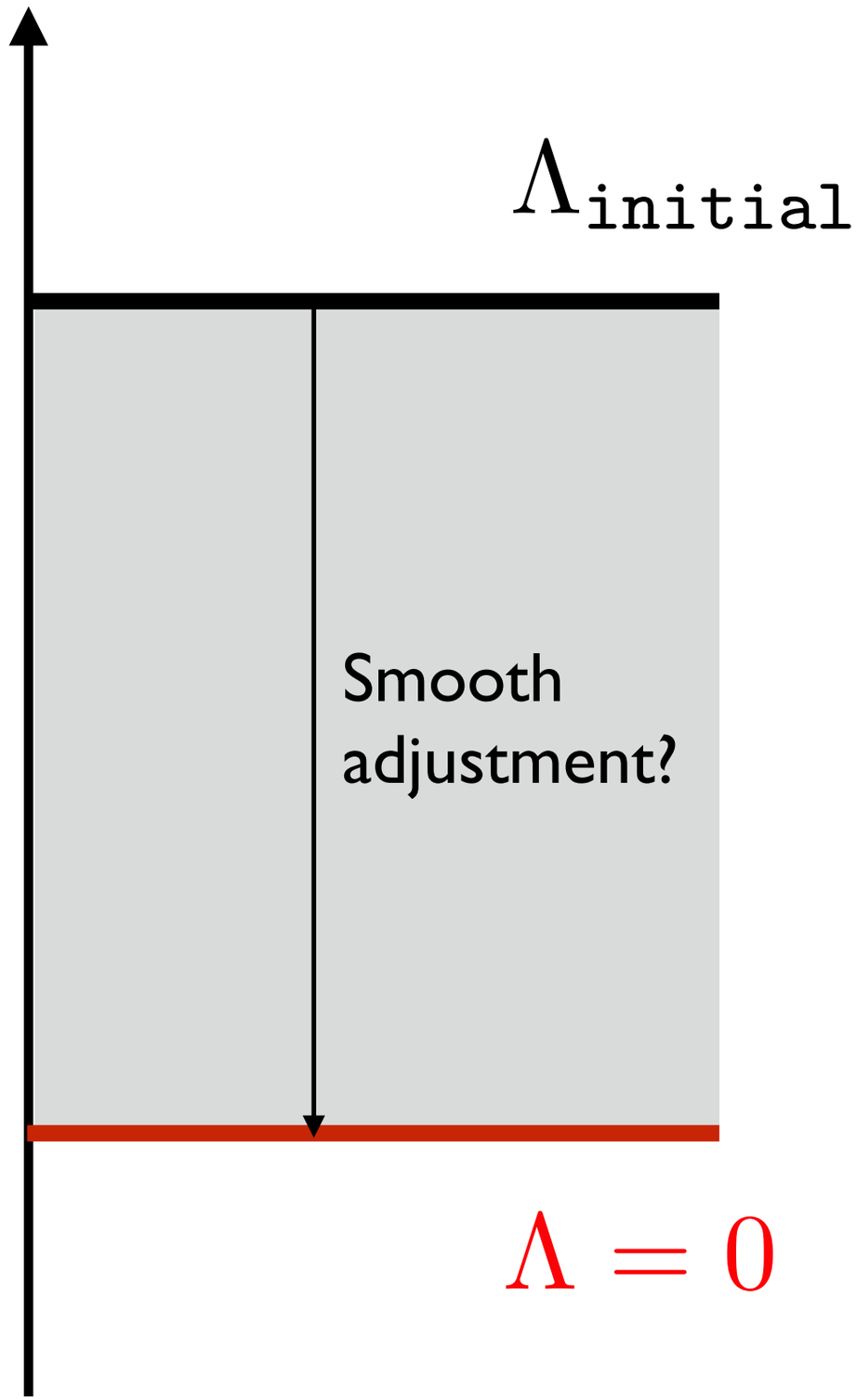


NO!



[Weinberg '89]

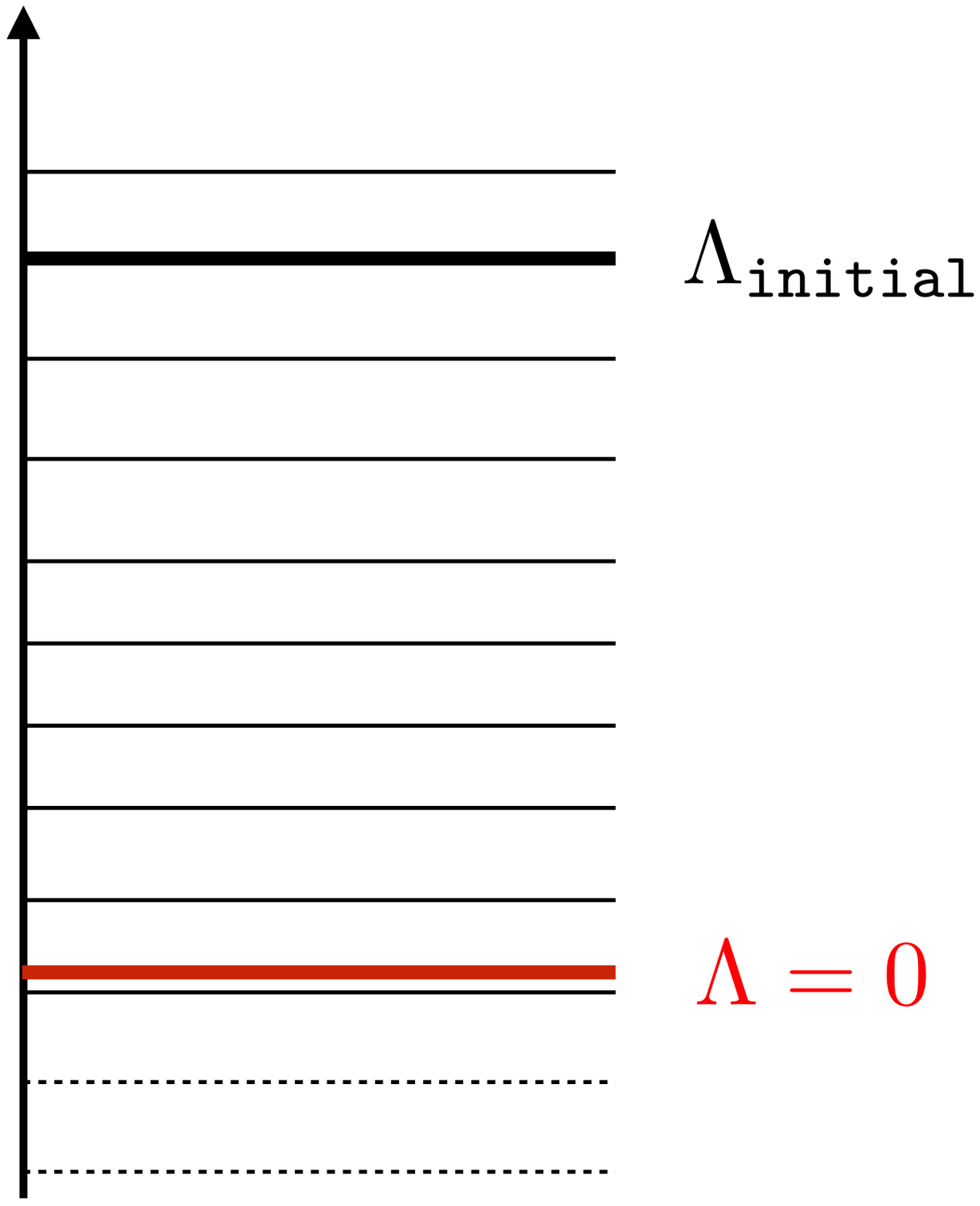
Stairway in Heaven

CC is unstable, it decays …

quantum mechanics:

tunneling !

for a single stairway,
steps too tiny [Abbott '85]



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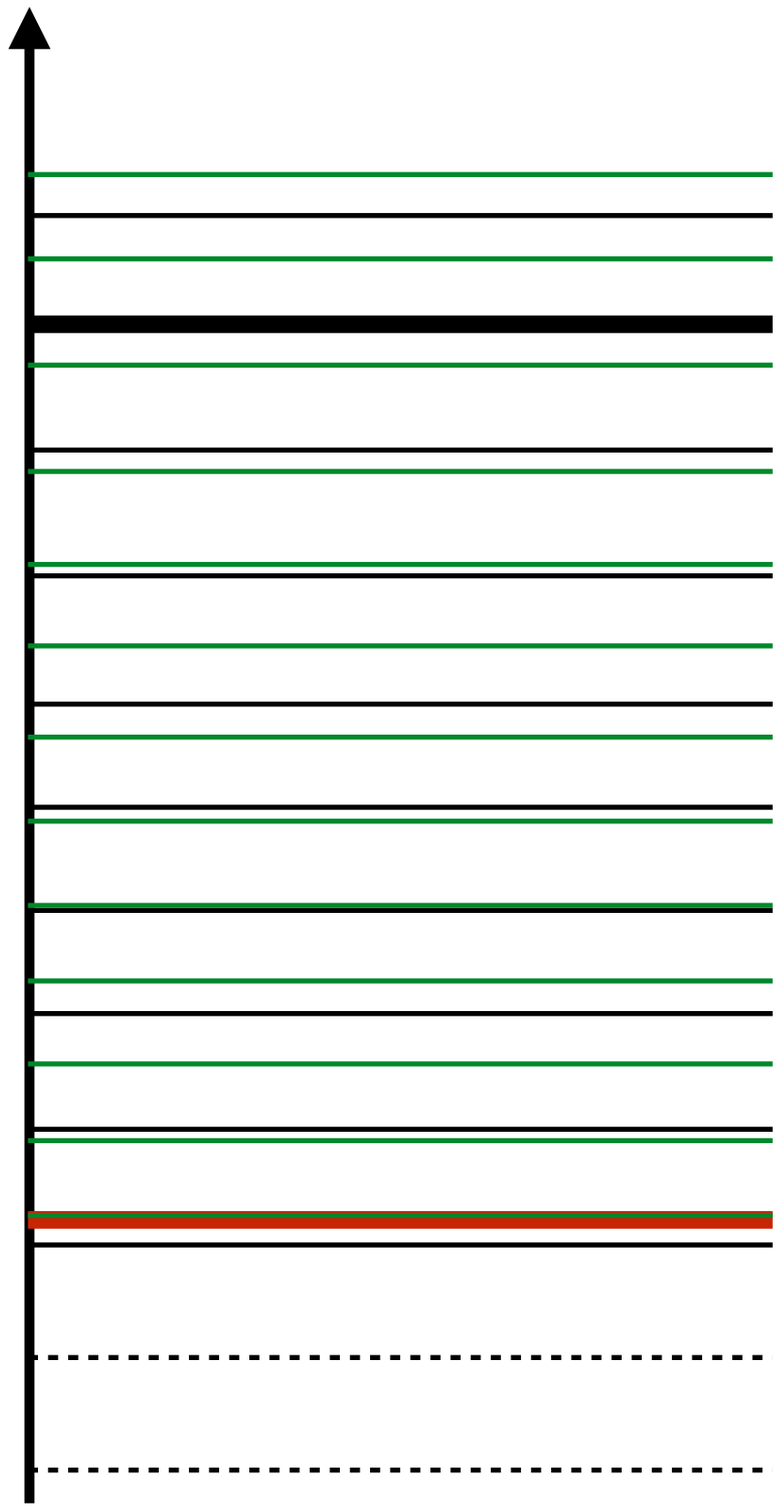


