some

more recent

axion theory

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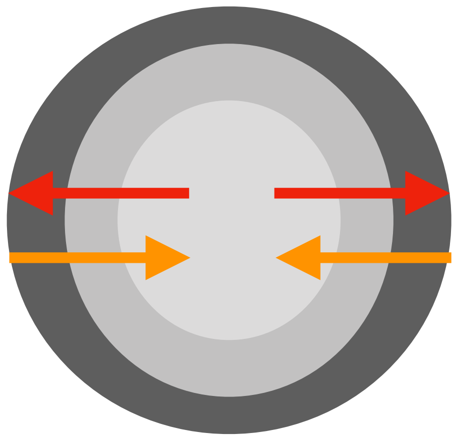
Quantum Connections Session 5: Axions in Stockholm - Reloaded

omissions

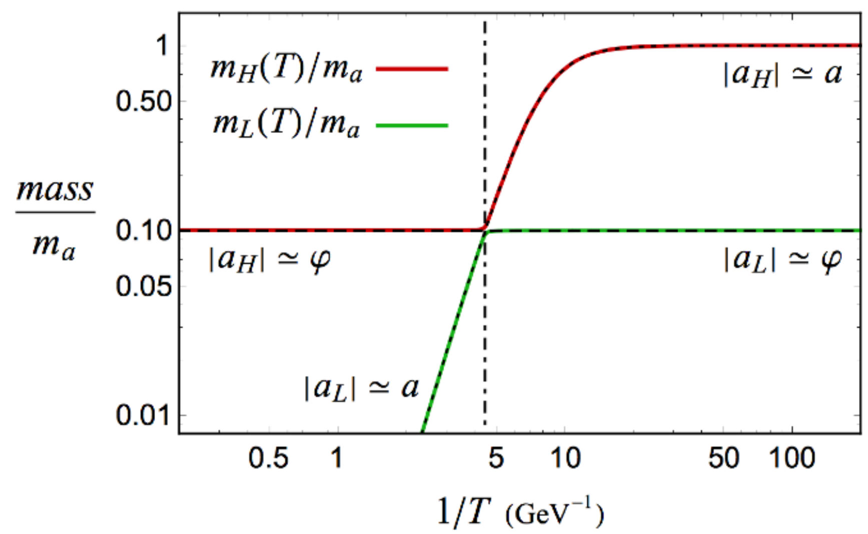
- Axion stars



$$U \sim -\frac{GM}{R} + \frac{1}{2}\int d^3\mathbf{x}(\nabla a)^2$$

[**Visnielli**, **Baum**, Redondo, Freese, **Wilzcek**]
[Widdicombe, Helfer, (Doddy) **Marsh**, Lim]
[Dietrich, **Day**, Clough, Coughlin, **Niemeyer**]

- Modified axion dark matter production mechanisms



[Ho, **Saikawa,** Takahashi]
[**Agrawal,** Marques-Tavares, Xue]

- Axions that also solve other problems

$$SO(3)_{\mathrm{F}} \times U(1)_{\mathrm{PQ}}$$

[**Reig**, Valle, **Wilzcek**]
[Ballesteros, Redondo, **Ringwald**, Tamarit]

focus

- New targets for the axion couplings?
- State of axions in quantum gravity and string theory

