Glimmers from the Axiverse

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w/ Naomi Gendler, Jakob Moritz, Liam McAllister, 2309.13145

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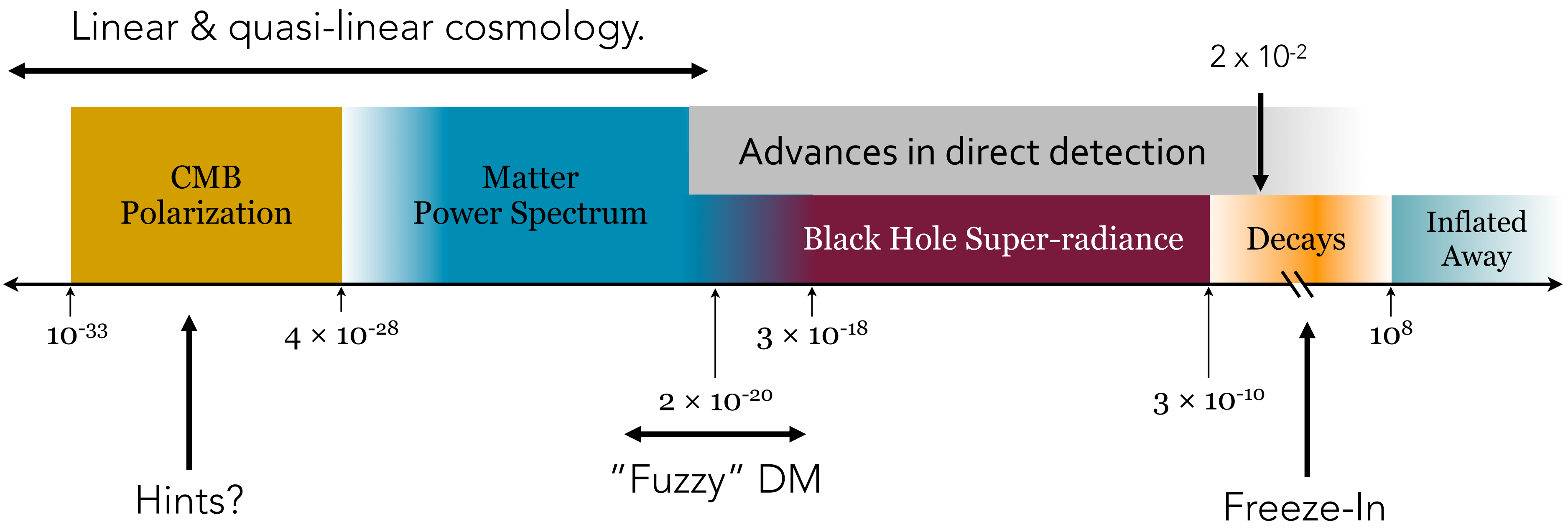
Axiverse in 2023

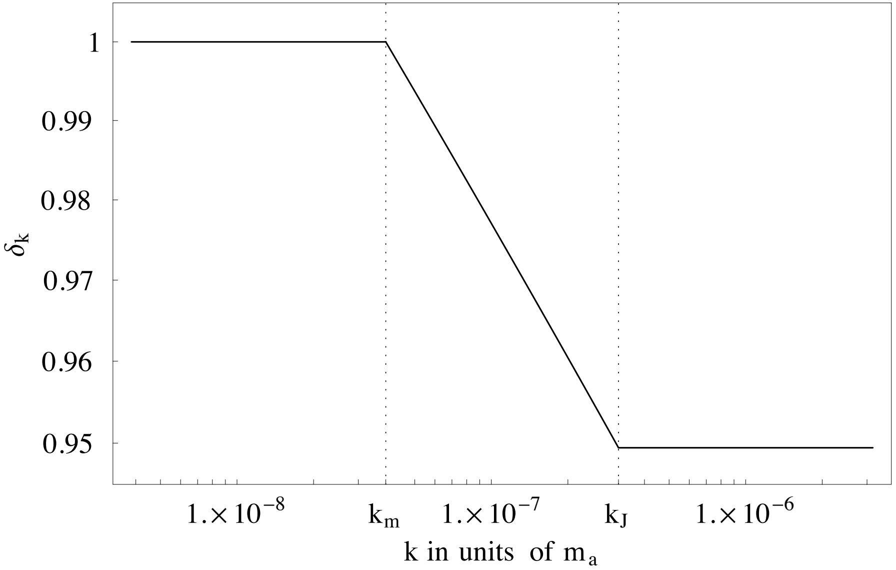


All of the suggested probes have been explored and become precise, along with some (unexpected?) new developments in cosmology and direct detection.