$\Lambda_{\texttt{initial}}$

to accommodate small CC,

need many stairways
somewhat out of step

… *a landscape*

$\Lambda = 0$

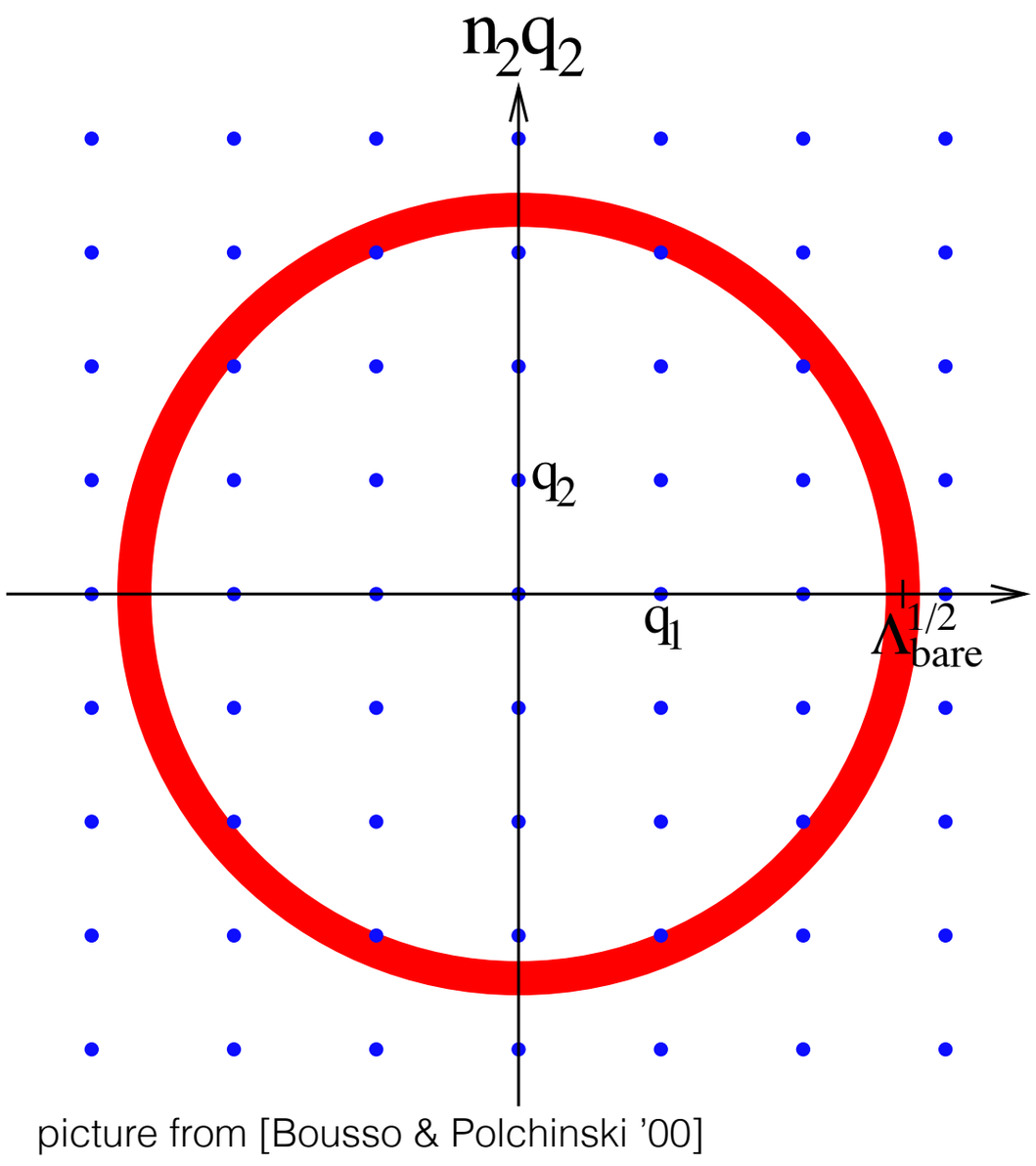
One idea …

[Brown-Teitelboim '87 & '88] , [Bousso-Polchinski '00] , [Feng, March-Russell, Sethi & Wilczek '00]

BT:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm P}^2}{2}R - \Lambda - |F_{\mu\nu\rho\sigma}|^2\right]$$

+ membrane charged under A_3



picture from [Bousso & Polchinski '00]

BP: $\Lambda = -\mathcal{O}(M_{\rm P}^4) + \sum_i q_i^2 N_i^2$

satisfies condition (ii): many different CC values, some right & realization mechanism via eternal inflation

possible origin? string vacua

One idea …

[Brown-Teitelboim '87 & '88] , [Bousso-Polchinski '00] , [Feng, March-Russell, Sethi & Wilczek '00]

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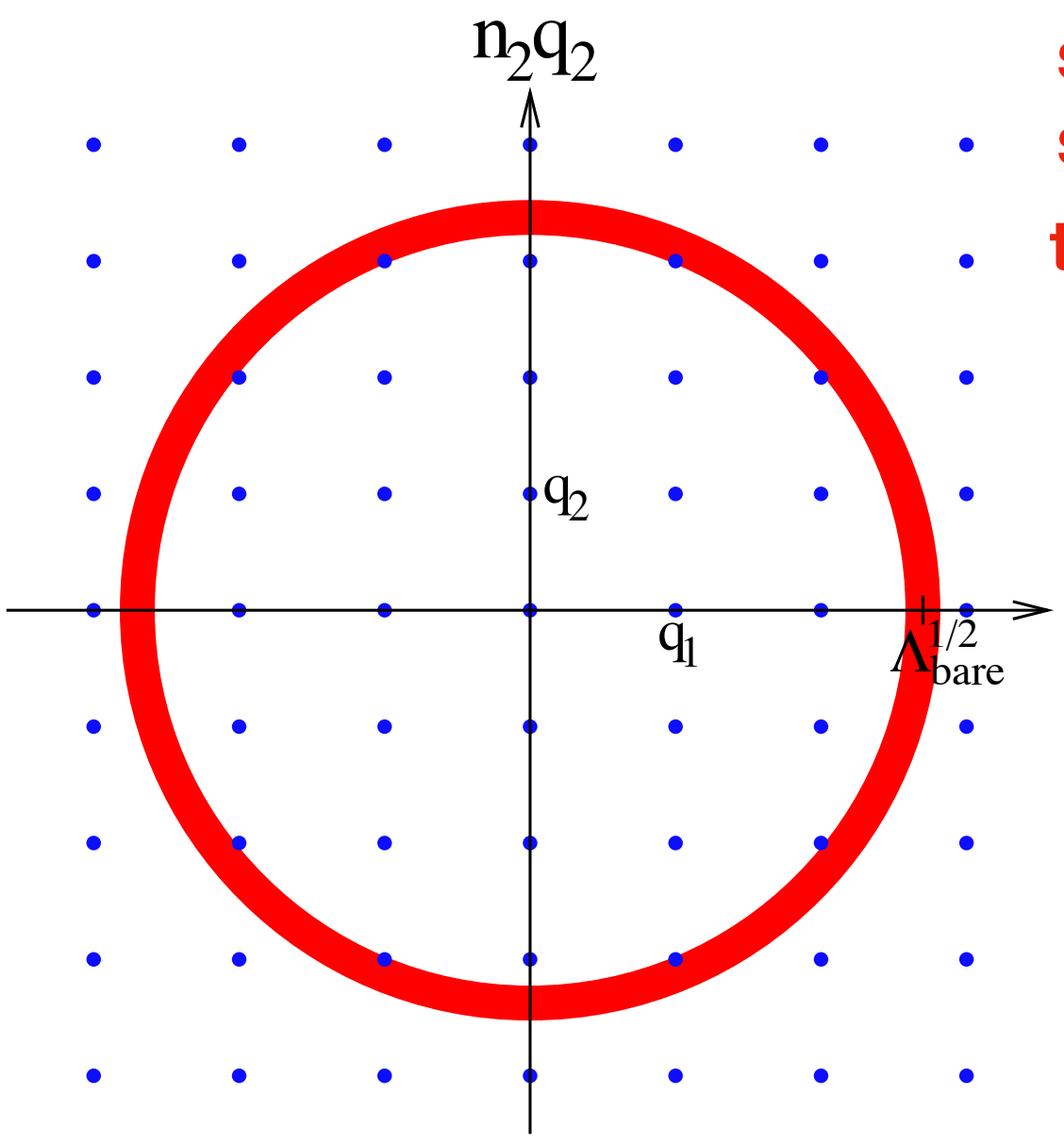

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strings
supergravity
tree level …

