ALESSIO-B

image credit: J. Leedom & Midjourney

Spectator-Verse Echoes from String Theory

based on:
2112.13861, 2312.23431, 2404.02993, 2409.xxxxx
with:
G. d'Amico, E. Dimastrogiovanni,
M. Fasiello, N. Kaloper, J. Leedom,
N. Righi & M. Putti

Alexander Westphal
(DESY)

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09]
type IIB LVS: [Cicoli, Goodsell & Ringwald '12]

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

★ string theory generically contains **many axions**

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

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

dark matter:

cold or fuzzy
[Hui, Ostriker, Tremaine & Witten '16]
[Cicoli, Guidetti, Righi & AW '21]

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

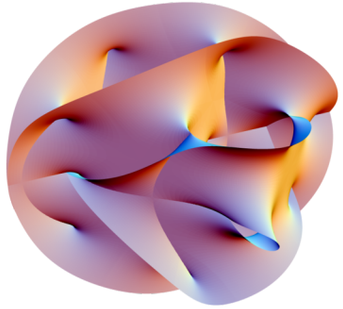
dark radiation
[Cicoli, Conlon & Quevedo '12]
[Higaki & Takahashi '12]

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

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

a string theory axiverse !

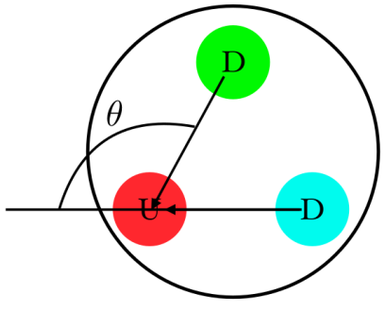
… flux monodromy axion masses: [Reece '24]



From Top-Down

- S
- -
- -

And Bottom-Up



How can we find them?

ε March-Russell '09]

Wise & Wilczek '83]
ε Sikivie '83]
'ischler '83]

matter:

or fuzzy

Tremaine & Witten '16]
tti, Righi & AW '21]

radiation

ɔnlon & Quevedo '12]
: Takahashi '12]

g))

McAllister & Moritz '23]
allister & Pajer '10]
& Kuespert '23] …

Reece '24]

image credit: J. Leedom

inflationary spectator-verse

- there was inflation (at least CMB+20 efolds)

- axions are spectators during inflation

inflationary spectator-verse

- there was inflation (at least CMB+20 efolds)

- axions are spectators during inflation

- multi-epoch inflation

[d'Amico & Kaloper '20]

- several axions φ & dark gauge field CS

- GWs

[d'Amico, Kaloper & AW '21]

inflationary spectator-verse

- there was inflation (at least CMB+20 efolds)

- axions are spectators during inflation

- multi-epoch inflation

[d'Amico & Kaloper '20]

- several axions φ & dark gauge field CS

- GWs

[d'Amico, Kaloper & AW '21]

- single-epoch inflation

- spect. axions χ & dS-universality

inflationary spectator-verse

- there was inflation (at least CMB+20 efolds)

- axions are spectators during inflation

- multi-epoch inflation

[d'Amico & Kaloper '20]

- several axions φ & dark gauge field CS

- GWs

[d'Amico, Kaloper & AW '21]

- single-epoch inflation

- spect. axions χ & dS-universality

gauge field CS

GW

[Dimastrogiovanni, Fastello, **Leedom**, Putti & AW '23]

inflationary spectator-verse

- there was inflation (at least CMB+20 efolds)

- axions are spectators during inflation

- multi-epoch inflation

[d'Amico & Kaloper '20]

- several axions φ & dark gauge field CS

- GWs

[d'Amico, Kaloper & AW '21]

- single-epoch inflation

- spect. axions χ & dS-universality

gauge field CS → GW

[Dimastrogiovanni, Fastello, **Leedom**, Putti & AW '23]

axionic preheating → $\Delta N_{\rm eff}$

[Leedom, Putti, Righi & AW 'soon]

inflationary spectator-verse

- there was inflation (at least CMB+20 efolds)

- axions are spectators during inflation

- multi-epoch inflation

[d'Amico & Kaloper '20]

- several axions φ & dark gauge field CS

- GWs

[d'Amico, Kaloper & AW '21]

- single-epoch inflation

- spect. axions χ & dS-universality

gauge field CS → GW

[Dimastrogiovanni, Fastello, **Leedom**, Putti & AW '23]

axionic preheating → $\Delta N_{\rm eff}$

[Leedom, Putti, Righi & AW 'soon]

may falsify anthropics!

[Kaloper & AW '24]

the inflating "spectator" ...

[d'Amico, Kaloper & AW '21]