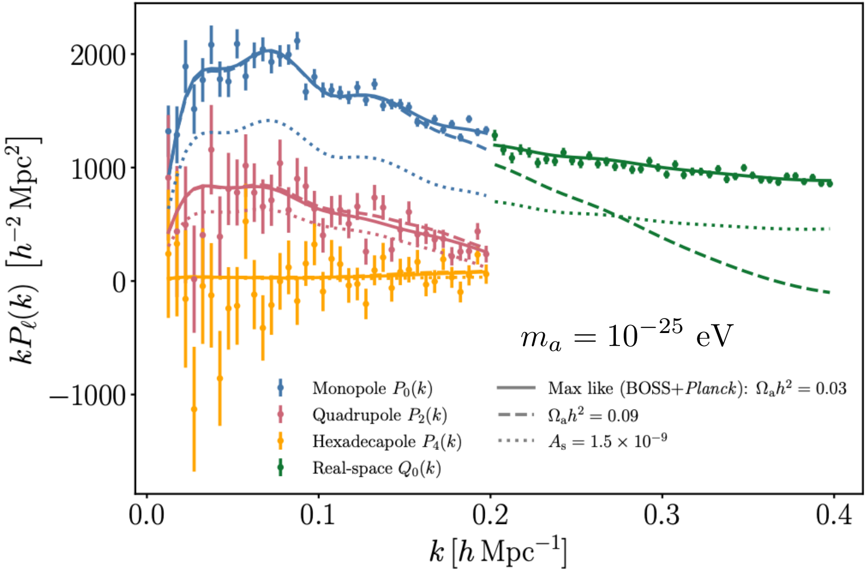
LINEAR++ COSMOLOGY

Matter
Power Spectrum

Recent advances in quasi-linear and non-linear modelling (halo models, EFTofLSS, emulators) allow precision limits from smaller scales → probe larger axion masses.

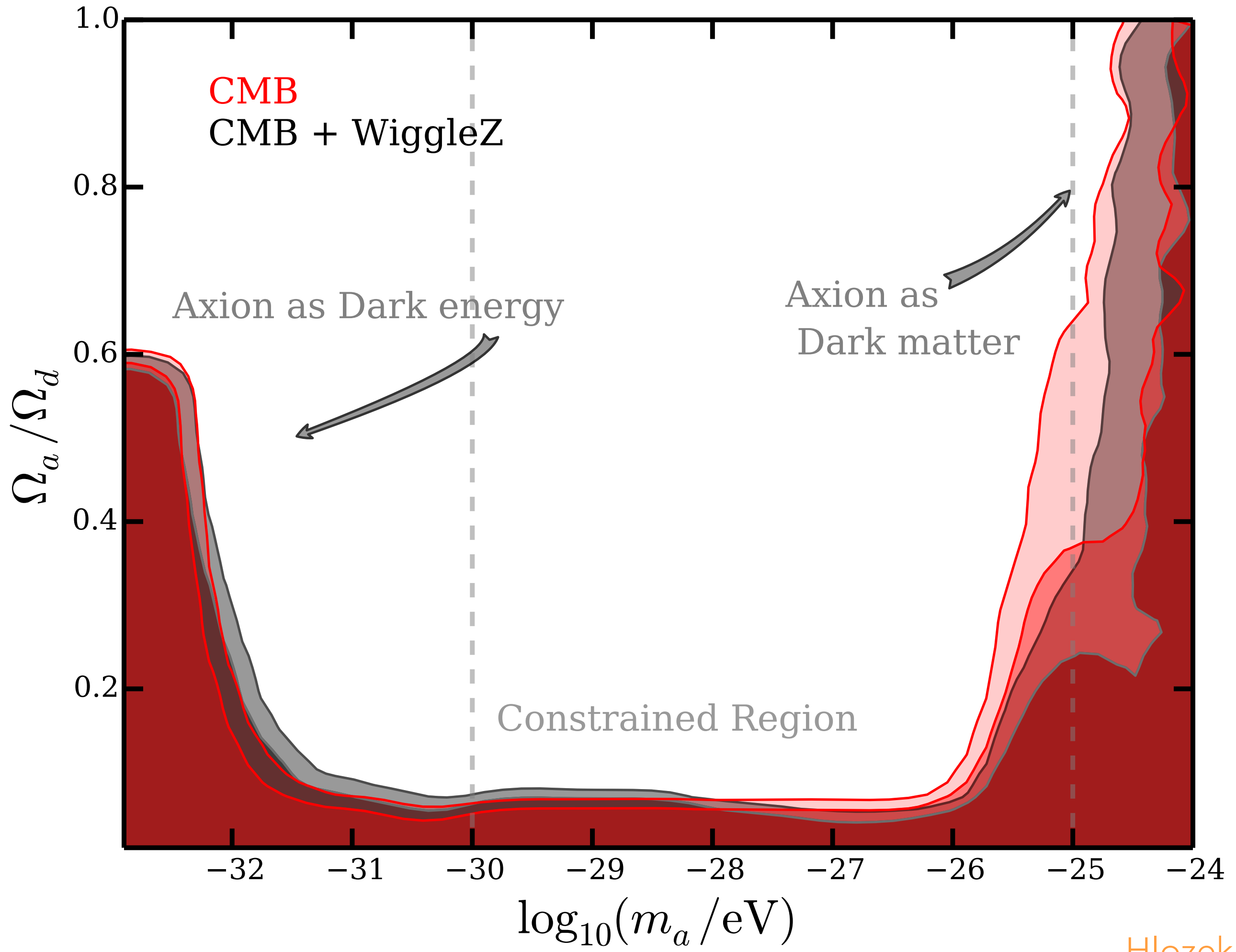


Axiverse 2009: "step in P(k)".



Axiverse 2023: EFTofLSS in the BOSS DR12 P(k) multipoles.