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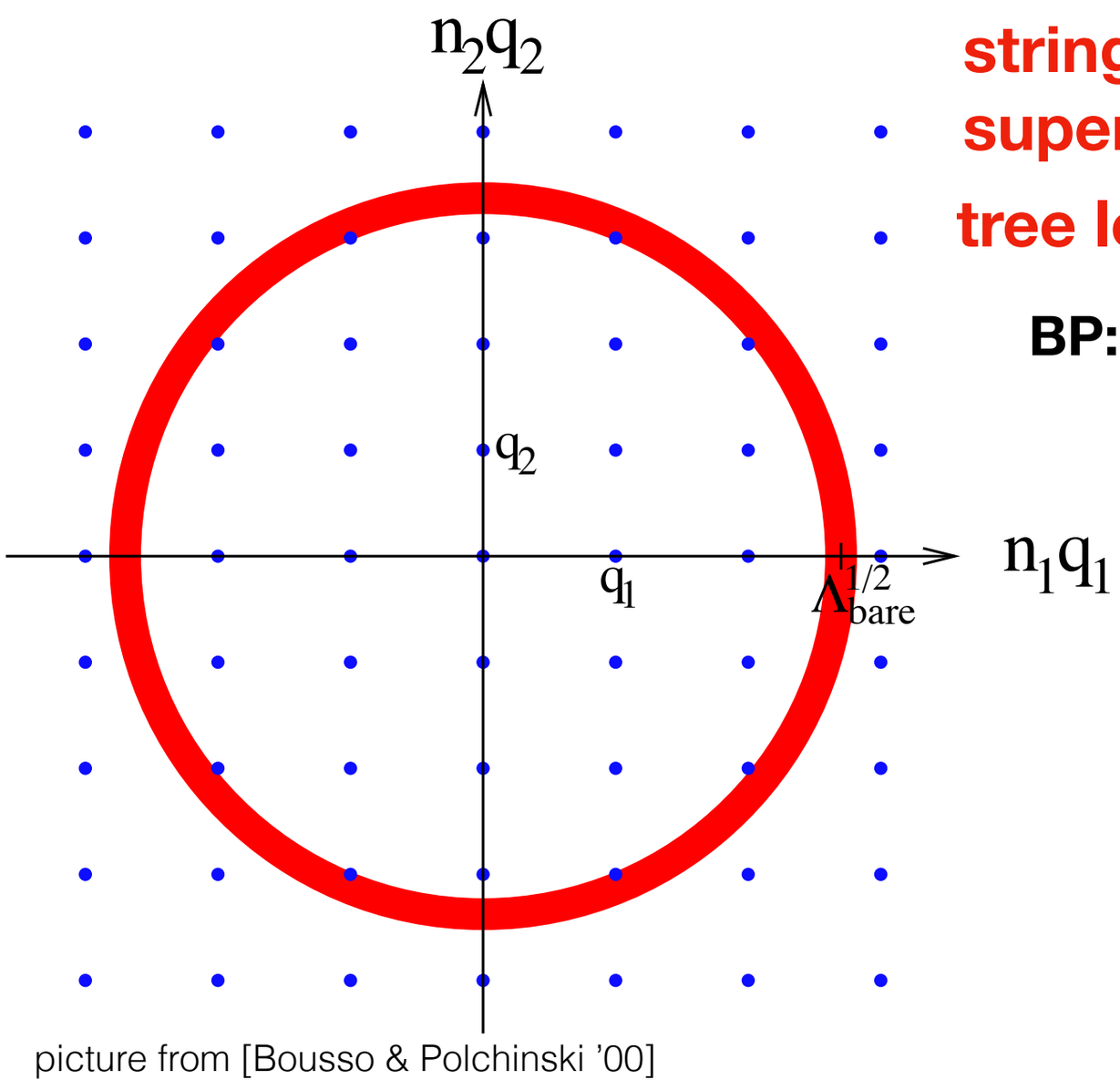


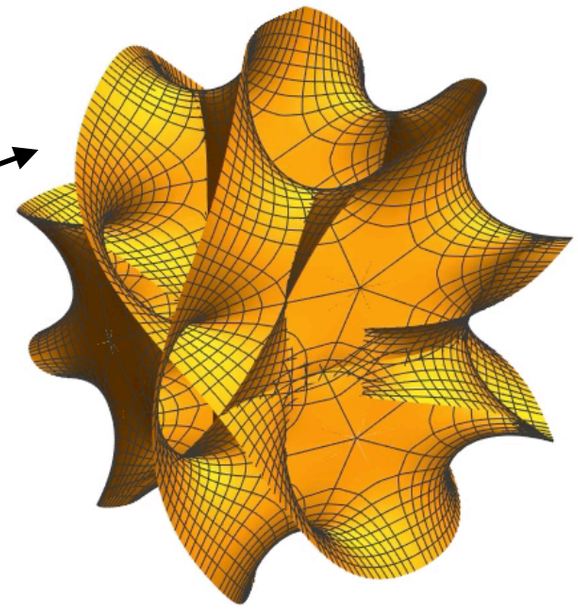
picture from [Bousso & Polchinski ’00]

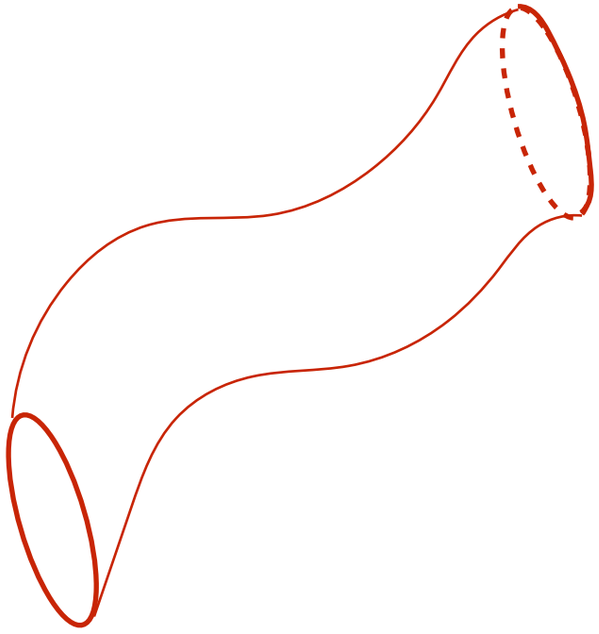
satisfies condition (ii):
many different CC values,
some right
& realization mechanism
via eternal inflation

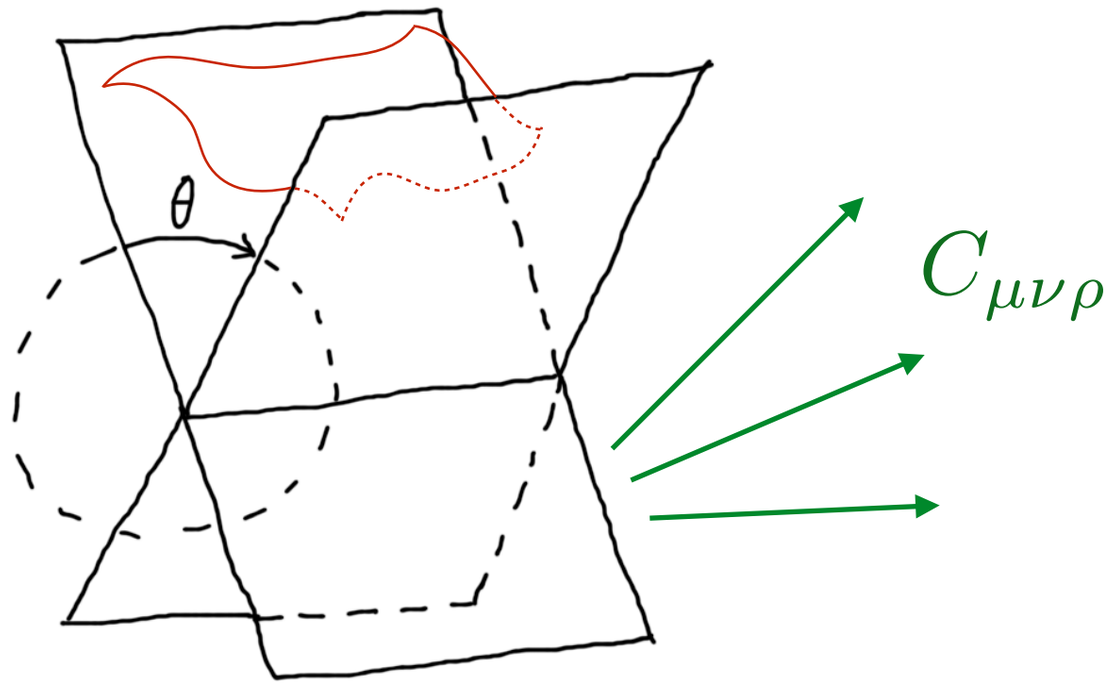
possible origin? string vacua

strings ...

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







strings ...

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

$+$ branes : matter, gauge fields

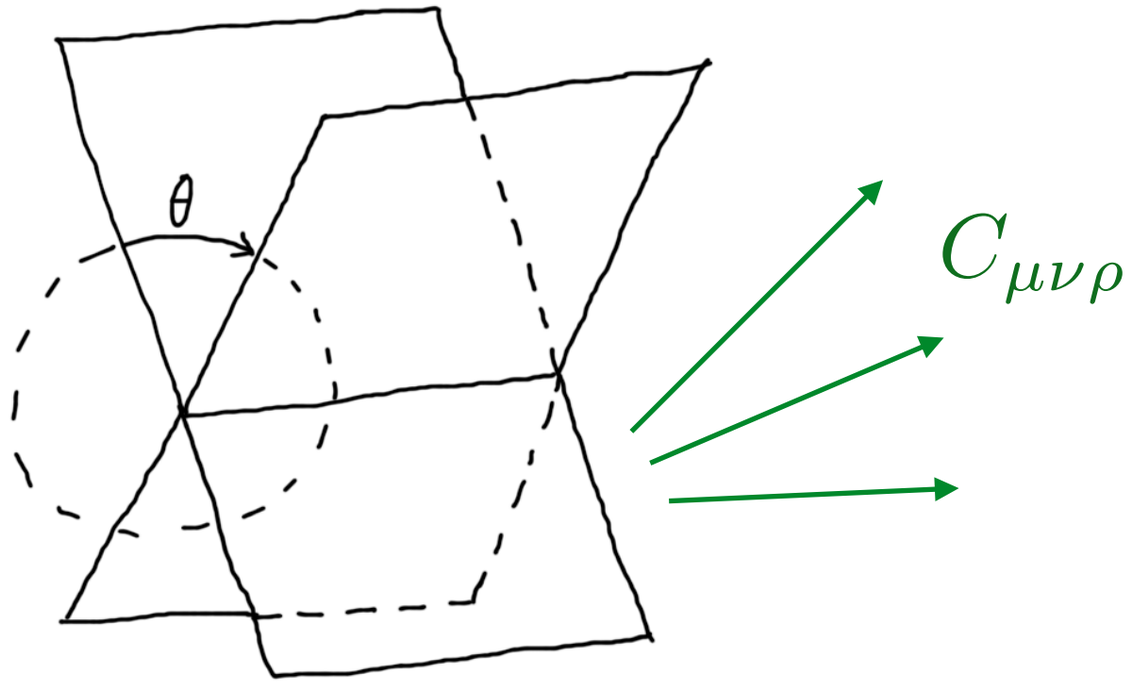
$\partial_{[M}B_{NP]}$

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

like Maxwell, but more indices

axions in string theory ...