the low-energy axion

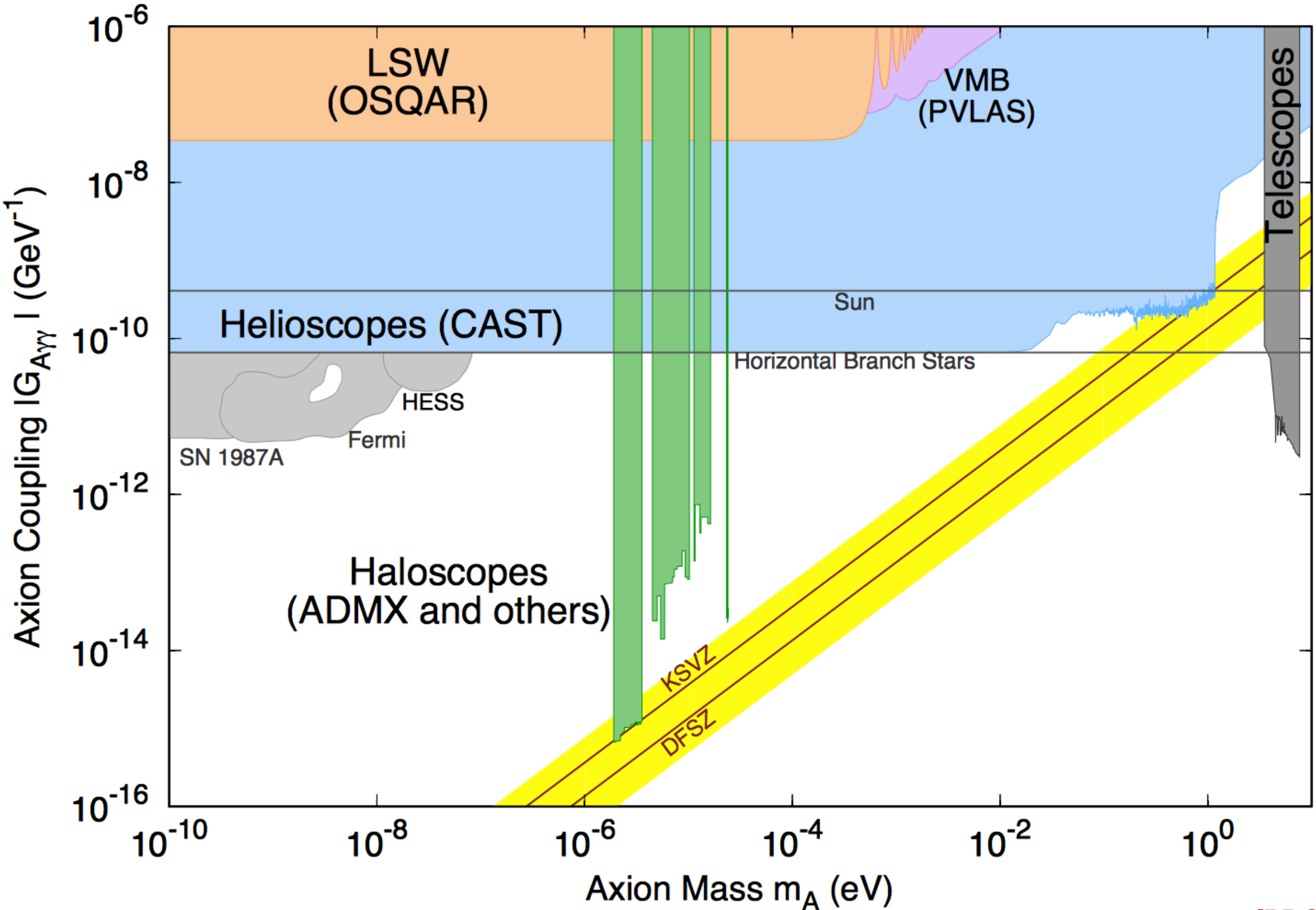
$$\mathcal{L} \sim \frac{a}{f_a}\frac{\alpha_s}{8\pi}\mathrm{tr}\left(\mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}\right) - \frac{g_{a\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_f}{f_a}\partial_\mu a\, \bar{\psi}\gamma^\mu\gamma_5\psi$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} c_{a\gamma}$$ with $$c_{a\gamma} = r - 1.92$$

r: high energy ("UV") contribution

1.92: meson mixing ("IR")

Natural target: $c_{a\gamma} \sim \mathcal{O}(1)$



LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes (CAST)
Sun
Horizontal Branch Stars
HESS
Fermi
SN 1987A
Haloscopes
(ADMX and others)
KSVZ
DFSZ
Axion Coupling |G$_{A\gamma\gamma}$| (GeV^{-1})
Axion Mass m$_A$ (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

[PDG]

what can enhance $g_{a\gamma}$?

1) Exotic "UV-completion"

$$r \lesssim \mathcal{O}(30-90)$$

will not discuss here

2) "Kinetic mixing"

$$\mathcal{L} \sim \boxed{\tfrac{1}{2}\partial_\mu a \partial^\mu a + \tfrac{1}{2}\partial_\mu b \partial^\mu b + \epsilon \partial_\mu a \partial^\mu b} + \frac{a}{f_a}\frac{\alpha_s}{8\pi}\mathrm{tr}\left(\mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}\right) - \frac{b}{f_b}\frac{\alpha}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\sim \tfrac{1}{2}\partial_\mu a \partial^\mu a + \tfrac{1}{2}\partial_\mu b \partial^\mu b + \frac{a}{f_a}\frac{\alpha_s}{8\pi}\mathrm{tr}\left(\mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}\right) - \left(\frac{b}{f_b} - \underbrace{\epsilon\left(\frac{f_a}{f_b}\right)}_{c_{a\gamma}}\frac{a}{f_a}\right)\frac{\alpha}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

[Cicoli, Goodsell, **Ringwald**]
[**Agrawal**, Fan, Reece, Wan]

3) “Gauge kinetic mixing”

$$\mathcal{L} \sim \left(\frac{a}{f_a} + \epsilon \frac{b}{f_b}\right) \frac{\alpha_s}{8\pi} \mathrm{tr}\left(\mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}\right) - \frac{b}{f_b}\frac{\alpha}{8\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\sim \left(\frac{a^{\mathrm{QCD}}}{f_a}\right) \frac{\alpha_s}{8\pi} \mathrm{tr}\left(\mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}\right) - \frac{\alpha}{8\pi}\left(\frac{b_\perp}{f_b} + \underbrace{\epsilon\left(\frac{f_a}{f_b}\right)^2}_{c_{a\gamma}} \frac{a^{\mathrm{QCD}}}{f_a}\right) F_{\mu\nu}\tilde{F}^{\mu\nu}$$

4) “KNP” alignement, clockwork

[**Agrawal**, Fan, Reece, Wan]