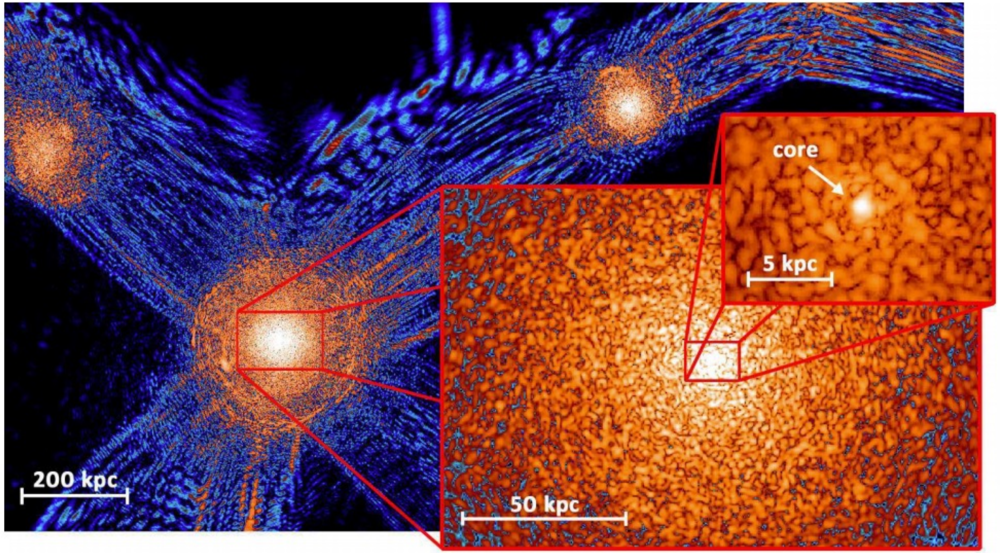
Lague DJEM et al (2021); Rogers, DJEM et al (2023).
Codes: axionCAMB, multinest, cosmosis, PeakPatch, CLASS-PT



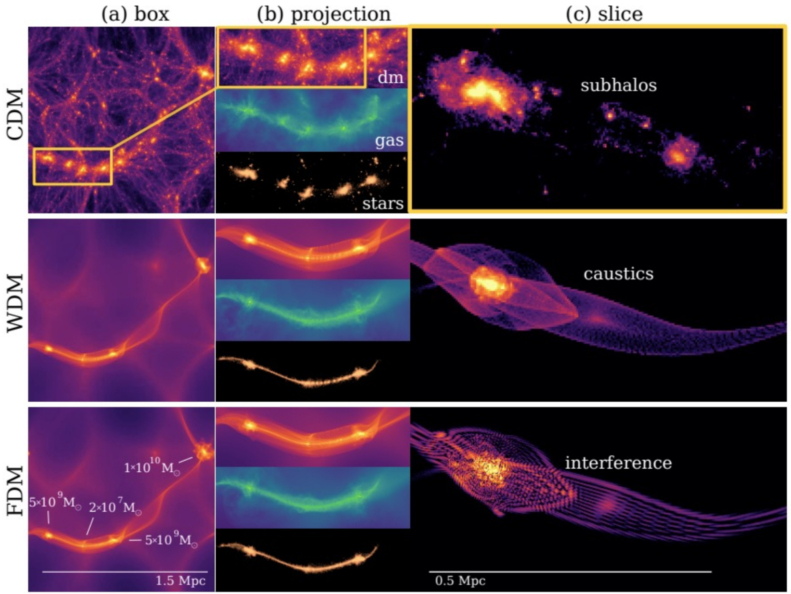
Hlozek, DJEM et al (2014)

Simulating Light Axions

Key advance since 2014: the cosmic web with wave effects at m~10^{-22} eV.



Schive et al (2014)



Mocz et al (2019)

Deeper understanding of dynamics (condensation, relaxation) + new soliton pheno.

FREEZE-IN AXIONS

Decays

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

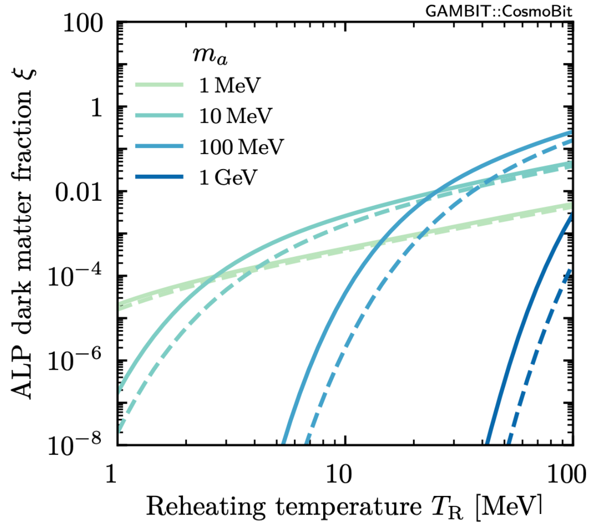
Cosmological constraints on decaying axion-like particles: a global analysis

Csaba Balázs,[a] Sanjay Bloor,[b] Tomás E. Gonzalo,[c,d] Will Handley,[e,f] Sebastian Hoof,[d,g] Felix Kahlhoefer,[c,d] Marie Lecroq,[a,h] David J.E. Marsh,[i] Janina J. Renk,[b,j,k] Pat Scott[b,k] and Patrick Stöcker[c,l]