[Svrcek & Witten '06]



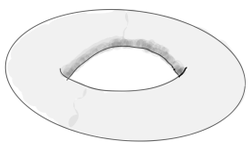
- axions:
  - Kaluza-Klein 0-modes of p-form gauge fields
  - angles θ_a between branes
  - ~~phases of open-string matter fields~~

axions from string theory

$$\int_{\Sigma^{(p)}} C_p = A_0$$

A_0 = 0-dim gauge field, i.e. an axion

$\Sigma^{(p)}$ = internal cycle of extra dimensions



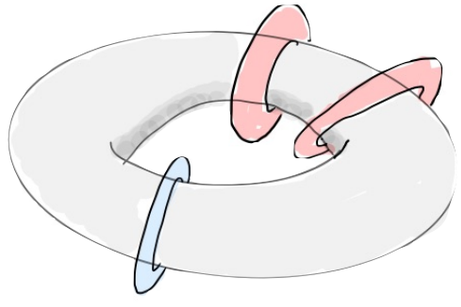
example - type IIB string theory :

$$\int_{\Sigma_i^{(4)}} C_4 = \theta_i \qquad \int_{\Sigma_a^{(2)}} C_2 = c_a \qquad \int_{\Sigma_a^{(2)}} B_2 = b_a$$

we call them axions because:

- after compactification: continuous shift symmetry
  inherited from the 10d gauge invariance

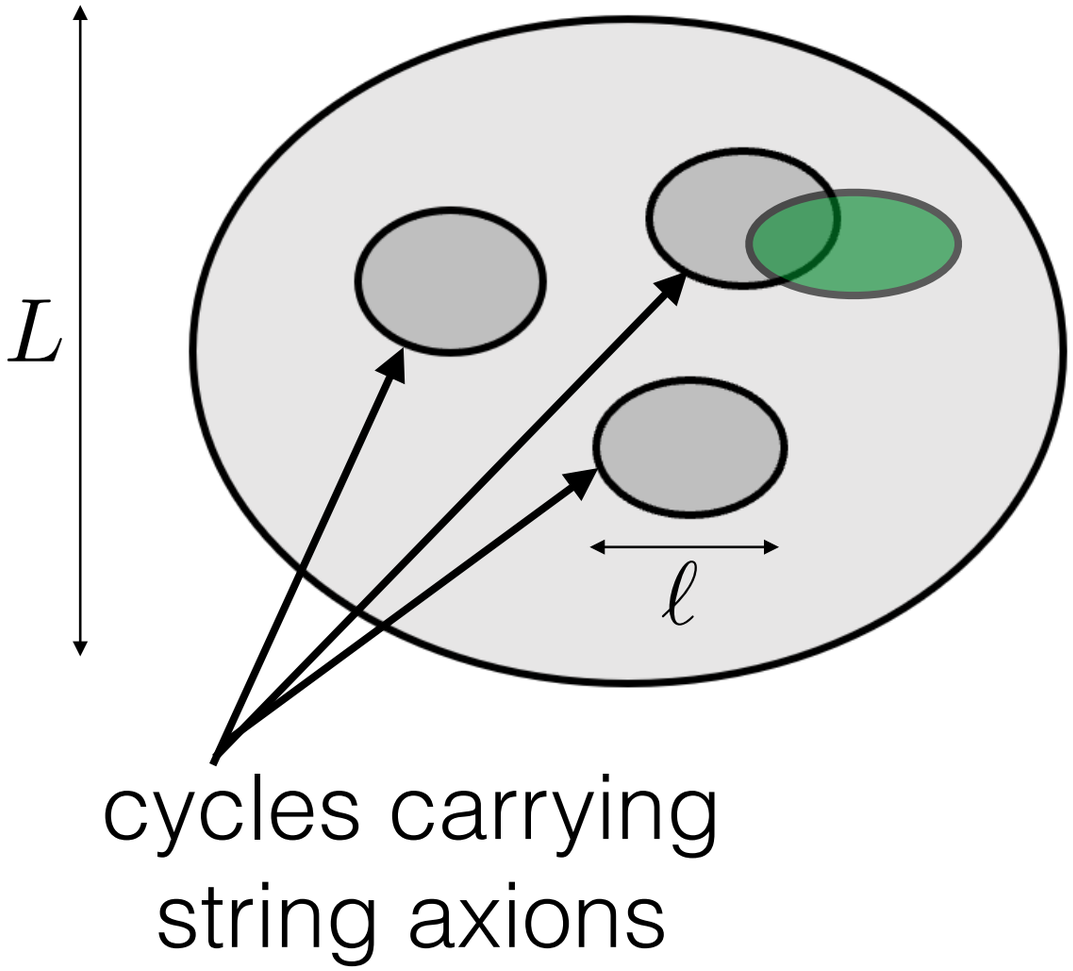
- introduce branes: shift symmetry broken to a discrete one
  ⇕ + generate a potential (hence a mass) for the axions
  instantons of complex action S : produce periodic potential



images by N. Righi

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]
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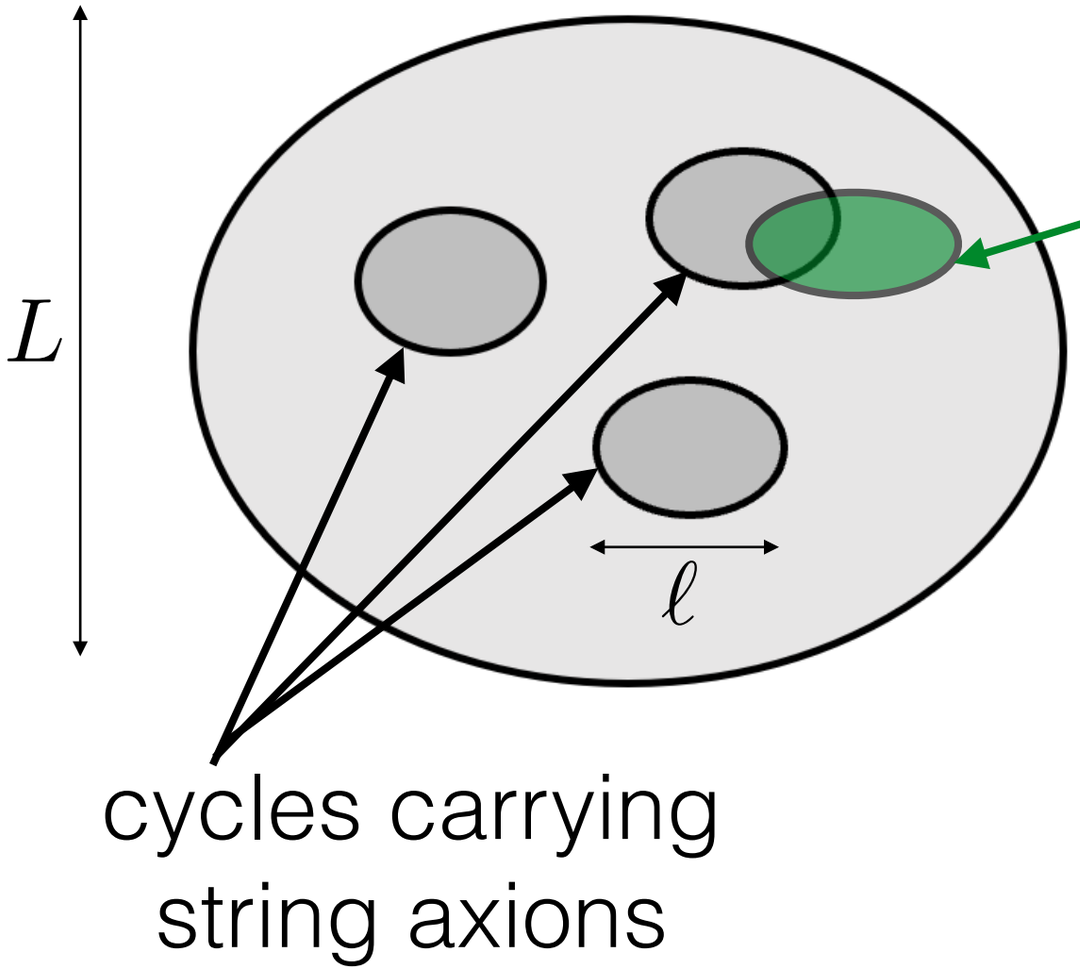

cycle carrying
branes with SM

fixes strong CP

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

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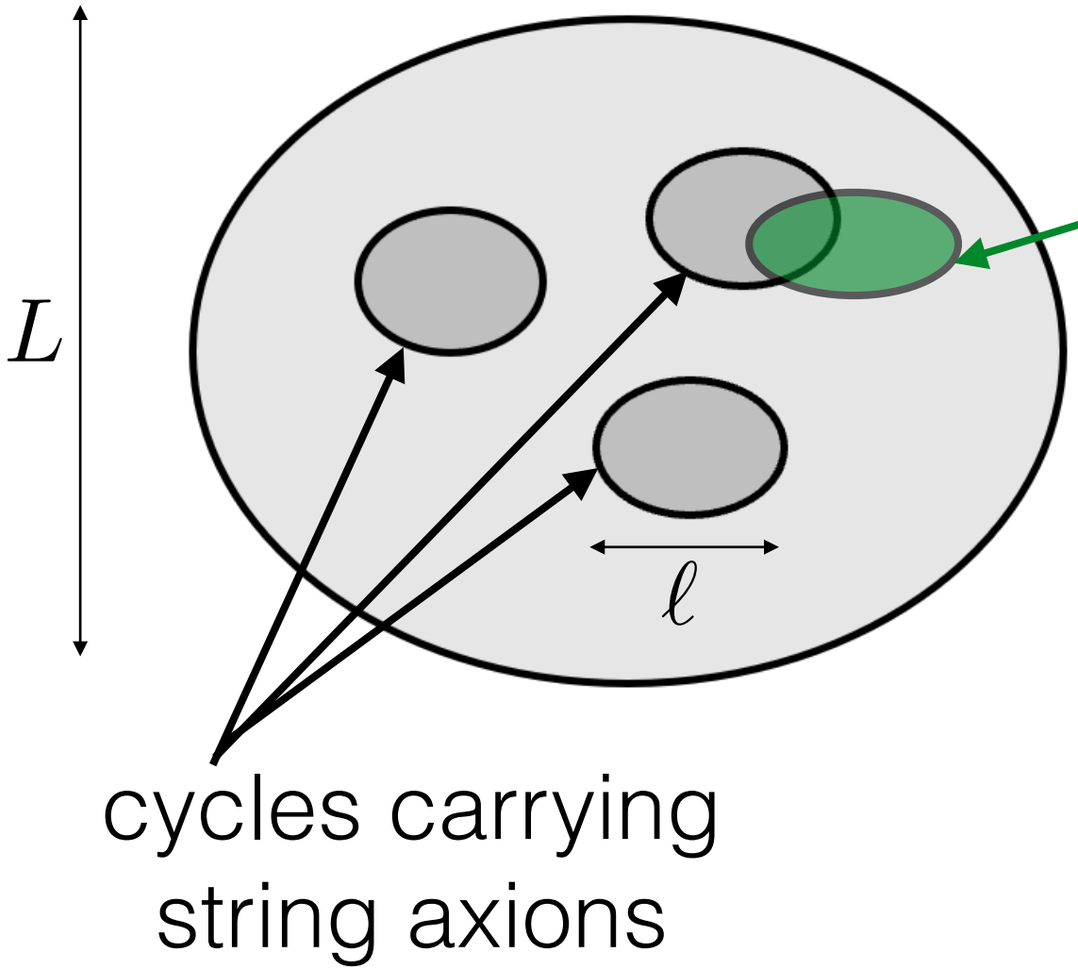