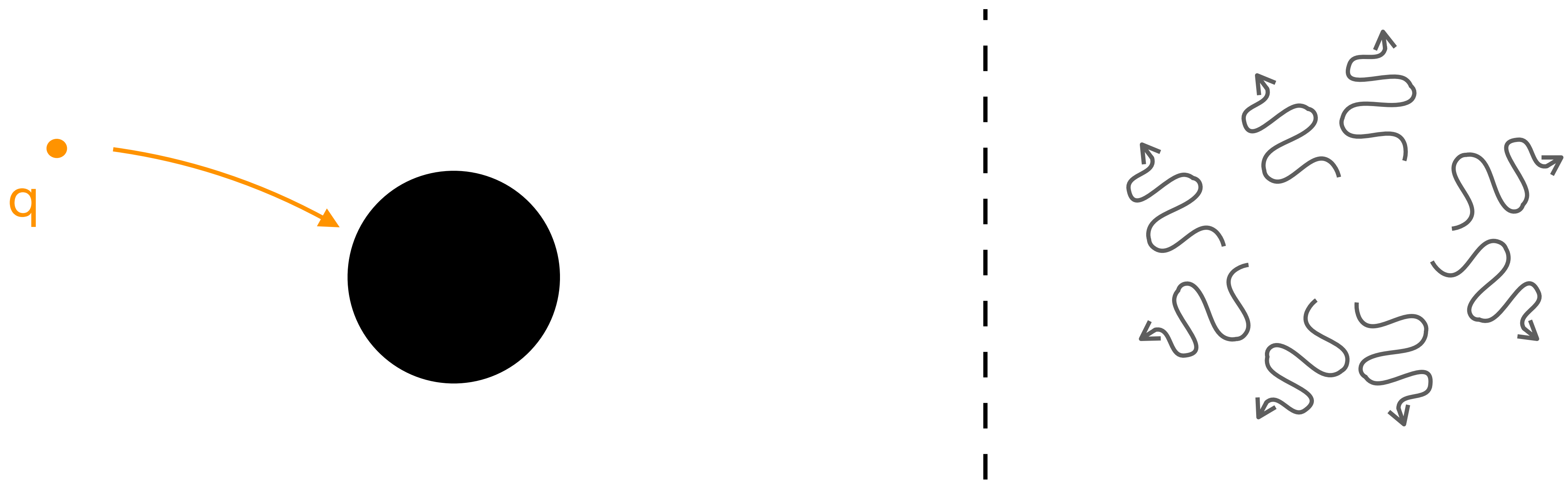
Enhanced axion-photon coupling need not be very contrived

(if there are at least two axions)

the axion and quantum gravity

Old topic, but recently renewed interest.

Folklore: quantum gravity does not respect global symmetries



$$V_{\mathrm{EFT}} \sim \frac{1}{M_{\mathrm{Pl}}^{\Delta-4}} \mathcal{O}_{\Delta}$$

Often irrelevant: $\Delta V_{\text{(B-L)-violation}} \sim \frac{1}{M_{\text{Pl}}^2} u^c\, d\, u^c\, e$

$$\tau(p \to e^+ \pi) \sim 10^{46}\,\text{years} \qquad (\gg 10^{34}\ \text{years})$$

(At least naively) more severe for the axion:

$$\Phi = \phi e^{ia/f_a}$$

$$\Delta V \sim g_5 \frac{|\Phi|^4 \Phi}{M_{\text{Pl}}} + \text{ h.c.} + \ldots$$

Reintroduces CP-violation unless $|g_5| \lesssim 10^{-55}$

[Barr, Seckel]
[Kaminokowski, March-Russell]

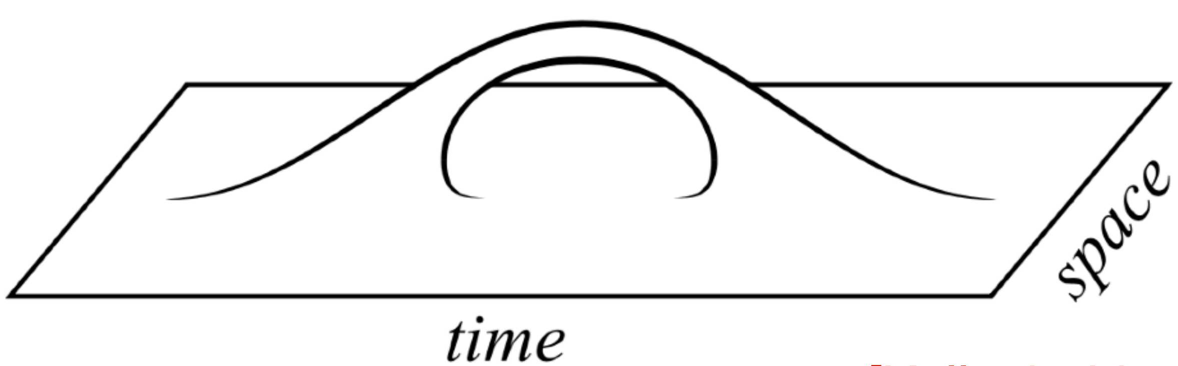
Are these terms generated?
What could the discovery of an axion tell us about quantum gravity?

quality problem resolutions

1. Dangerous terms forbidden by unbroken discrete symmetry.

2. Dangerous terms naturally small?

$$V_{\text{eff}} \sim \underbrace{f_a^2 m_a^2 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)}_{\text{QCD}} + \underbrace{c_w f_a^2 M_{\text{Pl}}^2 e^{-\frac{\pi\sqrt{6}}{8}\frac{M_{\text{Pl}}}{f_a}} \cos\left(\frac{a}{f_a} - \delta\right)}_{\text{gravitational instantons (“wormholes”)}} + \underbrace{\ldots}_{\text{other}}$$