PHYSICAL REVIEW LETTERS **129,** 241101 (2022)

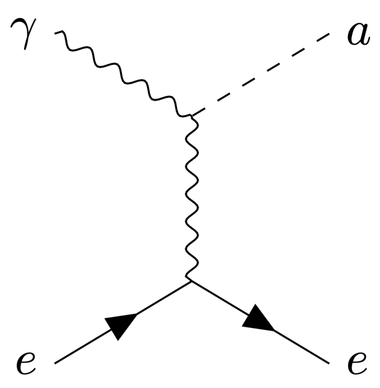
Irreducible Axion Background

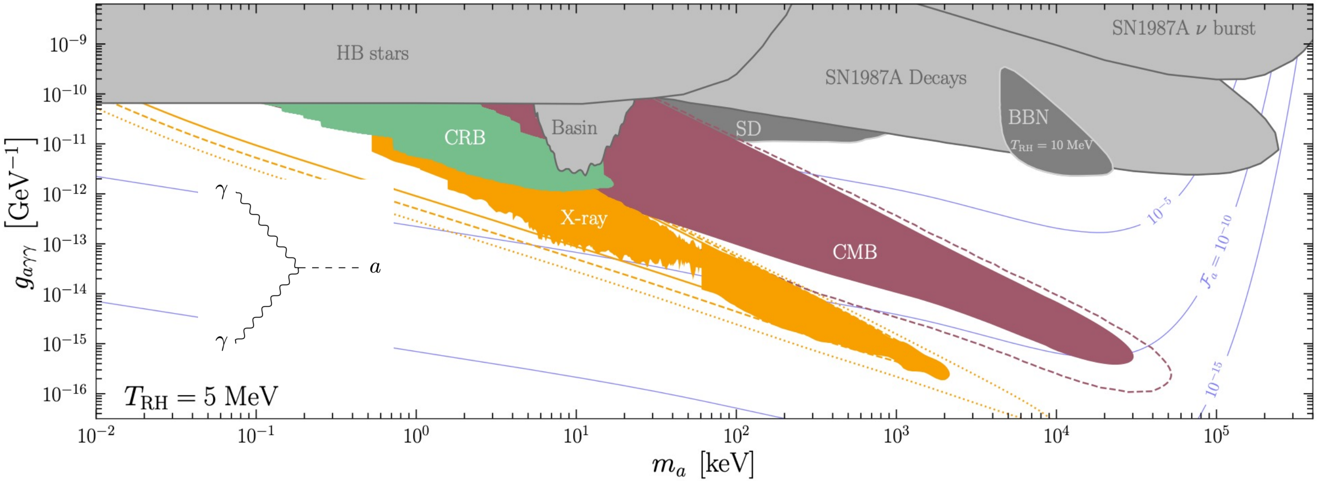
Kevin Langhoff,[1,2] Nadav Joseph Outmezguine,[1,2] and Nicholas L. Rodd[3]



- Primakoff process produces axions from γ+e+- with zero initial state → freeze-in axions.
- Minimal contribution reheating to BBN, TR = 5 MeV.
- keV -GeV axions subsequently decay → limits for DM fractions as low as 10^{-10} and τ>10^{10} yrs!

$$g = \frac{\alpha}{2\pi f_a} \Rightarrow f_a \gtrsim 10^{13}\ \mathrm{GeV}$$





SUPERRADIANCE!

Black Hole Superradiance

Review: Brito et al (2015)

Solve for instabilities of KG equation on Kerr: $\Box\phi - \partial_\phi V(\phi) = 0$

Non-relativistic limit in "tortoise coords", find instability ($\omega^2<0$):

$$\frac{d^2\psi_{lm}}{dr^{*2}} = \left[\omega^2 - V(r,\omega)\right]\psi_{lm}\,.$$

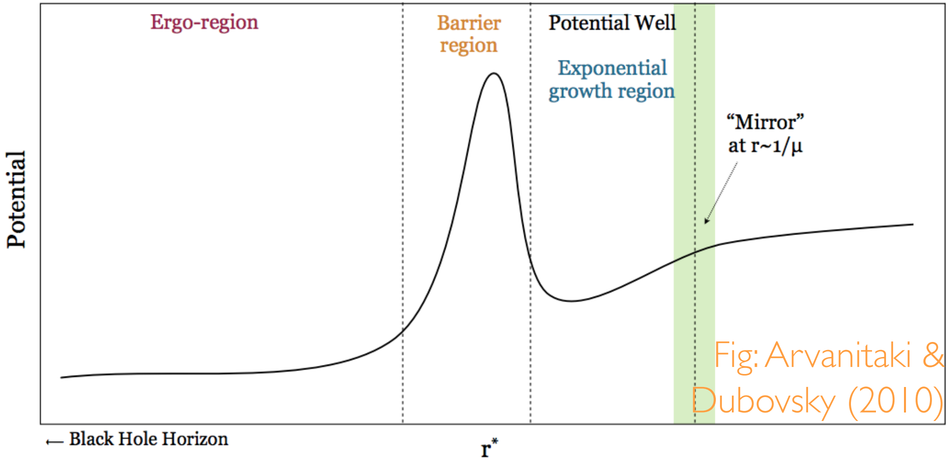
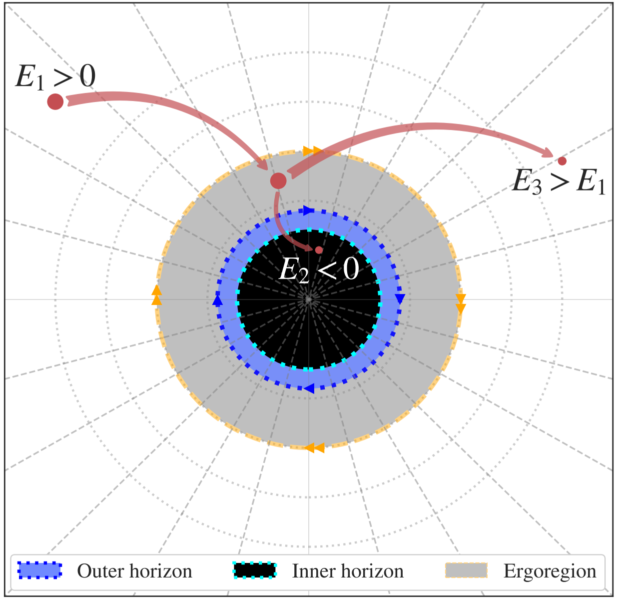