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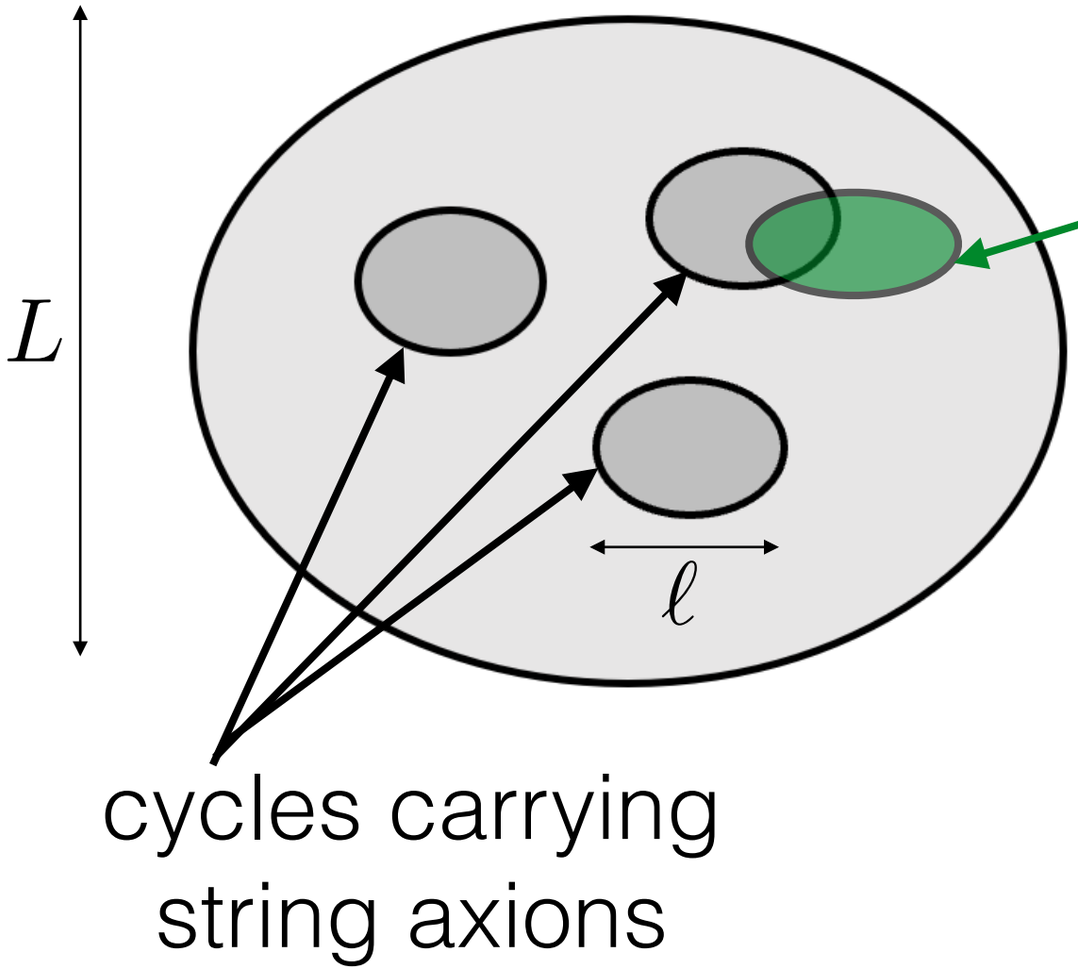

cycle carrying branes with SM

cycles carrying string axions

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

continuous shift symmetry
broken to: $a \to a + 2\pi n$

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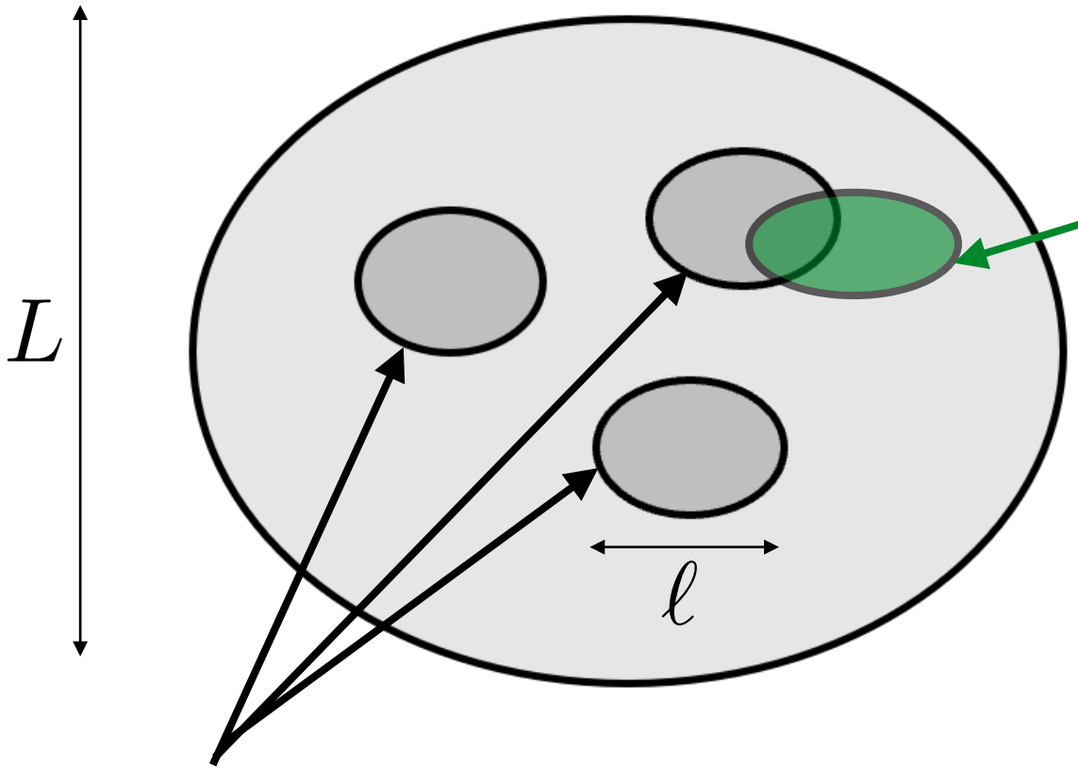

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… most axions are dark!

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

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

- consequence of string extra dimensions:
  - many cycles — $O(100)$
  - each cycle: a p-form 0-mode axion

★ string theory generically contains **many axions**

★ **decay constants** are **high**
… **power-law** in extra-dim. size

★ **masses** distribute **exponentially wide**
… **exponential** in extra-dim. size

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

a string theory axiverse !

- **closed string axion pheno:**

  - dark matter

[Preskill, Wise & Wilczek '83]
[Abbott & Sikivie '83]
[Dine & Fischler '83]

high-scale decay constants: $f > H$ (PQ broken) even during inflation

but exponentially light: $m << H$ during inflation

population of non-relativistic axion matter density ρ
via kick+kination or misalignment from inflation:

[Gouttenoire, Servant & Simakachorn '21]

random displacement of axion *a* during inflation from de Sitter vacuum fluctuations

every Hubble patch has different ρ

axion abundance:
$(H < f)$

$$\frac{\Omega_a h^2}{0.112} \simeq 2.2 \times \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \left(\frac{f}{10^{17}\,\mathrm{GeV}}\right)^2 a_{\mathrm{in}}^2$$

[Cicoli, Goodsell & Ringwald '12]

- closed string axion pheno:

  - what dark matter?