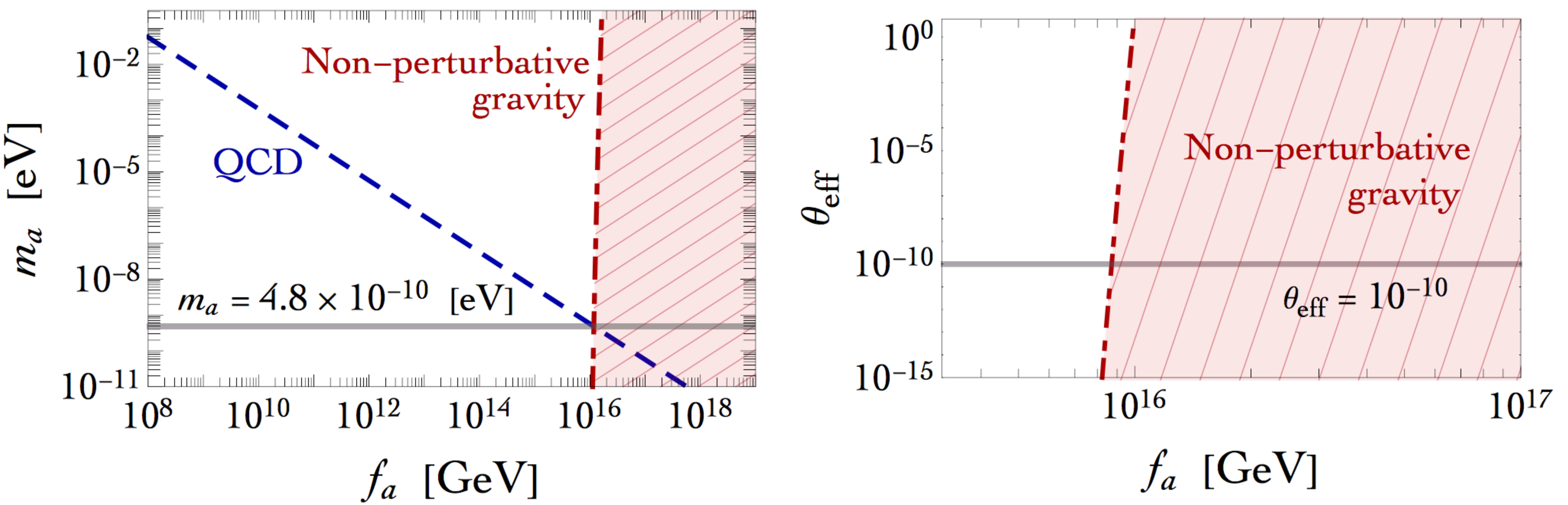


[Kallosh, Linde, Linde, Susskind]
[Alonso, Urbano]
[Hebecker, Mikhail, Soler]

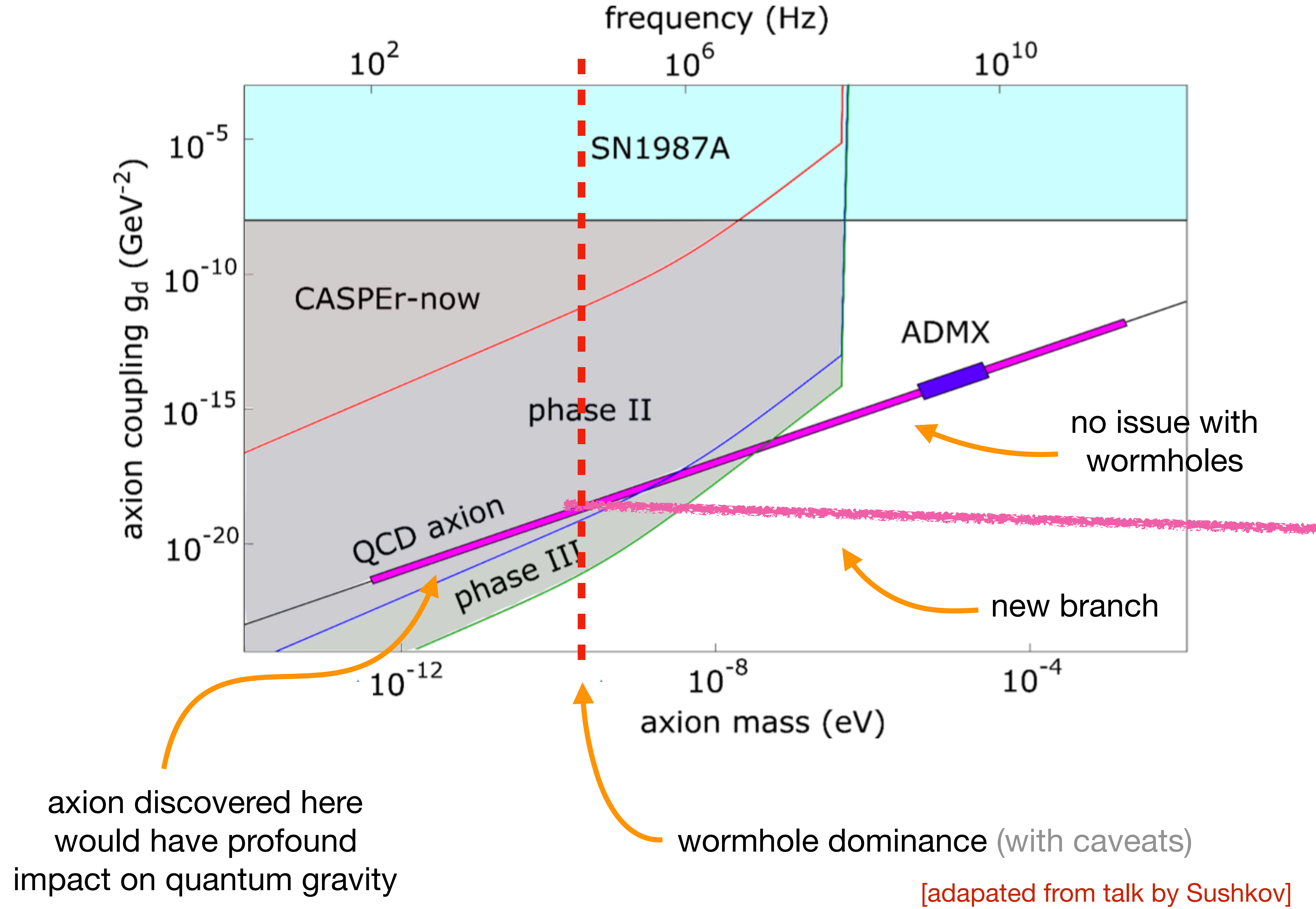
With some assumptions ($\delta \sim 1$, $c_w \sim 24\pi^4$):