Fig: Arvanitaki & Dubovsky (2010)

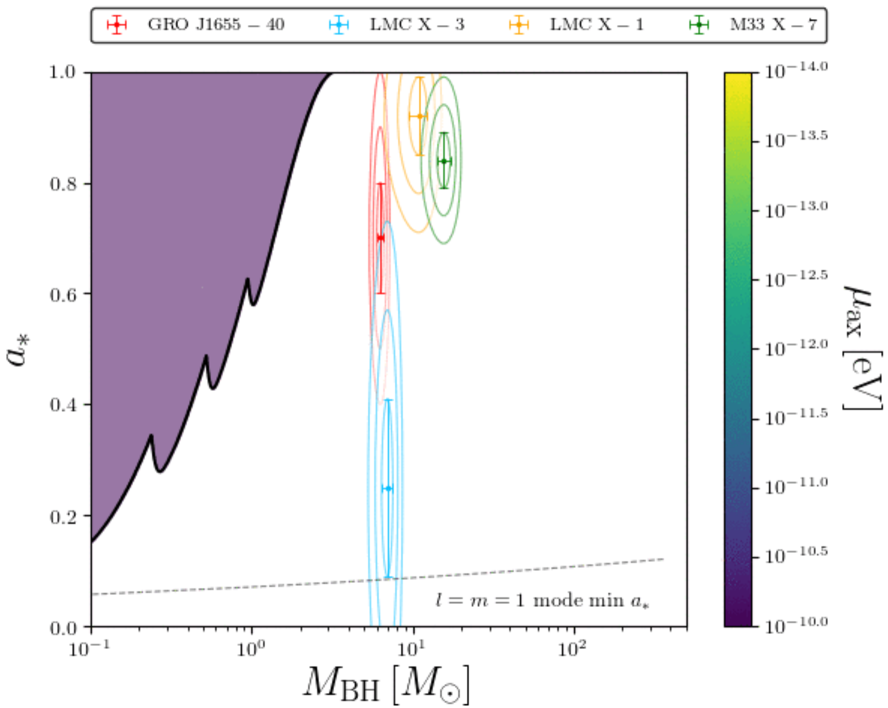
Physical picture: "Penrose process/ black hole bomb"

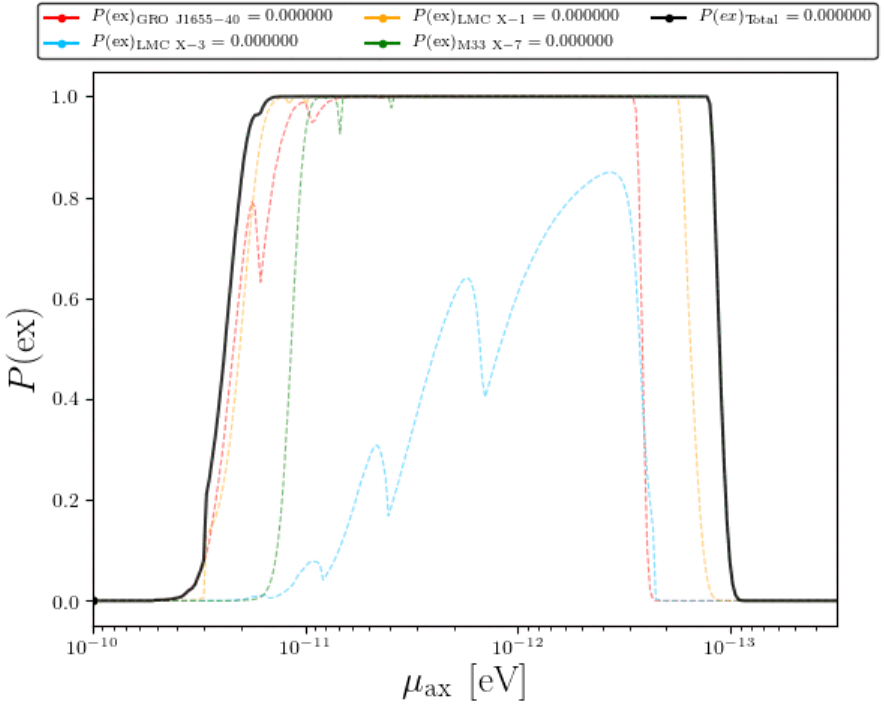


Resonant bosons extract spin from astrophysical BHs, if $\Gamma_{SR} > \Gamma_{others}$