Double monodromy inflation

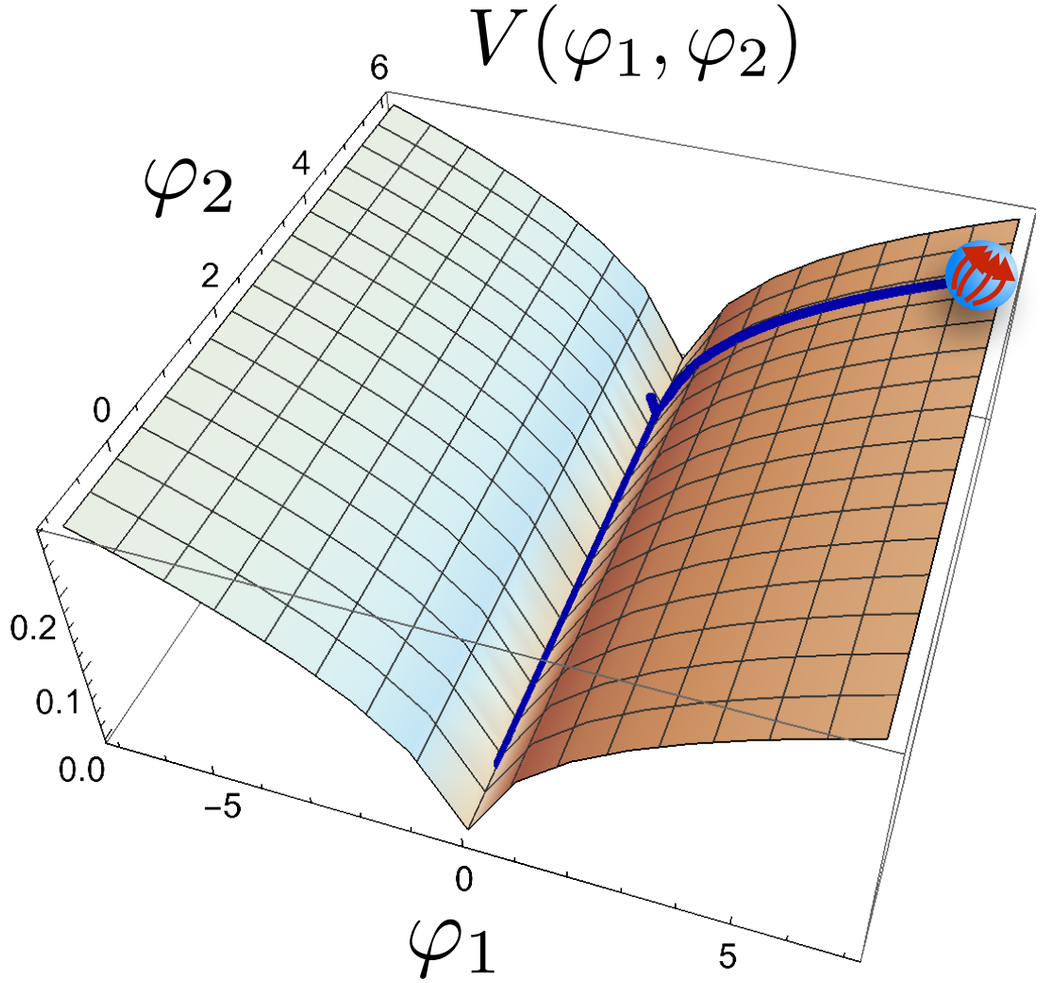
[d'Amico, Kaloper & AW '21]

Two stages of monodromy inflation, separated by matter domination when the first ends

$$V(\varphi_1,\varphi_2) = M_1^4\left[\left(1+\frac{\varphi_1^2}{\mu_1^2}\right)^{p_1/2}-1\right] + M_2^4\left[\left(1+\frac{\varphi_2^2}{\mu_2^2}\right)^{p_2/2}-1\right]$$

$$M_1 > M_2$$

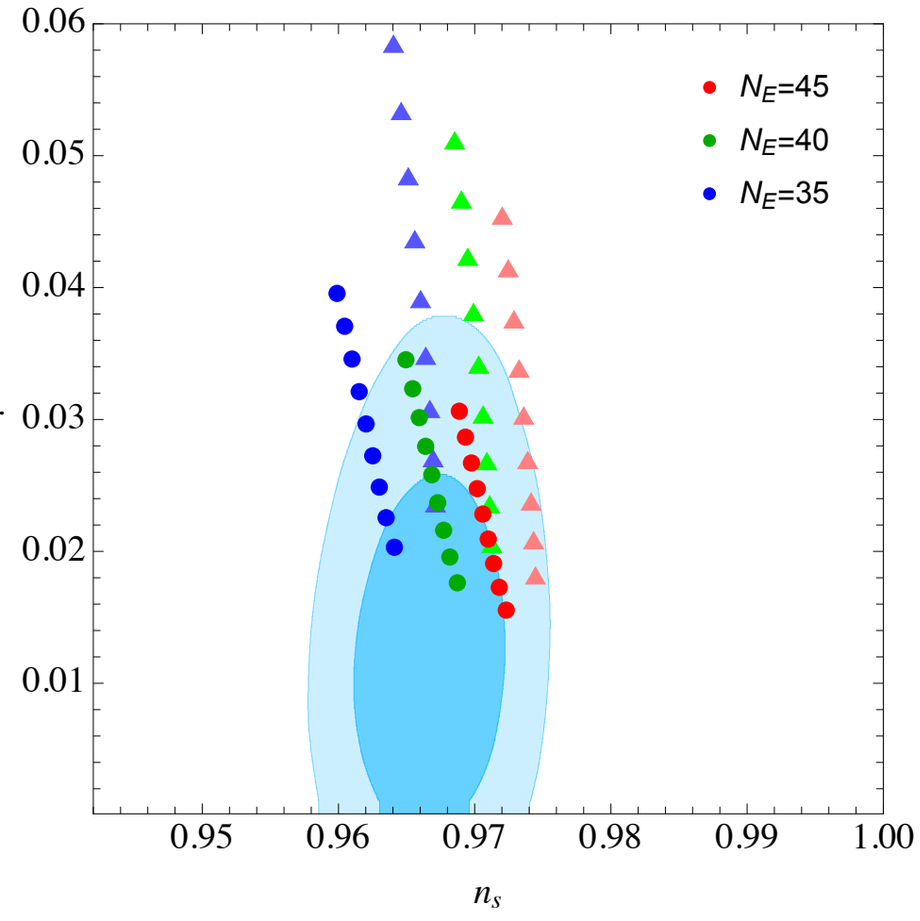
$$\mu_i \sim \mathcal{O}(0.1 M_{\rm Pl})$$



- reduced field ranges — links to Swampland
- probably more generic in UV setups

gravitational wave predictions

[d'Amico, Kaloper & AW '21]