1. $m_a \gtrsim \mathcal{O}(10^{-9}\text{eV})$

2. To solve strong CP-problem: $f_a \lesssim \mathcal{O}(10^{16}\text{GeV})$



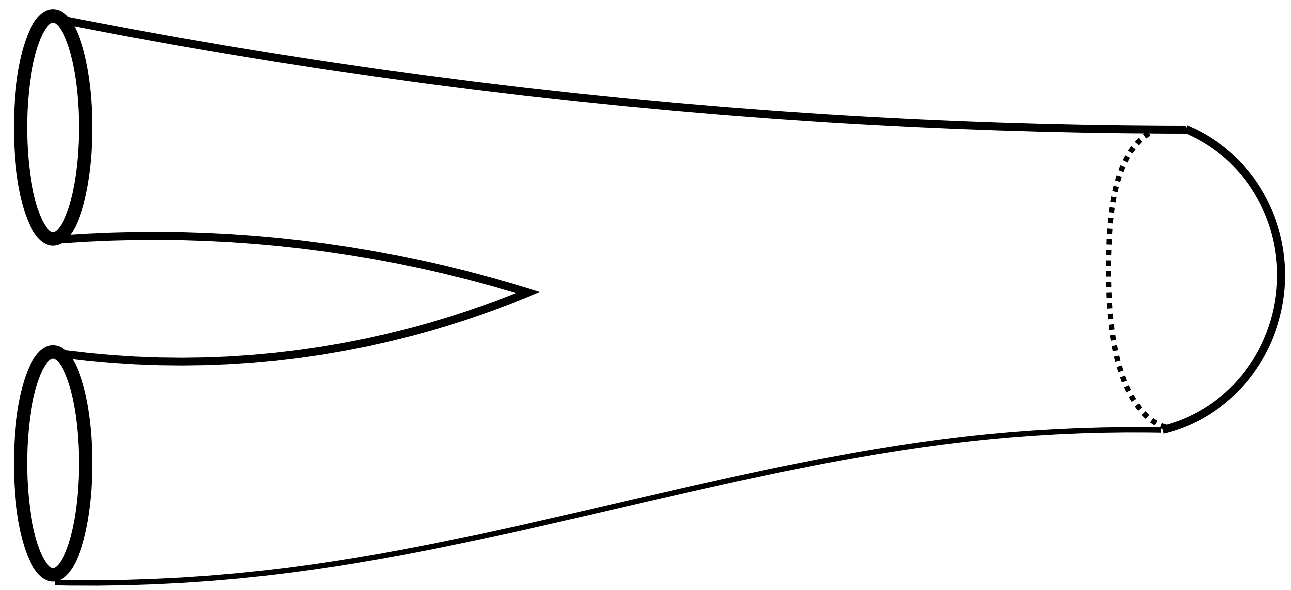
[Alonso, Urbano]



frequency (Hz)
10^2
10^6
10^10
10^-5
10^-10
10^-15
10^-20
axion coupling g_d (GeV^-2)
SN1987A
CASPEr-now
ADMX
phase II
phase III
QCD axion
no issue with
wormholes
new branch
10^-12
10^-8
10^-4
axion mass (eV)
axion discovered here
would have profound
impact on quantum gravity
wormhole dominance (with caveats)
[adapated from talk by Sushkov]