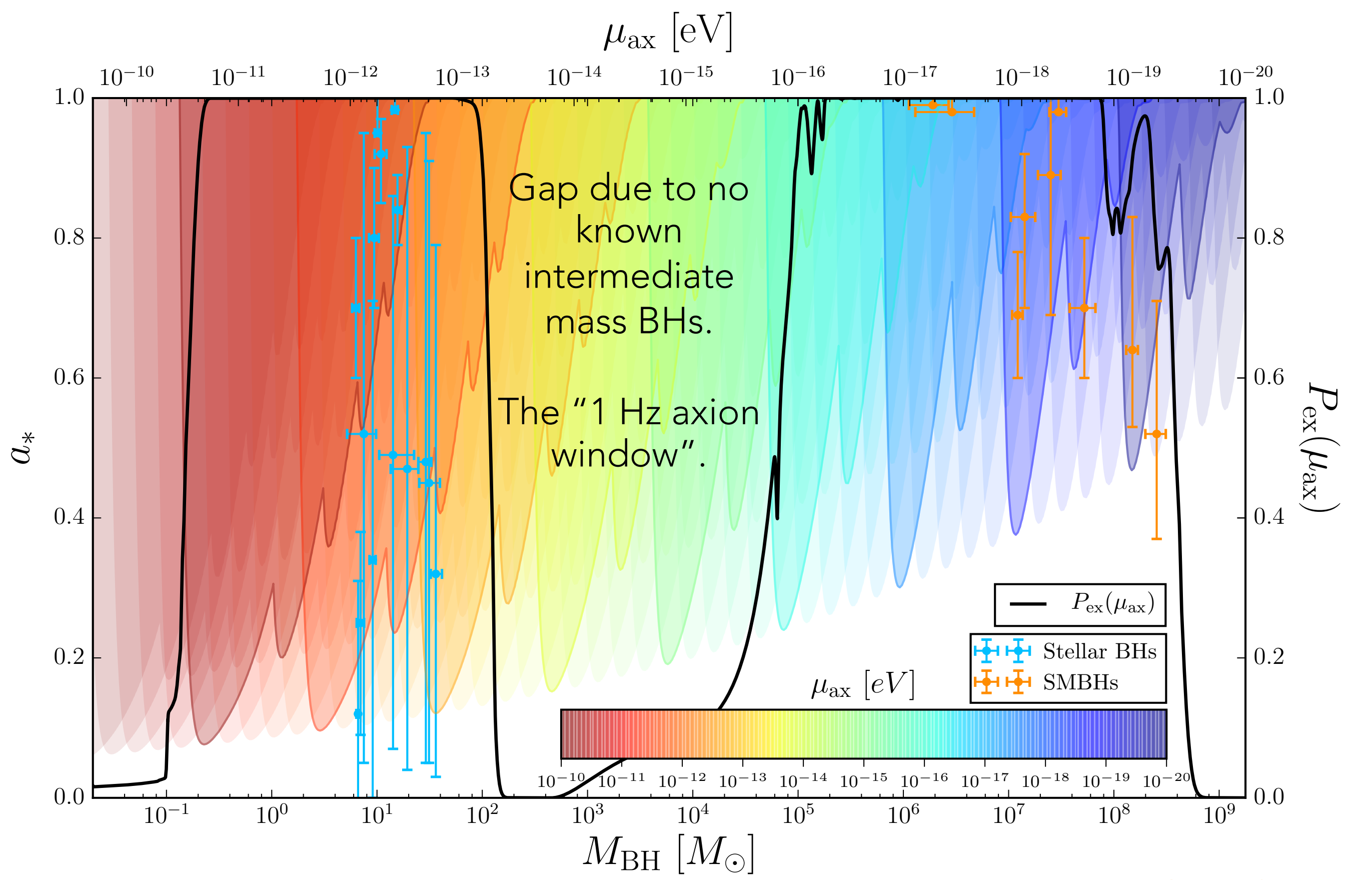
Exclude axion masses where known BHs exist in the superradiant forbidden region.
This sample: X-ray stellar BHs. Gaussian composite likelihood.

GIF by Matthew J. Stott





"Exclusion probability" is marginal likelihood. Statistically robust constraints.



Stott & DJEM (2018)

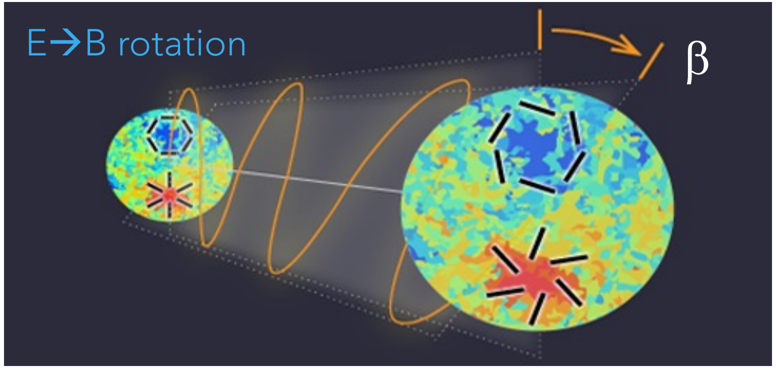
(NB: difference to Baryakhtar+ mass limits due to overly conservative stats model. See backup slides.)