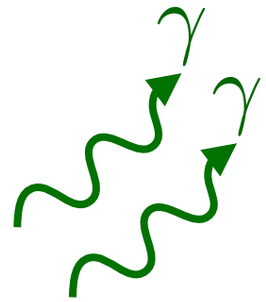
gravitational wave predictions

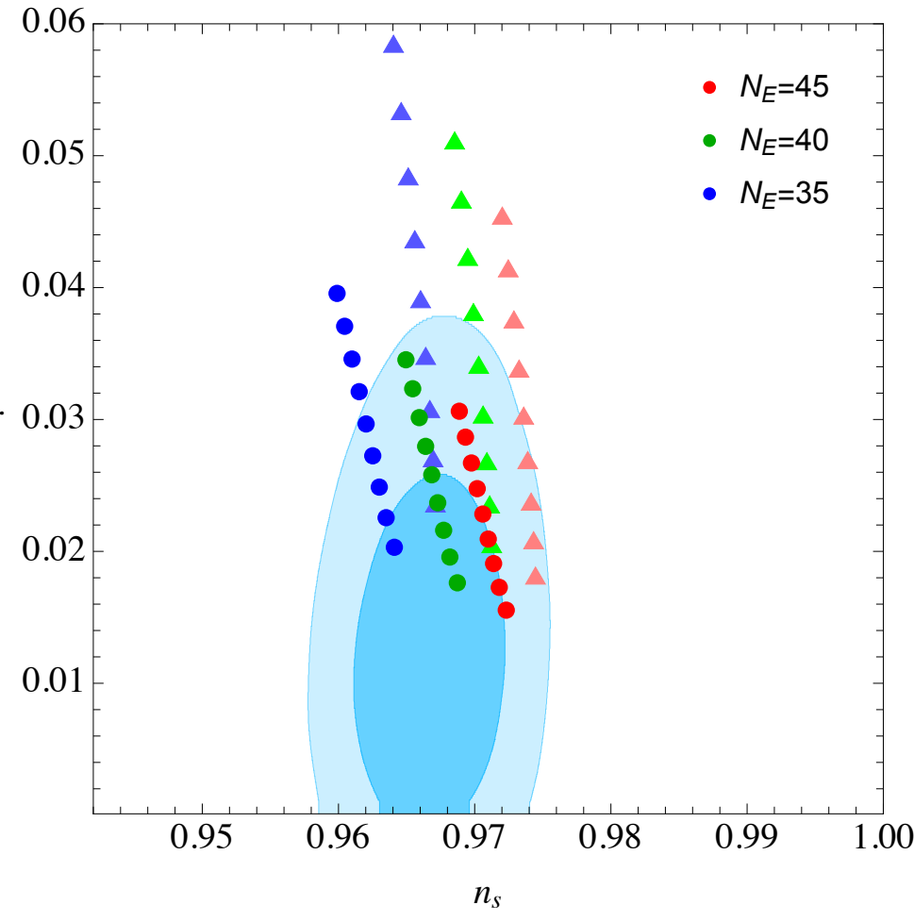
[d'Amico, Kaloper & AW '21]

Tachyonic dependence of one helicity gauge field mode - additional GWs !

based on [Anber & Sorbo '09]
[Domcke, Pieroni & Binetruy '16]

$$\mathcal{L}_{\rm CS} = -\sqrt{-g}\frac{\varphi_1}{4f_\varphi}F_{\mu\nu}\tilde{F}^{\mu\nu} \xrightarrow{\dot{\varphi}_1}$$





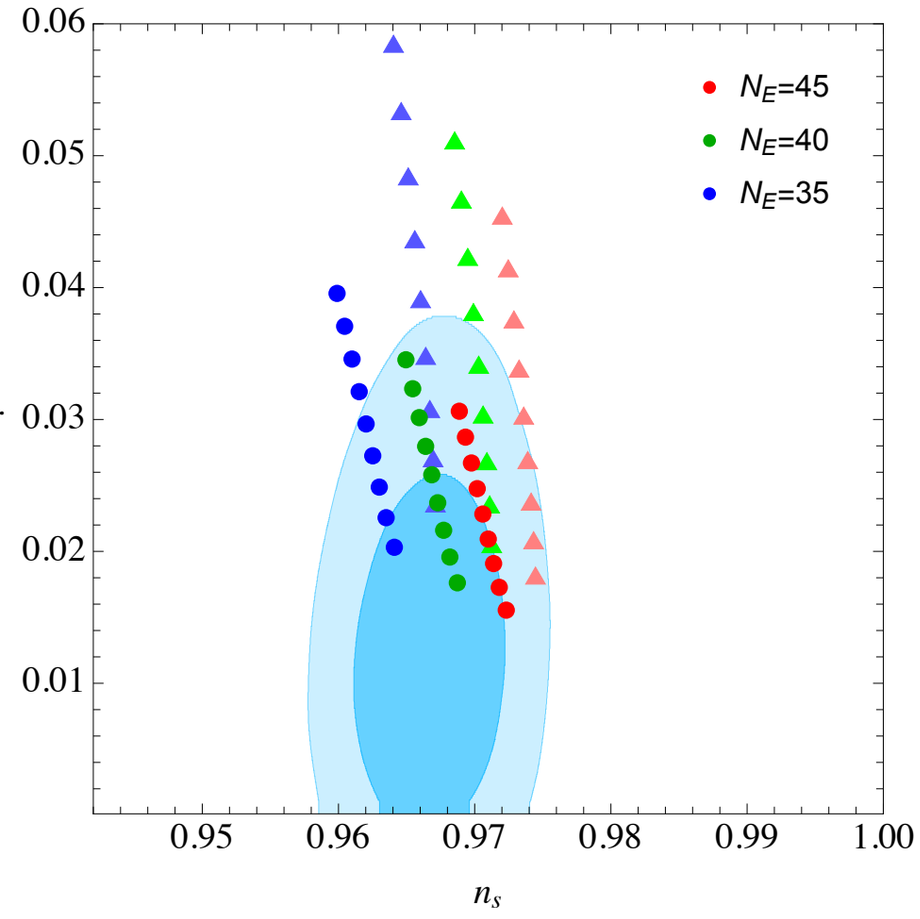
gravitational wave predictions

[d'Amico, Kaloper & AW '21]

Tachyonic dependence of one helicity gauge field mode - additional GWs !

based on [Anber & Sorbo '09]
[Domcke, Pieroni & Binetruy '16]

$$\mathcal{L}_{\rm CS} = -\sqrt{-g}\frac{\varphi_1}{4f_\varphi}F_{\mu\nu}\tilde{F}^{\mu\nu} \xrightarrow{\dot{\varphi}_1} \gamma\gamma \longrightarrow \delta T_{\mu\nu}$$