string theory & axions

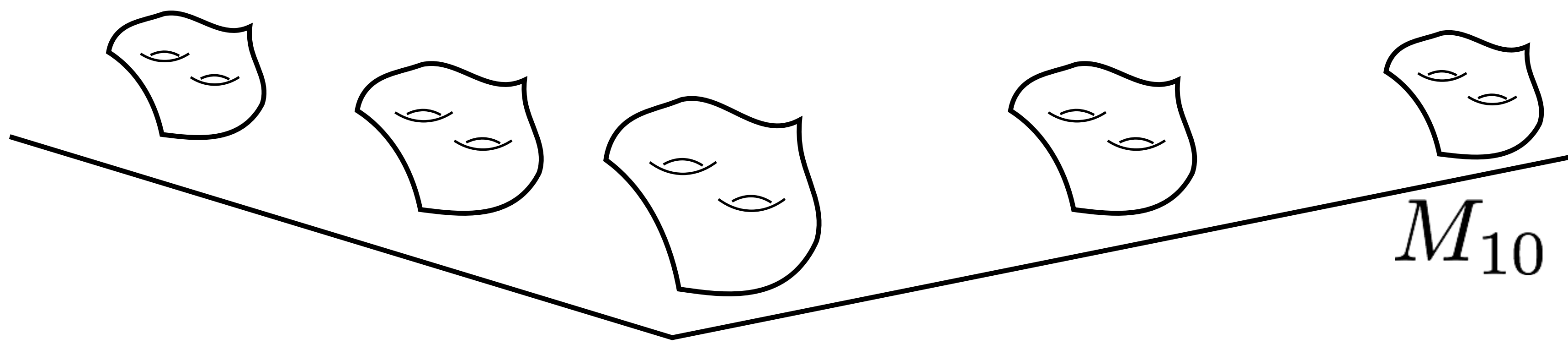
String theory



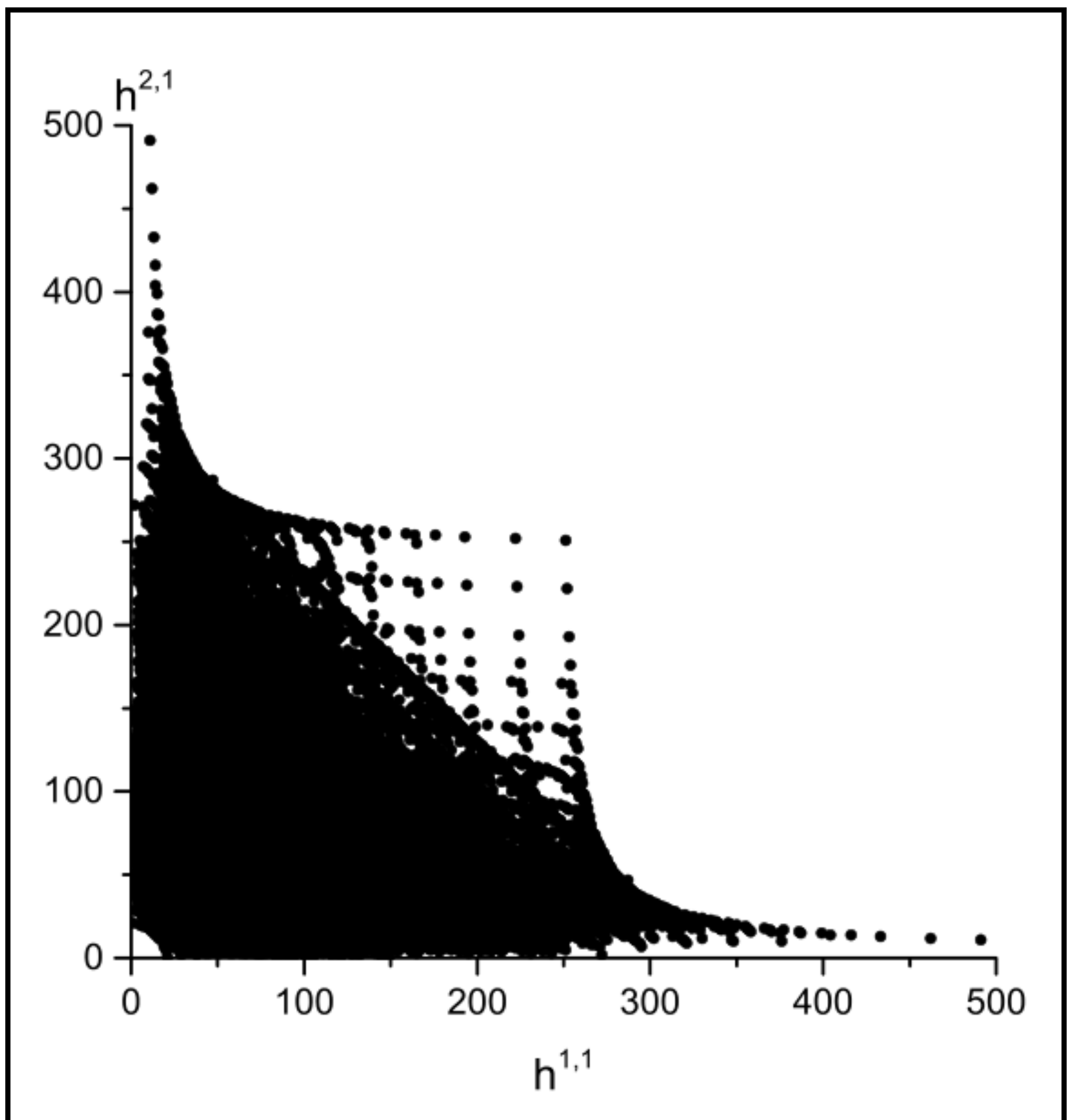
10-dimensional EFT

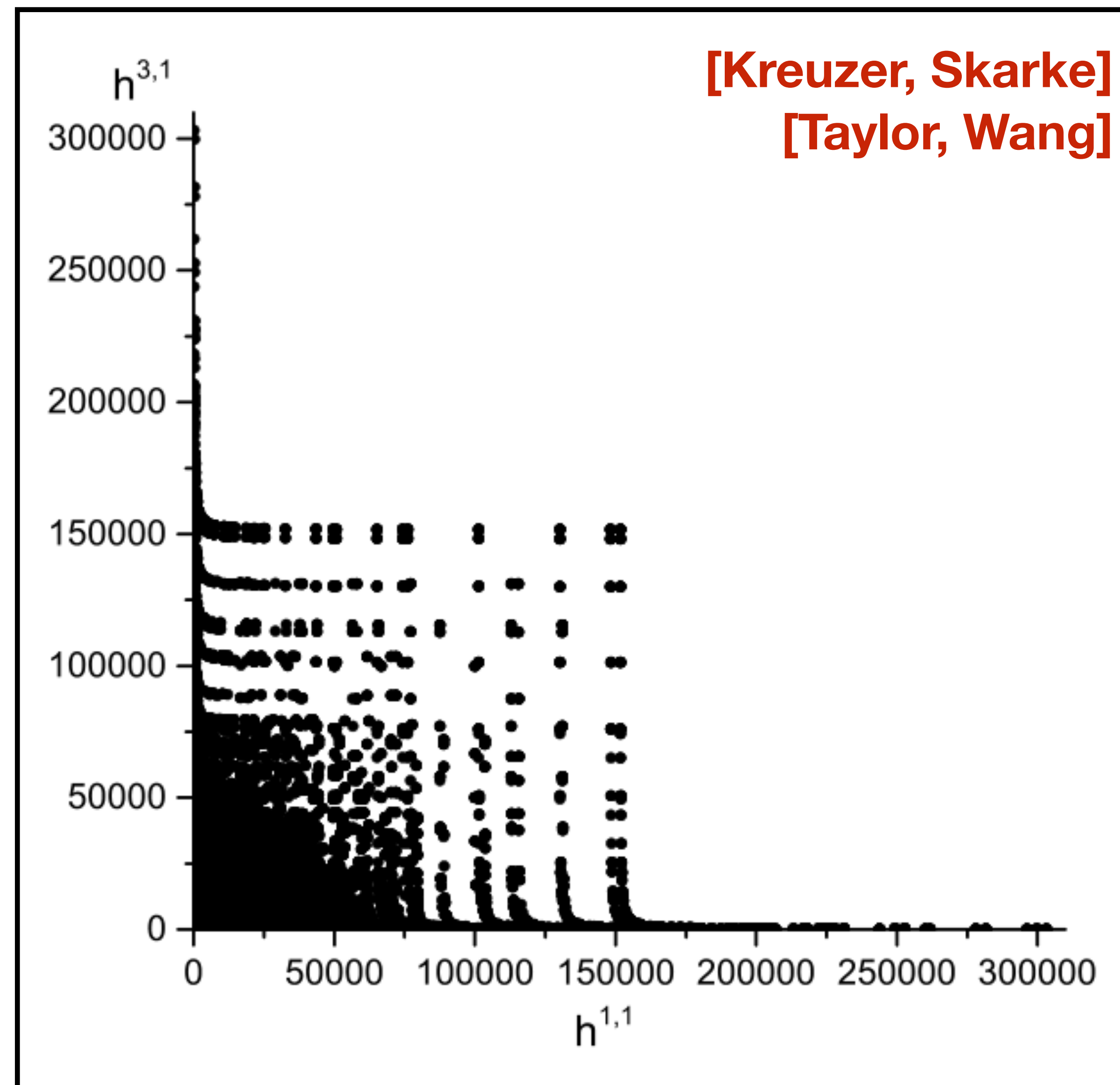
$$S_{10} \sim M_{10}^4 \int d^{10}x \sqrt{-g} \left(R + F_{M_1 \ldots M_p} F^{M_1 \ldots M_p} + \ldots\right)$$