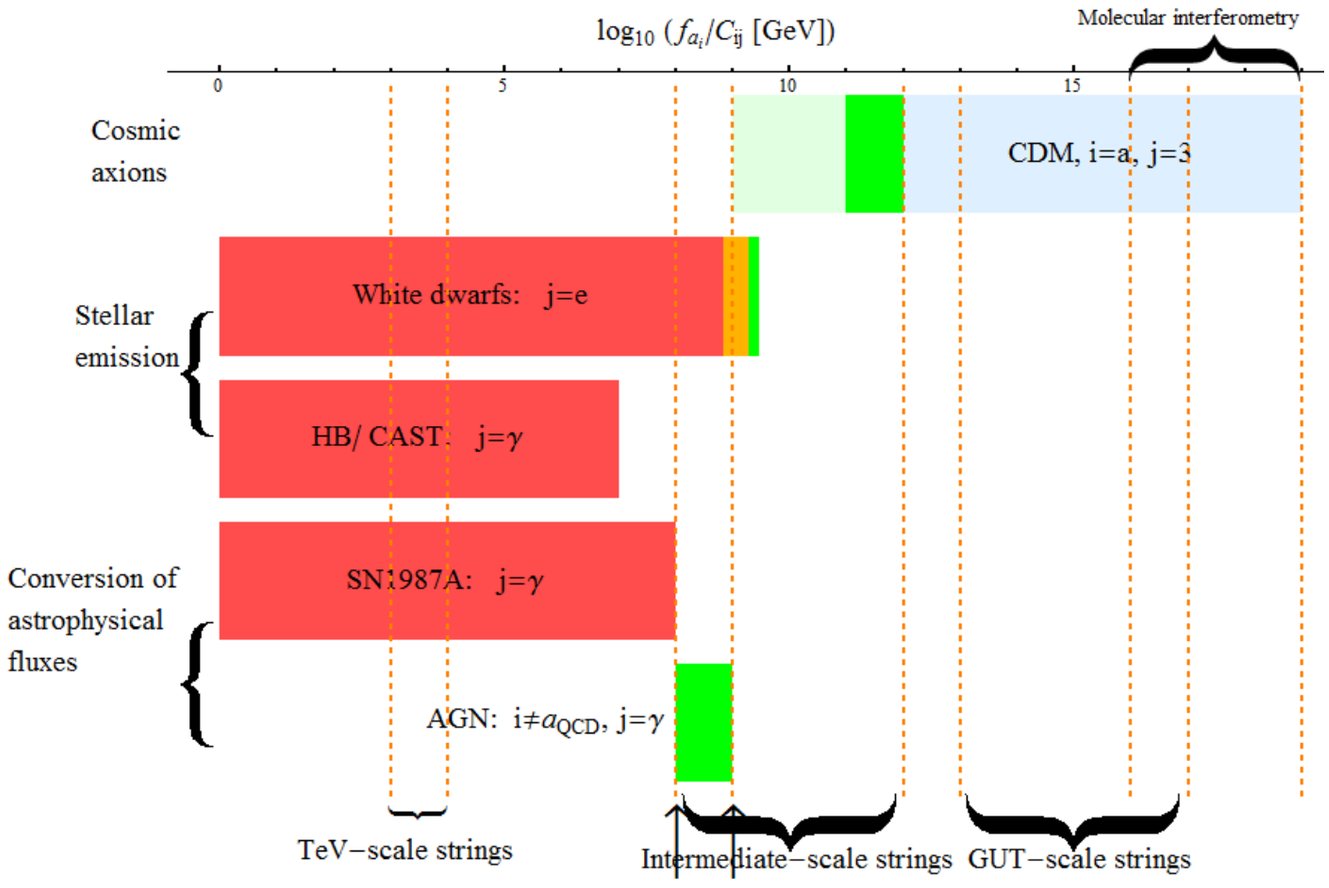
  if $m > 10^{-18}$ eV … cold dark matter

  if 10^{-25} eV $< m < 10^{-19}$ eV … fuzzy (or wave) dark matter

[Hu, Barkana & Gruzinov '00]
[Hui, Ostriker, Tremaine & Witten '16]
[Cicoli, Guidetti, Righi & AW '21]

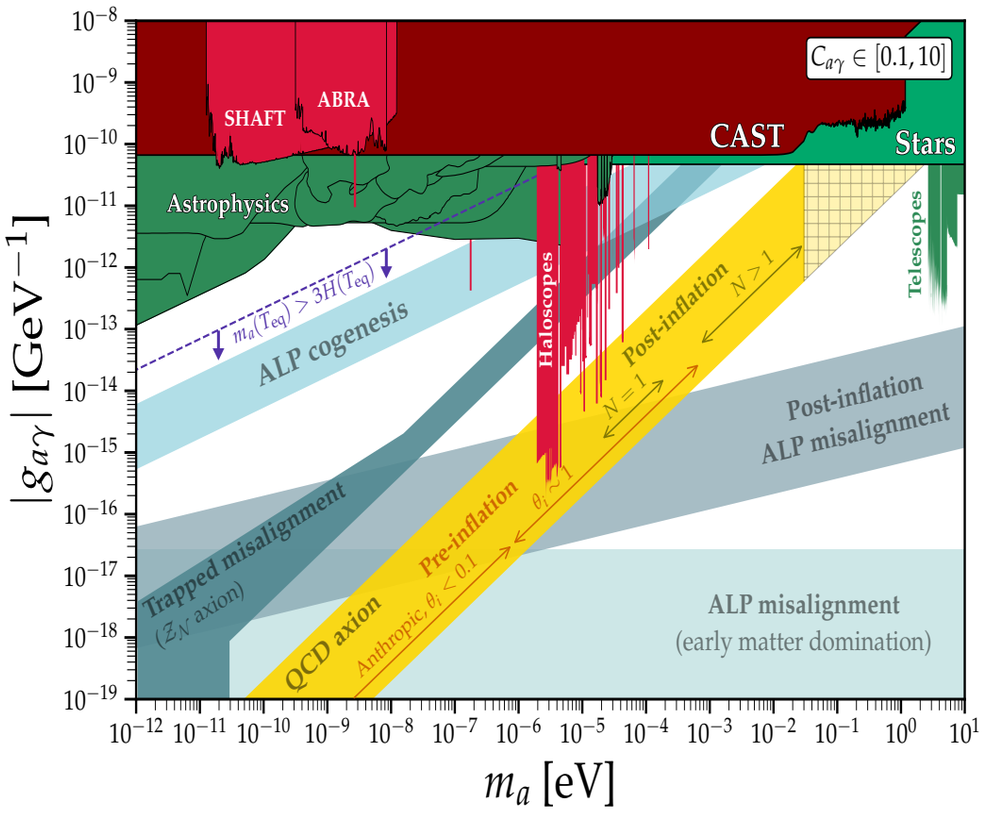
  - other production mechanisms …

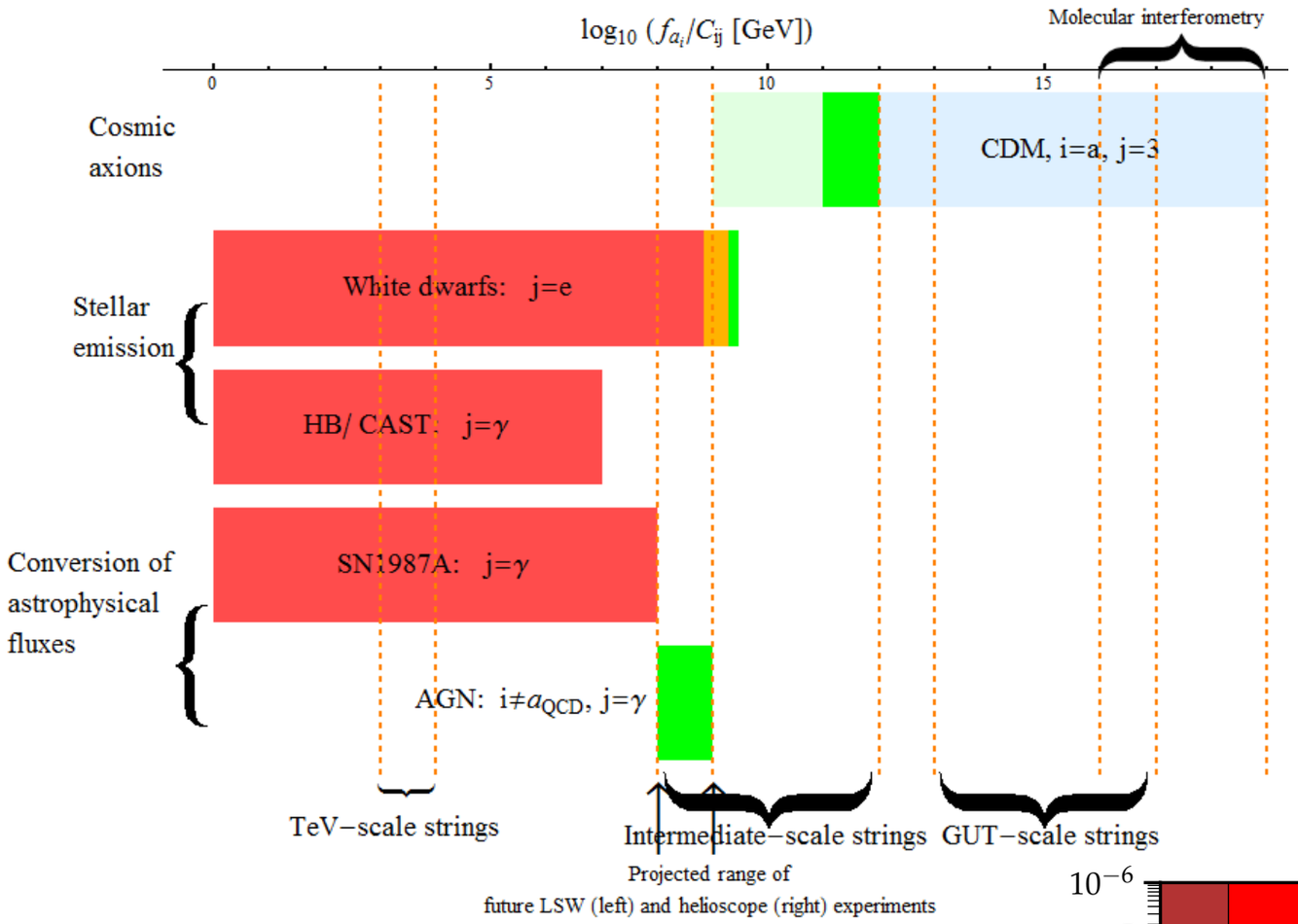
  … from topological defects, cosmic strings