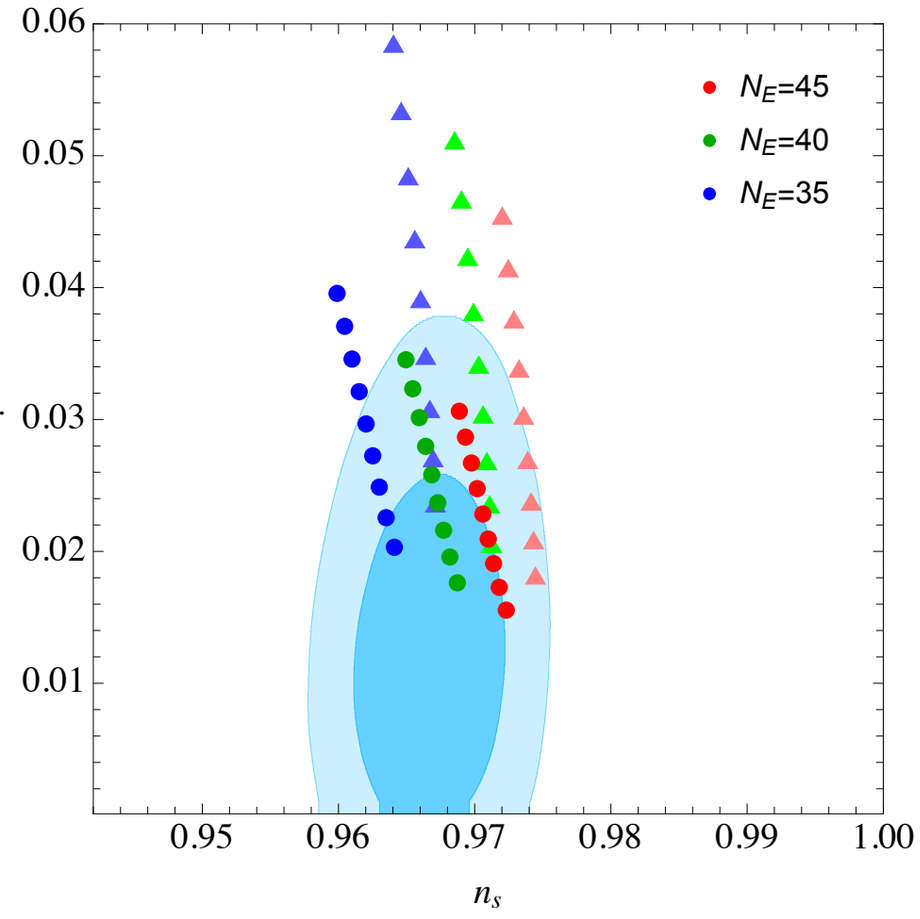
gravitational wave predictions

[d'Amico, Kaloper & AW '21]

Tachyonic dependence of one helicity gauge field mode - additional GWs !

based on [Anber & Sorbo '09]
[Domcke, Pieroni & Binetruy '16]

$$\mathcal{L}_{\rm CS} = -\sqrt{-g}\frac{\varphi_1}{4f_\varphi}F_{\mu\nu}\tilde{F}^{\mu\nu} \xrightarrow{\dot{\varphi}_1} \gamma\,\gamma \longrightarrow \delta T_{\mu\nu} \longrightarrow h_{\mu\nu}\,h_{\mu\nu}$$