New analysis forthcoming w/Seb Hoof+

COSMIC BIREFRINGENCE

CMB
Polarization

Birefringence



E, B are CMB polarization states (Stokes)

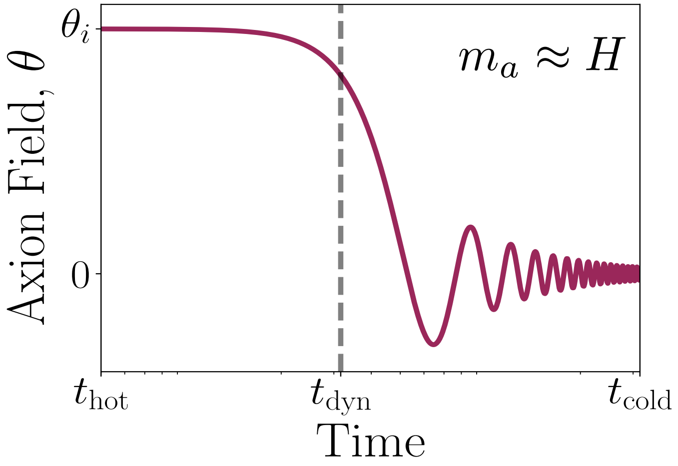
$$\beta = 5.2 \pm 1.9 \times 10^{-3}$$

Minami & Komatsu (2020)
Planck collab. (2022)

Calibrate absolute polarization angle with galactic measurement. Mask dependence consistent with cosmic signal (?).

Isotropic birefringence can be caused by an ultralight axion via:

$$\mathcal{L} = g\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \;\Rightarrow \beta = \int_{\eta_{\rm CMB}}^{\eta_0} g\frac{d\phi}{d\eta}d\eta$$



Fixes the axion mass:

$$10^{-33}\text{ eV} \lesssim m \lesssim 10^{-28}\text{ eV}$$

H_0 $\qquad$ $H_{\rm CMB}$

STRING THEORY PROGRESS

Specifically, type IIB on CY3's.

Demirtas, Rios-Tascon, McAllister

10D SUGRA has p-form fluxes.
Consider IIB 4-form, C_4:

$$S = -\frac{1}{2}\int F_5 \wedge \star F_5, \;\; F_5 = \mathrm{d}C_4$$

Decompose field into harmonic forms:

$$C_4 = \frac{1}{2\pi}\sum_i a_i(x)\omega_{4,i}(y)$$

Basis of harmonic forms given by closed 4-cycles (divisors) in X:

$$a_i(x) = \int_{D_i} C_4$$

basis elements given by h11 Hodge number = topological

Compactify → massless fields in 4D:

$$S = -\frac{1}{8}\int \mathrm{d}a_i \mathcal{K}_{ij} \wedge \star \mathrm{d}a_j \; ,$$

$$\mathcal{K}_{ij} = \frac{\partial^2 \mathcal{K}}{\partial\sigma_i \partial\sigma_j} \; , \;\; \mathcal{K} \propto \ln \mathcal{V}_X$$

V from "triple intersections" = topological

$$\tau_i = \sigma_i + i a_i$$

SUSY → τ = Kähler modulus.

Eigenvalues of K give kinetic term → "decay constant". Parametrically:

$$\mathrm{Eig}(K) \sim \frac{M_{pl}^2}{(\mathrm{Vol} D_i)^2}$$

Axion potential generated by ED3 instantons wrapping D:

$$V = \sum_j \Lambda_j^4 (1 - \cos Q_i^j a^i)$$

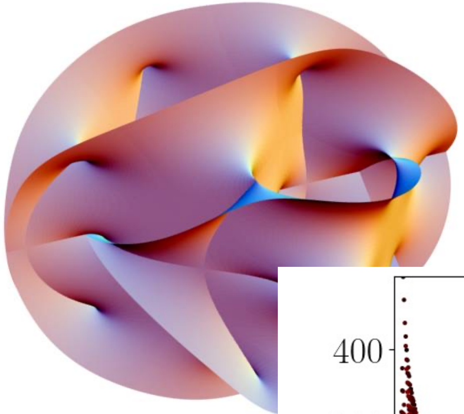
Q = instanton charge = topological

$$\Lambda_j \sim M_{pl}^3 m_{\mathrm{SUSY}} \exp[-\mathrm{Vol}\, D_i]$$

→ massive "closed string" axions from gravity sector unavoidable.