Projected range of
future LSW (left) and helioscope (right) experiments

the 1…3 string axions with SM couplings





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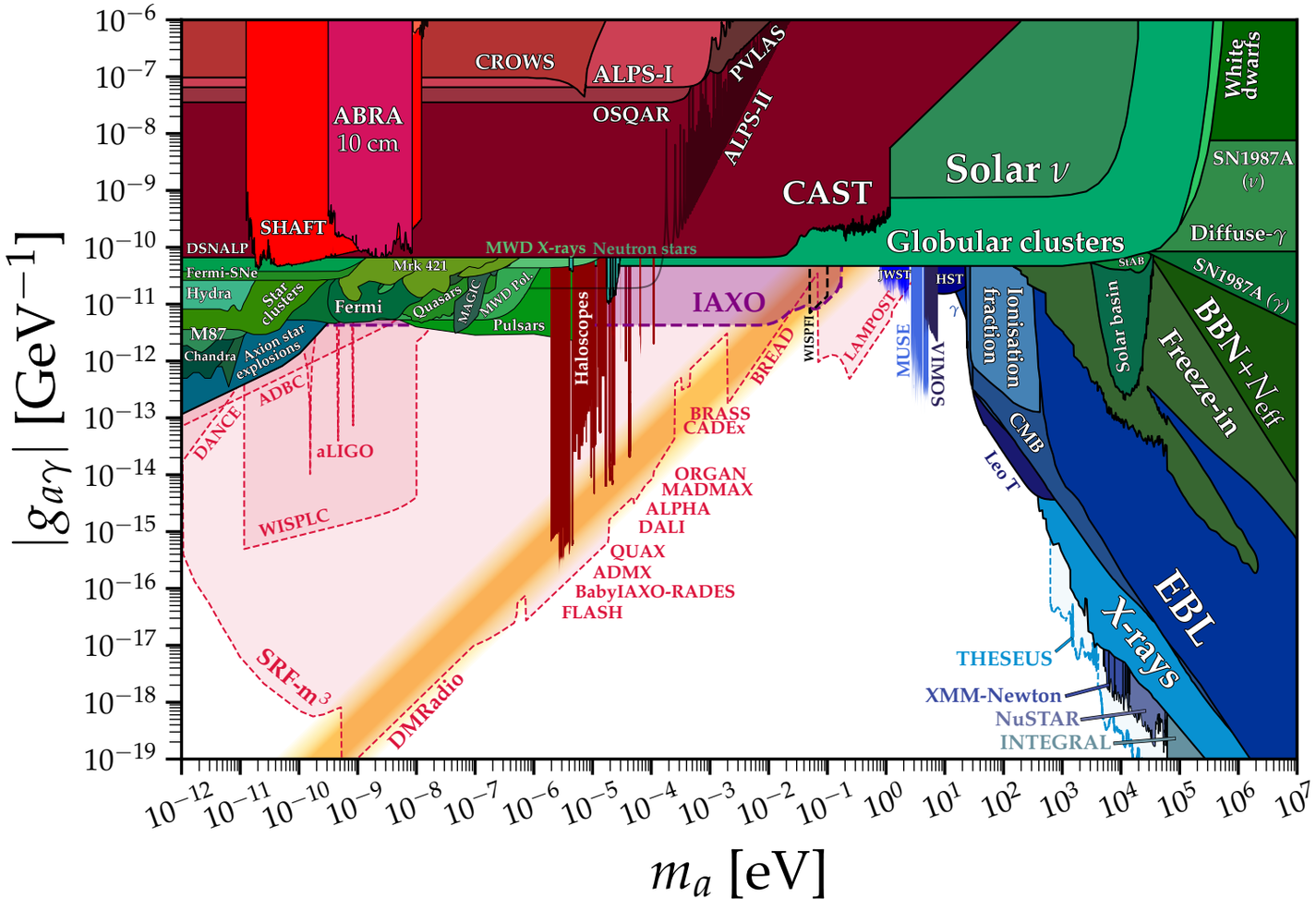


the many other string axions are dark …

- couplings are either gravitational (Planck-suppressed):

  - can be part of dark matter

  - or dark radiation: visible e.g. in CMB as $\Delta N_{\rm eff}$

[Cicoli, Conlon & Quevedo '12]
[Higaki & Takahashi '12]

  - axion clouds around fast-spinning BHs deplete spin: detection via BH superradiance

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

the many other string axions are dark …

- and/or to dark sectors, e.g. dark U(1) gauge fields:

  - spectator role during inflation

[Biagetti, Dimastrogiovanni, Fasiello & Peloso '14]
[Dimastrogiovanni, Fasiello & Fujita '16]
[Obata & Soda '17]

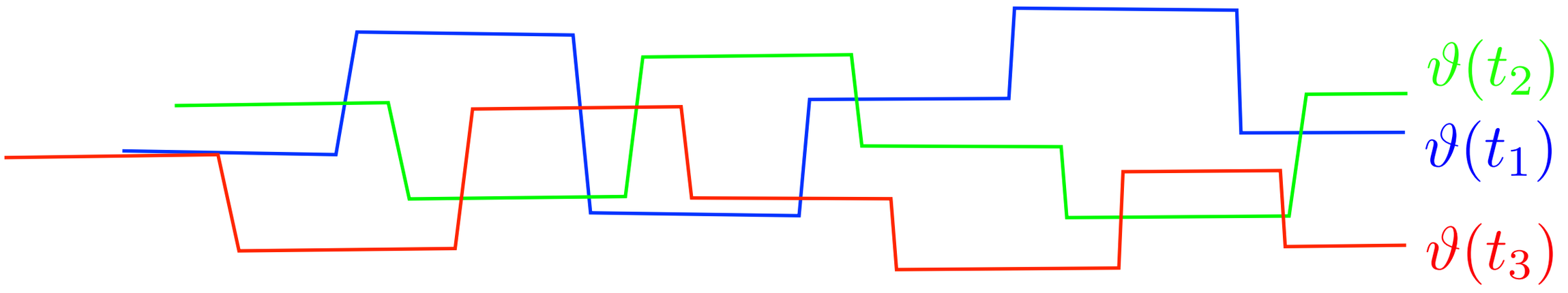
  - slow-rolling axion coupled to dark U(1) during inflation: production of dark gauge field & induced peaked GWs

[Anber & Sorbo '09, Sorbo '11] [Adshead & Wyman '12]
… [Namba, Peloso, Shiraishi, Sorbo & Unal '15] [Dimastrogiovanni, Fasiello & Fujita '16], [Domcke, Pieroni & Binetruy '16] …

  - for string axions quite generic & constrains axiverse

[Dimastrogiovanni, Fasiello, Leedom, Putti & AW '23]

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



- additional production channels (axions from inflation decay or parametric resonance) only add to this

[Garcia, Pierre & Verner '22]

[Leedom, Righi, Putti & AW '24]

light axion ϑ : $f_\vartheta \sim M_{\rm GUT}$

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

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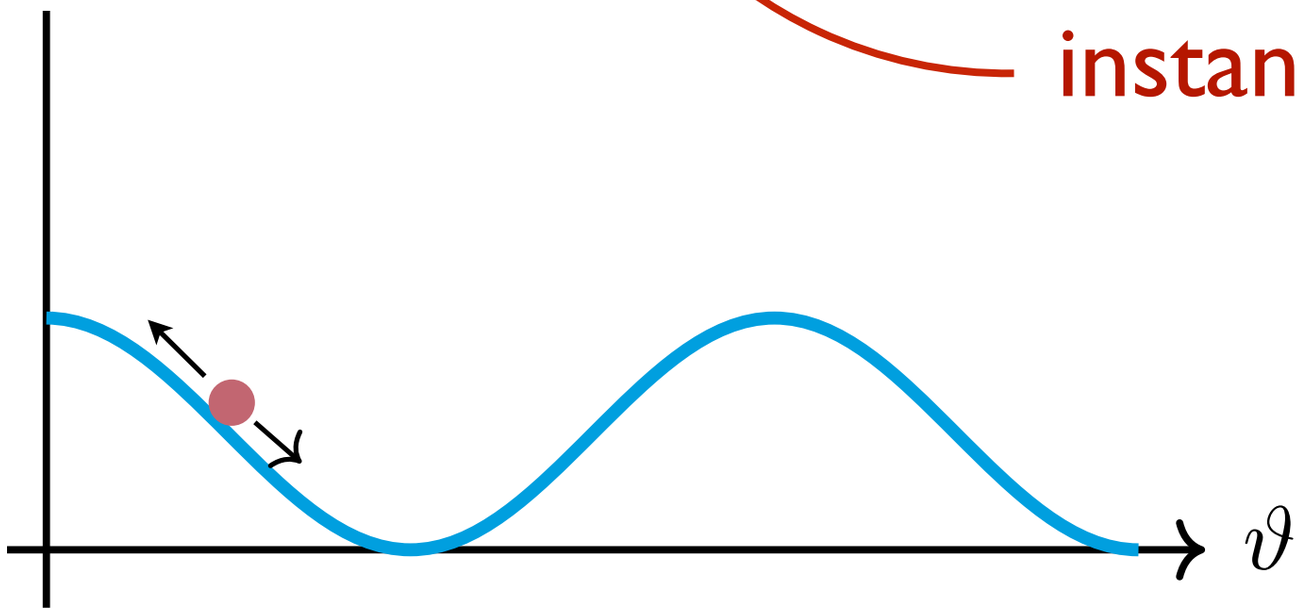
instanton effects



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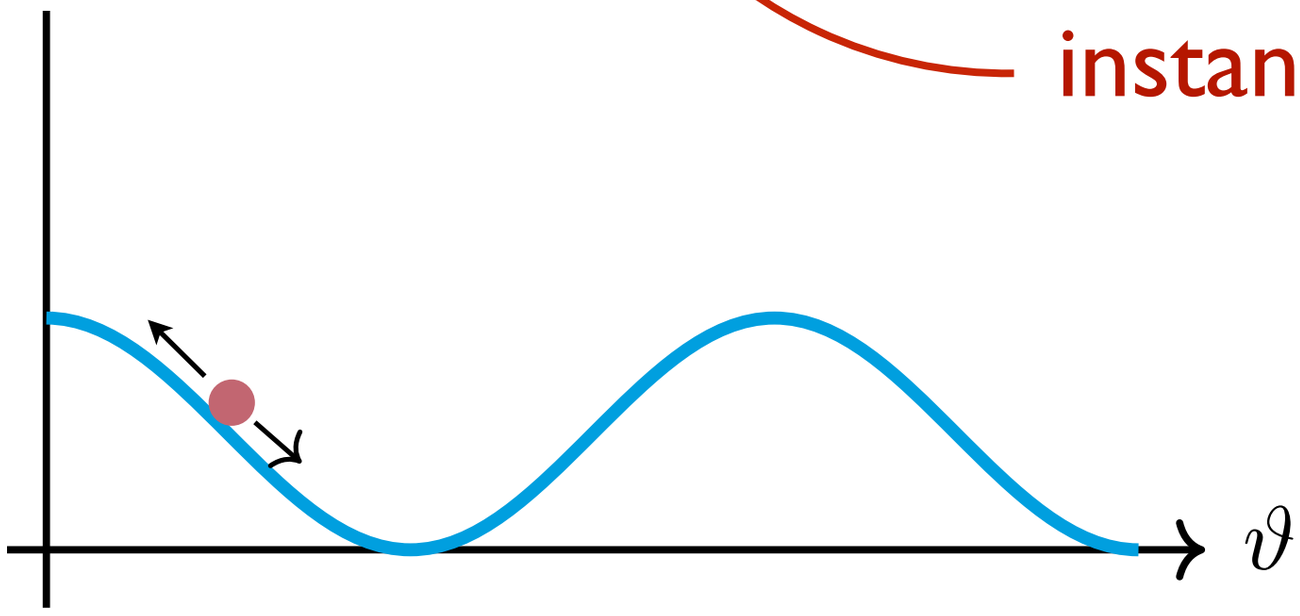