compactifications

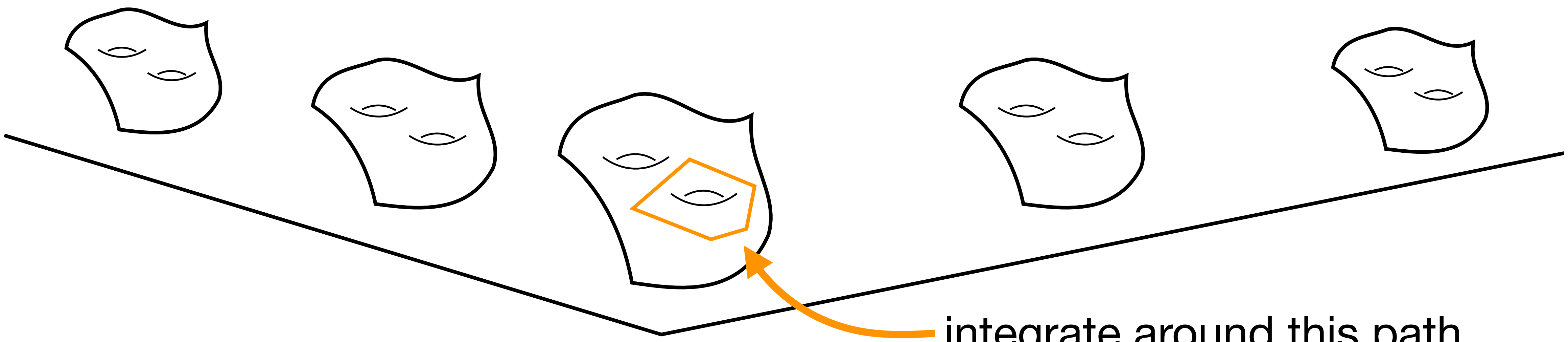


$$M_{10} = M_4 \times M_6$$





string theory axions



“Axions”: $\int_{\Sigma_n} A_n = a \qquad (F_{n+1} = dA_n)$

neither KSVZ or DSFZ
(no 4d UV-completion)