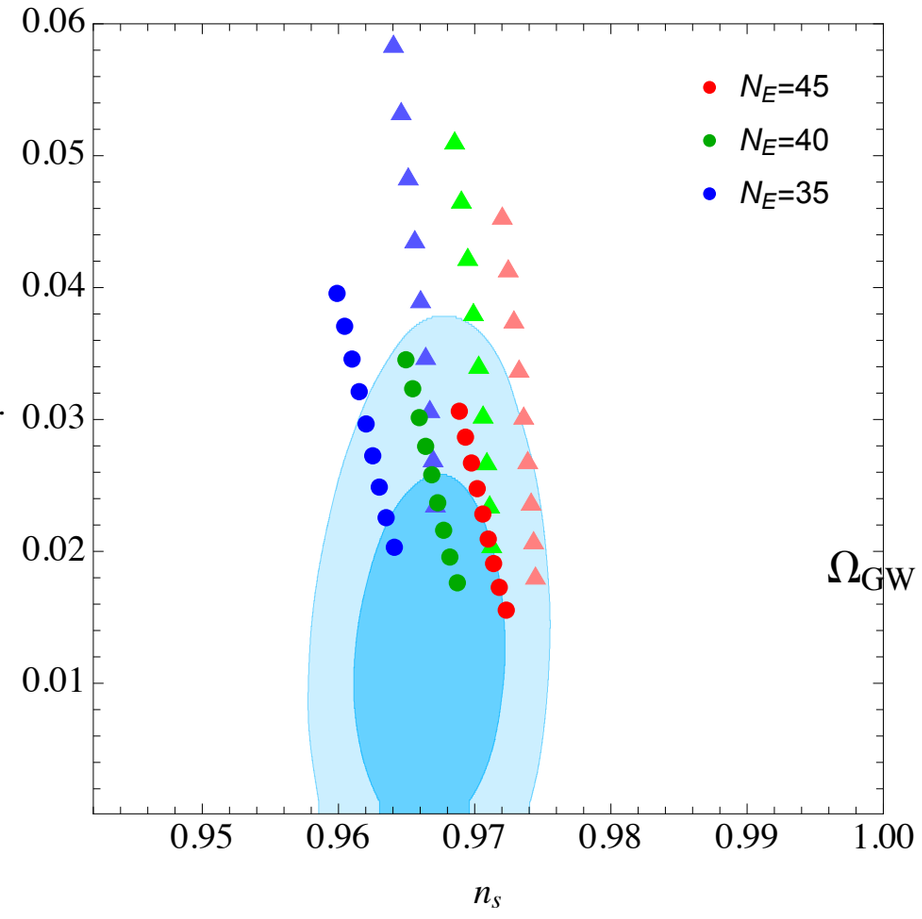
gravitational wave predictions

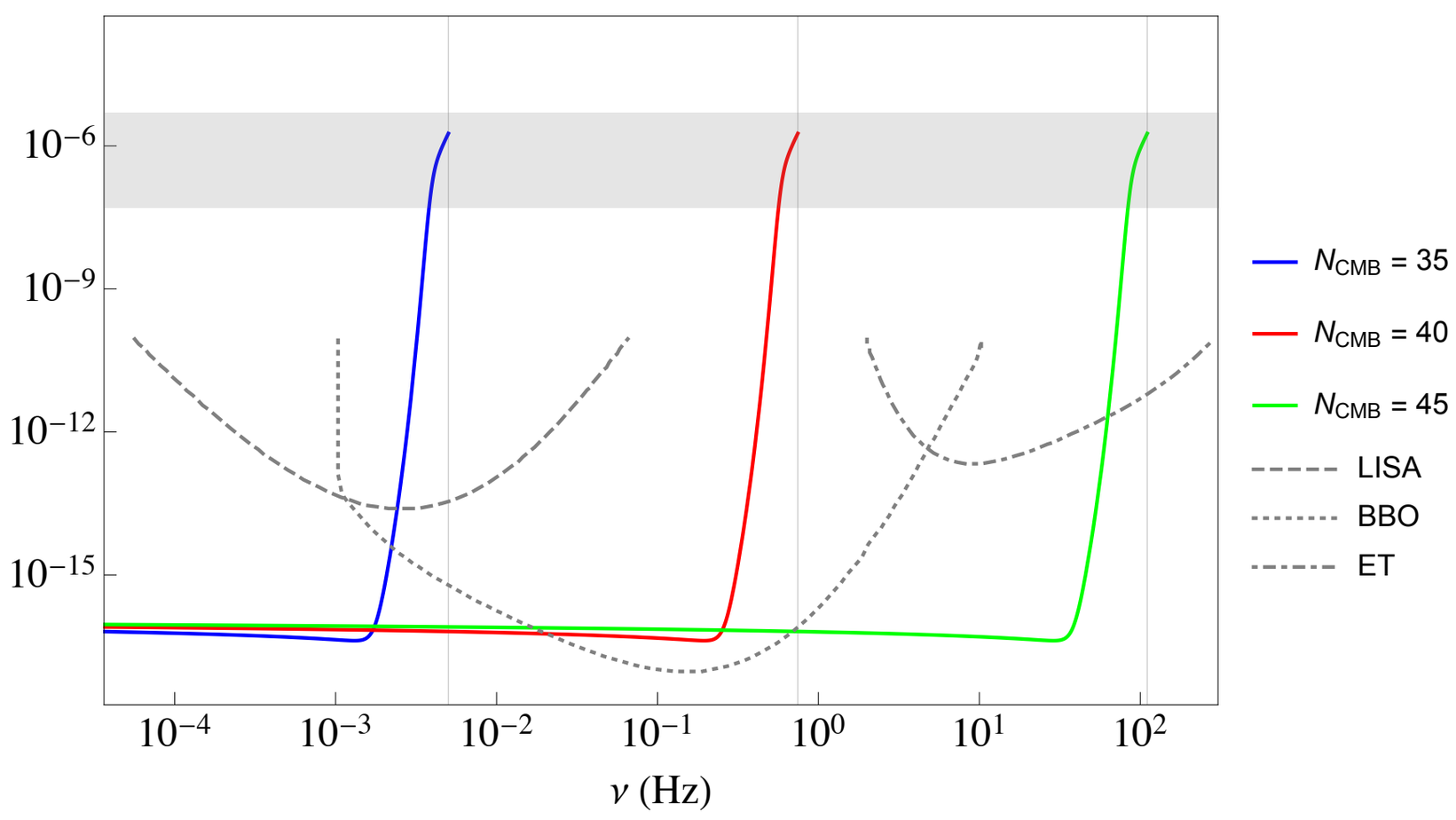
[d'Amico, Kaloper & AW '21]

Tachyonic dependence of one helicity gauge field mode - additional GWs !

based on [Anber & Sorbo '09]
[Domcke, Pieroni & Binetruy '16]

$$\mathcal{L}_{\rm CS} = -\sqrt{-g}\frac{\varphi_1}{4f_\varphi}F_{\mu\nu}\tilde{F}^{\mu\nu} \xrightarrow{\dot{\varphi}_1} \gamma\,\gamma \longrightarrow \delta T_{\mu\nu} \longrightarrow h_{\mu\nu}\,h_{\mu\nu}$$





the radiated spectator …

[Leedom, Putti, Righi & AW ’24 — **Soon / 2409.xxxx**]

- Fibre inflation in LVS

$$\text{modulus } \tau_f \text{ drives inflation,}$$

$$V(\tau_f) \text{ from string loops \& } F^4\text{-terms}$$

- axion partner a_f perturbatively flat

couplings:

$$\text{kinetic} - \Delta\mathcal{L} \sim \frac{1}{\tau_f^2}(\partial a_f)^2$$

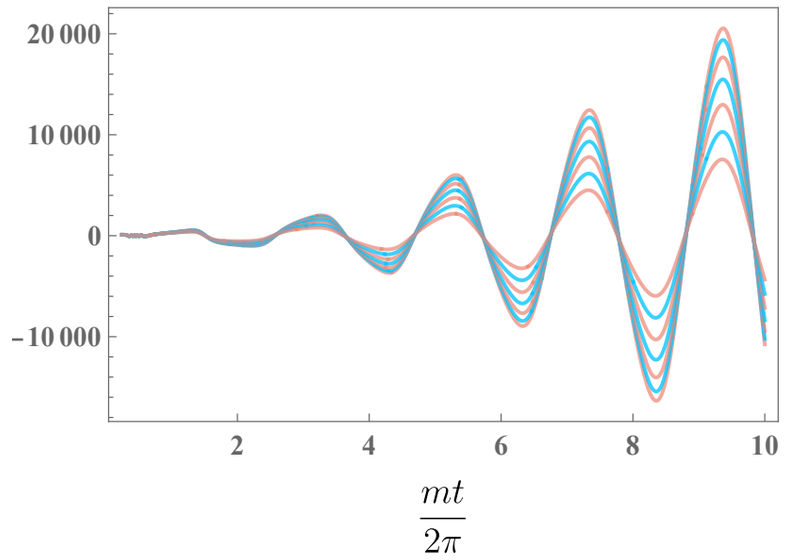
… axion production from perturbative τ_f decay [Cicoli, Sinha & Wiley Deal '22]

… universal !

$$\text{potential} - \Delta V = C(W_0, A_f, g_s, \mathcal{V}) \cdot e^{-a_f \tau_f} \cos(a_f)$$

… from instanton effects

- couplings drive parametric resonance
  — Hill equation, not Mathieu!