axion is in deep slow-roll = frozen on the slopes

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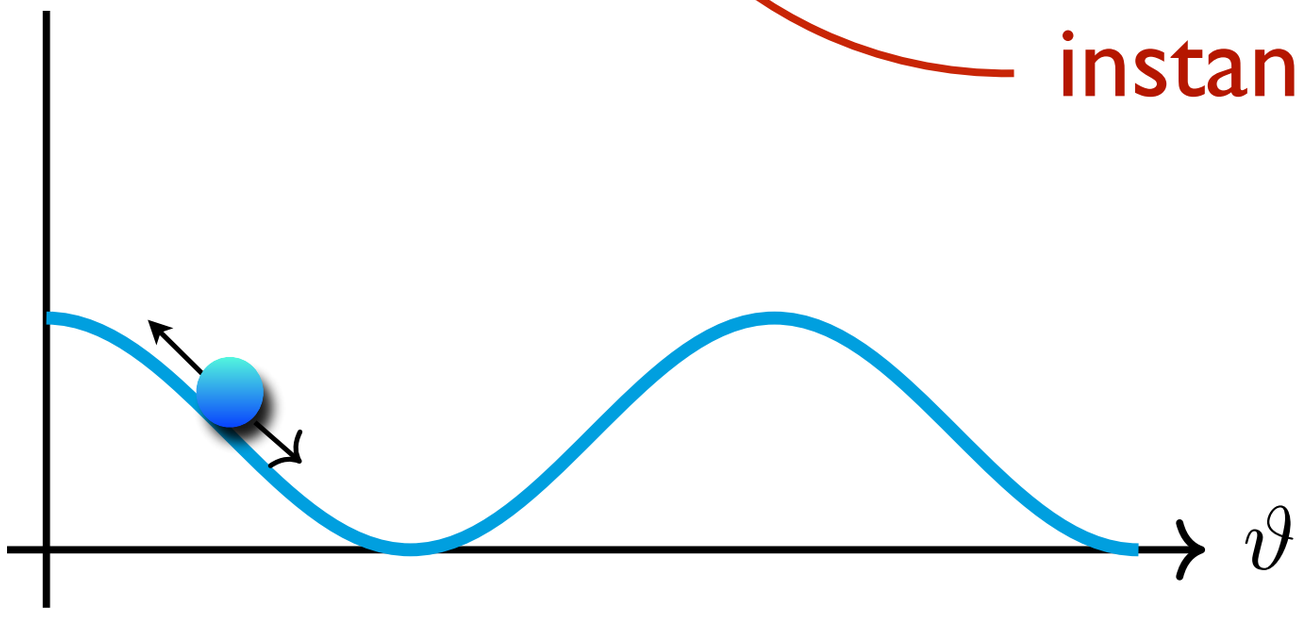

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quantum drift from dS fluctuations dominates = it walks up the hill …

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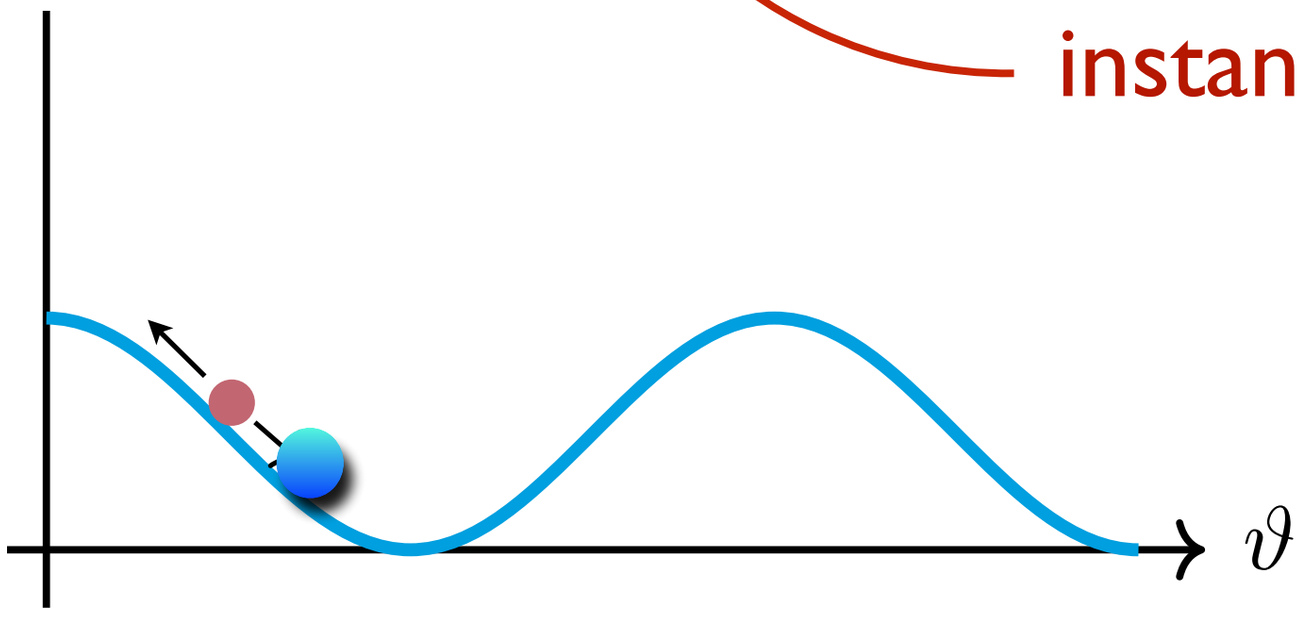

axion is in deep slow-roll = frozen on the slopes

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- after inflation …

[Kaloper & AW '24]

$m_\vartheta > H$: frozen ϑ melts …

$$m_\vartheta^2 M_{\rm P}^2 = \frac{T_{reh}^4}{a_{melt}^4} \quad \Rightarrow \quad a_{melt} = \frac{T_{reh}}{\sqrt{m_\vartheta M_{\rm P}}}$$

ϑ oscillates - it is matter !

- after inflation …

[Kaloper & AW '24]

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

$$\Rightarrow \quad T_\star = \frac{T_{reh}}{a_\star} = \frac{m_\vartheta^{1/2} f_\vartheta^2}{M_{\rm P}^{3/2}}$$

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

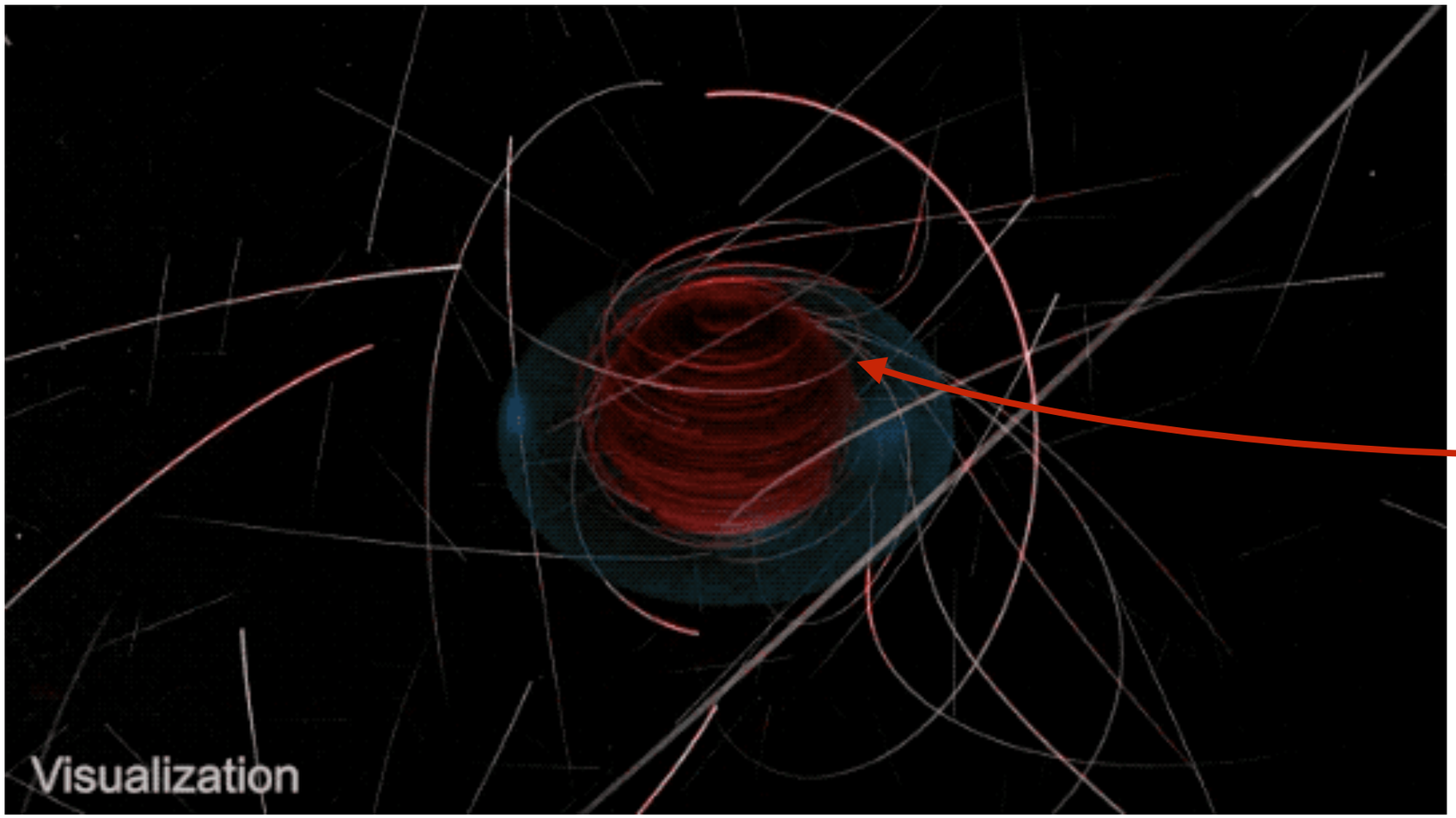
see also: [Cicoli, Guidetti, Righi & AW '21]

too much DM !

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

black hole superradiance

[Penrose '69 ; Christodoulou '70]



spinning black hole (BH)

Credit: NASA's Goddard Space Flight Center

black hole superradiance production of axions

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

… from ergo region of near-extremal rotating BH:

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

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

… ultra-light axions, if DM, also potentially detectable via PTAs

[Kim & Mitridate '23]

- a possible future observational outcome …

[Kaloper & AW '24]

(i) BH superradiance detects a ϑ with

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

(ii) other experiment determines: DM largely NOT ϑ

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

… anthropics has failed !

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’ …

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