#’s at tree-level: $\mathcal{O}(100 - 1000)$

may include the QCD axion

string theory axion problems

- light axions come with potential instabilities of the compactification

[Conlon]

only partially addressed
in literature

[Acharya, Bobkov]
[Cicoli, Goodsell, **Ringwald**]

- light axions may be essentially required

controlled compactifications with
many axions have large sub-volumes

[Demirtas, Long, McAllister, Stillman]

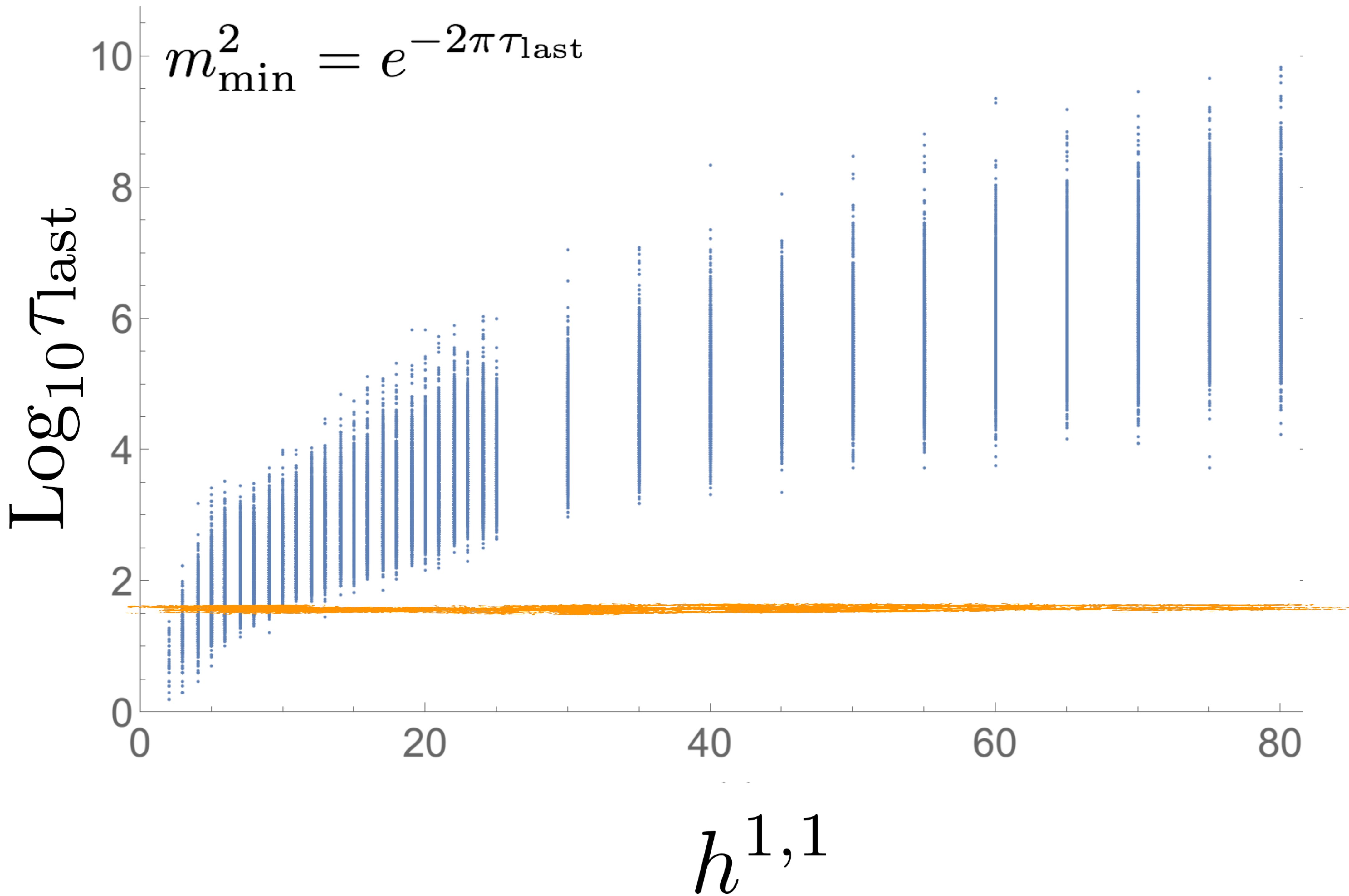
- multiple-axion mixing can be dangerous for the QCD axion

$$V_0(a_{\rm QCD}) + \Lambda_1^4\left(1-\cos\left[\frac{a_{\rm QCD}+a_{\rm other}}{f_a}-\varphi_1\right]\right) + \Lambda_2^4\left(1-\cos\left[\frac{a_{\rm other}}{\tilde{f}_a}-\varphi_2\right]\right)$$

how serious is this?

lightest axion mass distribution

as function of topological complexity



[Demirtas, Long, McAllister, Stillman]

summary

- many developing directions in axion theory
- multiple-axion models motivate broad targets
- in part of the parameter space, the discovery of an axion may challenge notions of quantum gravity
- string theory axions provide strong motivation, but many issues remain