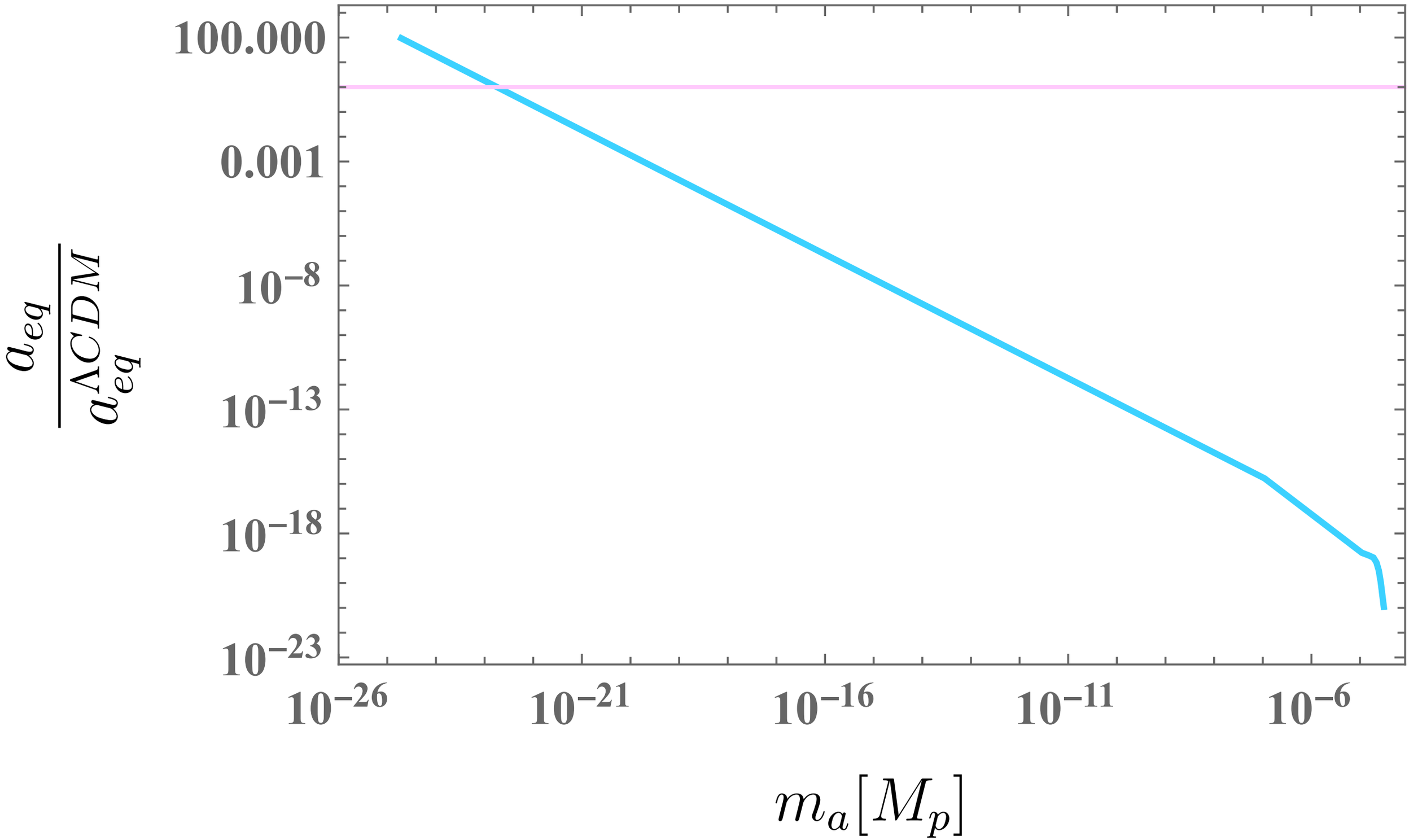
- lots of axions produced, then expansion-diluted

if light $m_{a_f} \ll H_{inf}$: CaB
$\Rightarrow$ small $\Delta N_{eff} \sim 10^{-5} \ldots 10^{-6}$

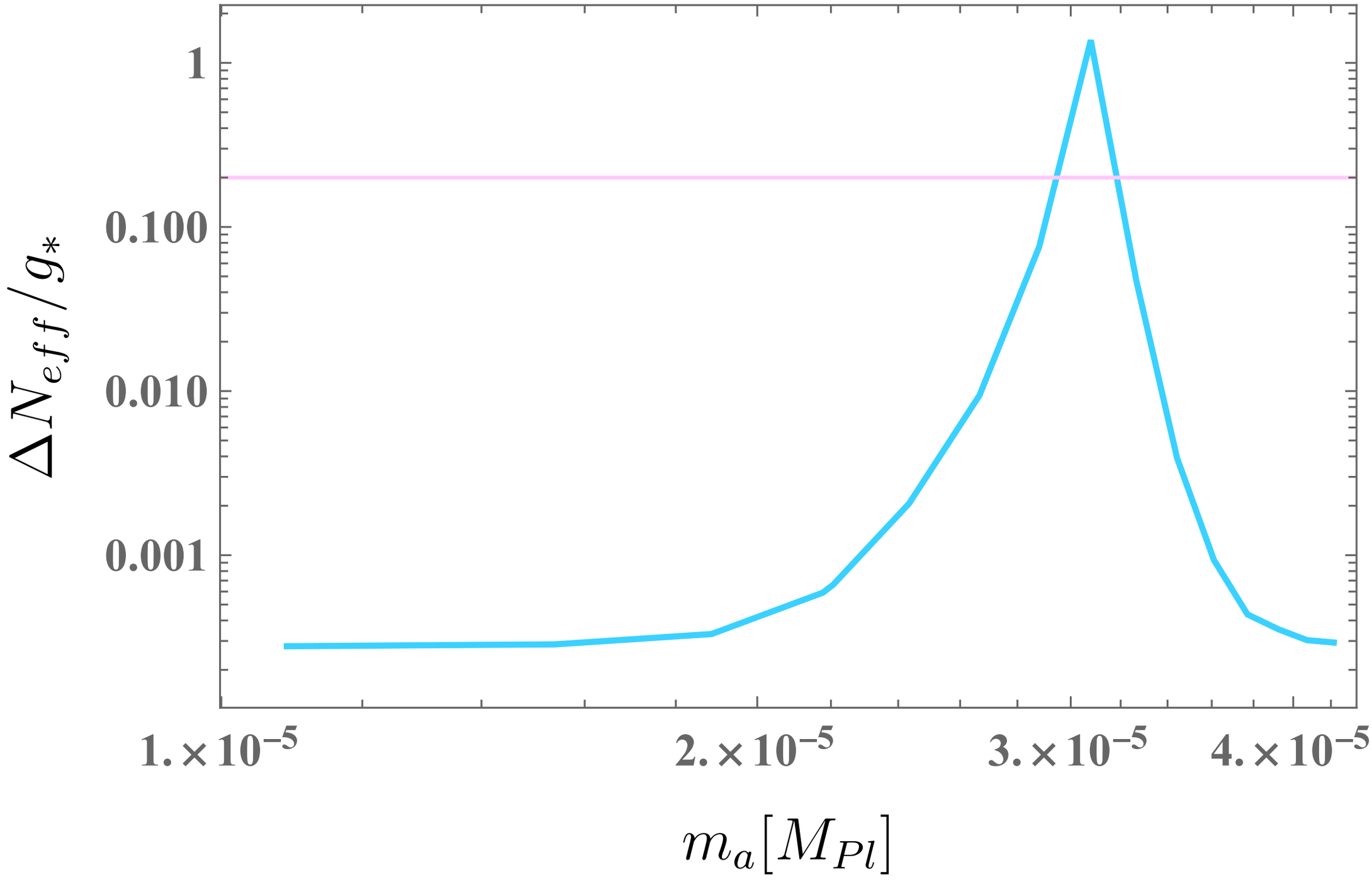
if heavy : potentially dark matter overproduction
$\Rightarrow$ upper bound on m_{a_f}
$\Rightarrow$ constraint on stringy inflaton+axion sector

- decay rates matter (axion → radiation …)

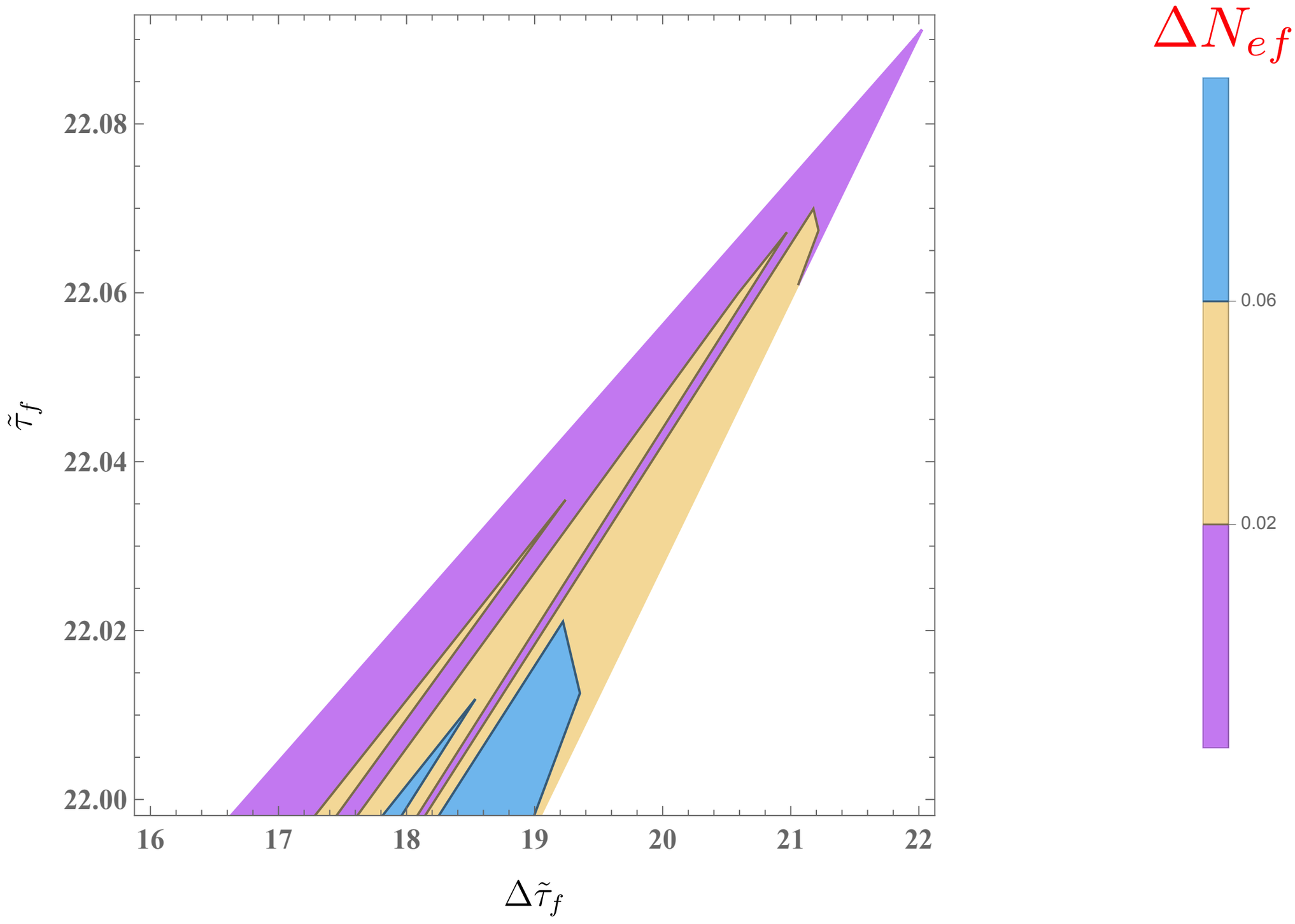
- axion stays around or only decays to ~ m_a stuff



- axion is ultra-light & stable
  or decays quickly into radiation …



- (non-)detection of $\Delta N_{\rm eff}$ implies constraints on string model parameters



the mis-anthropic spectator ...

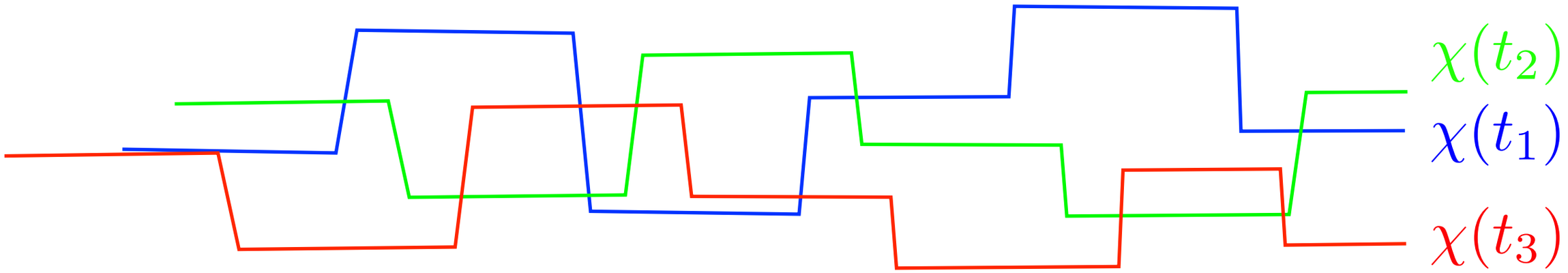
[Kaloper & AW '24]

DISCLAIMER

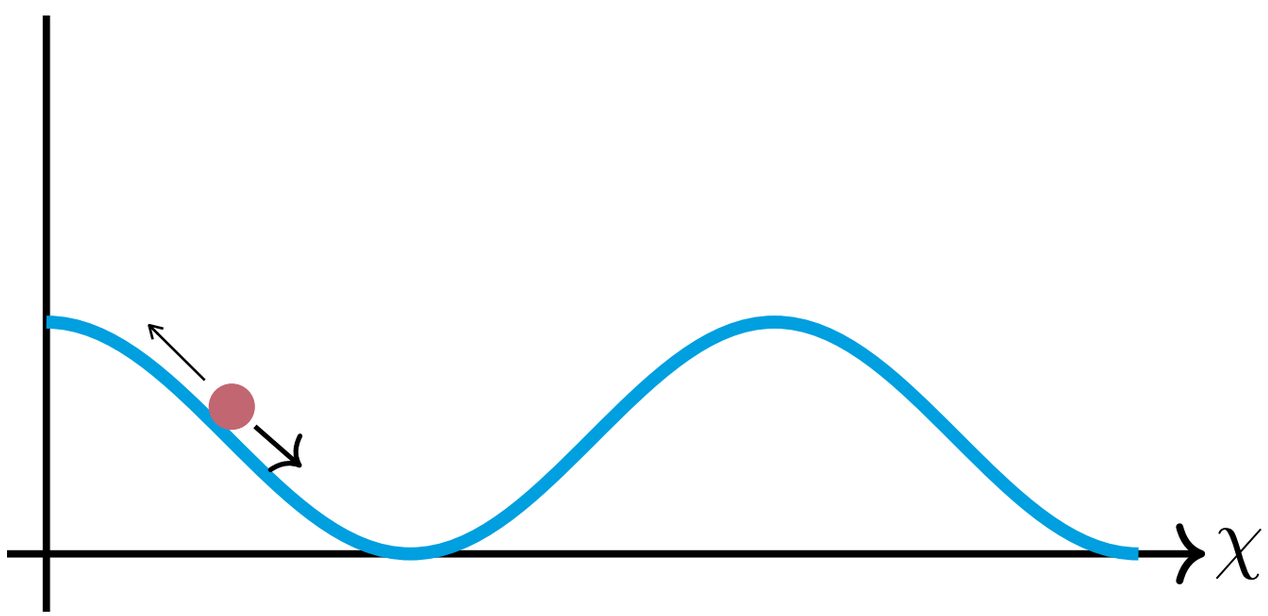
Attributed to S. Weinberg:

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...

- in dS, all light stuff drifts & decays …



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



[Kaloper & AW '24]

$m_\chi > H$: frozen χ melts …

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

χ oscillates - it is matter !

[Kaloper & AW '24]

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

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

$f_\chi \sim M_{\rm GUT}$, then for $m_\chi > 10^{-19}$ eV we have $T_\star > {\rm eV}$.

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

too much DM: anthropic cut $\langle\chi\rangle_{\rm anthr.} < f_\chi$ so $T_\star = {\rm eV}$

- a possible future observational outcome …

[Kaloper & AW '24]

(i) BH superradiance detects a χ with

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

(ii) other experiment determines: DM largely NOT χ

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

… anthropics has failed !

summary

- there is a string theory axiverse of p-form axions

- most of these axions are dark! - visible gravitationally

- axions coupled to dark U(1) gauge fields:

CS-coupled to dark U(1) — a gravitational wave forest!

parametric resonance production — small but finite ΔN_{eff}

↔ task : correlate coupling structures & signals !

- minimum axion excitation — random walk ↔ dS universality !

may lead to anthropics-testing dark matter sector!

ALESSIO-B