This discussion then suggests the following scenario for the distribution of f_a and m for different axions. The values of f_a are inversely proportional to the area of the corresponding cycle, so they do not change much from one axion to another. Given that the compactification is such that $S \gtrsim 200$ for string contributions to the QCD axion, and no special fine-tuning is allowed, *all* axion decay constants in this scenario are likely to be close to the GUT scale $M_{\mathrm{GUT}} \simeq 2 \times 10^{16}$ GeV. On the other hand, axion masses are exponentially sensitive to the area of the cycles, so that we expect their values to be homogeneously distributed on a log scale. Given that, as argued

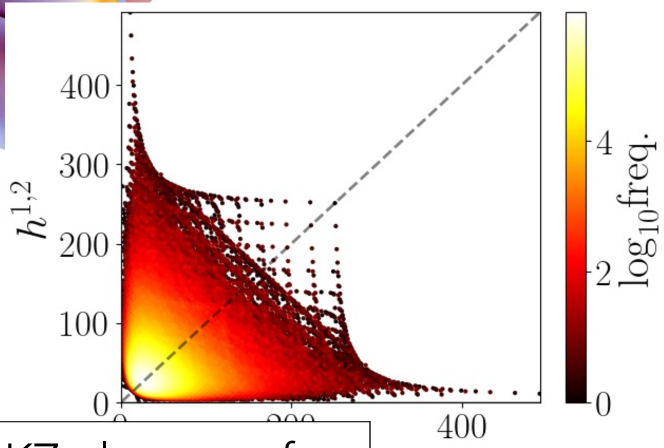
KS Axiverse

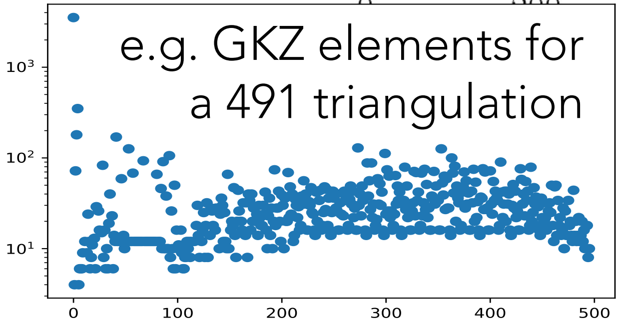


h11=27: most polytopes
h11=491: most CYs $<10^{428}$

Year	$h^{1,1}$	CPU time
2014	25	a few hours
2017	491	2s
2019	491	20ms

- CY3s constructed as hypersurfaces in "ambient toric varieties". E.g. Fermat quintic in CP4.
- KS database gives all 4d reflexive polytopes ~4 x 10^8.
- Triangulation of these gives ambient toric varieties. Unique polynomial → CY with h11 Kähler moduli.
- Automated fun with CY-Tools!
- Axions: Q unique for polytope. Kij fixed by CY. Saxion,σ, must be fixed in "stretched Kähler cone" where all curve and divisor volumes > 1.





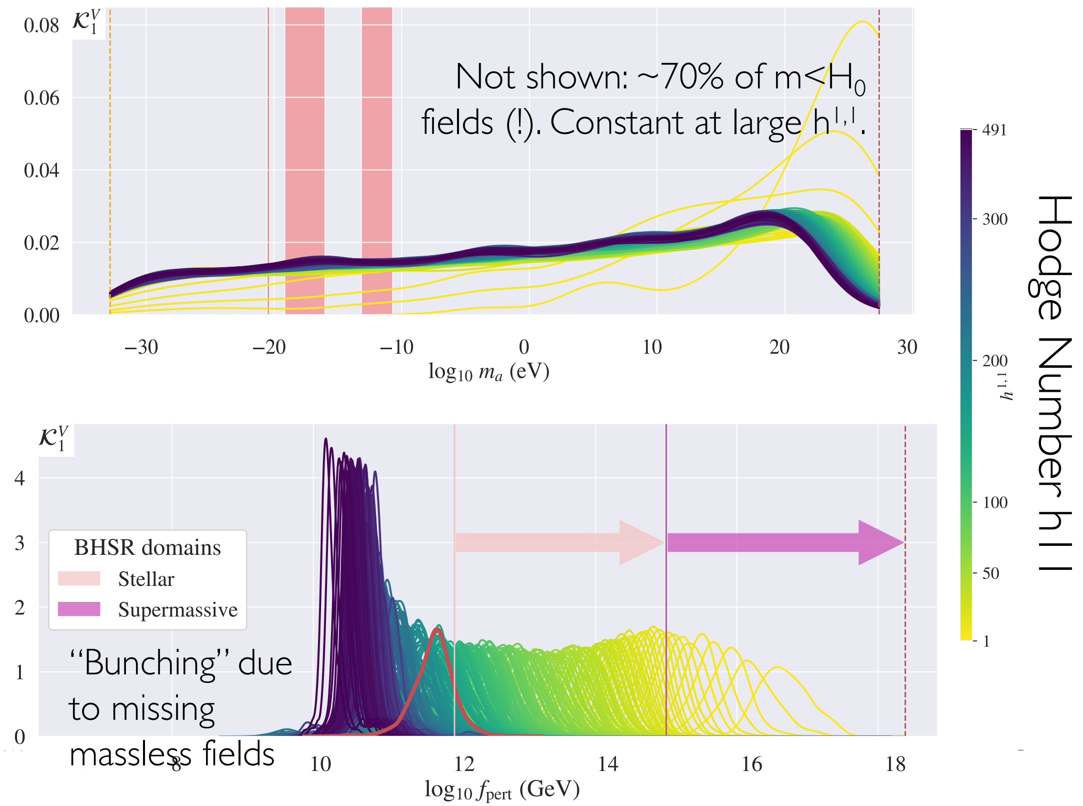
Axion Spectra from KS

Mehta, DJEM et al (2021)

Find vacua of V in fundamental domain. Expand to quartic order → masses +quartics (“fpert”).

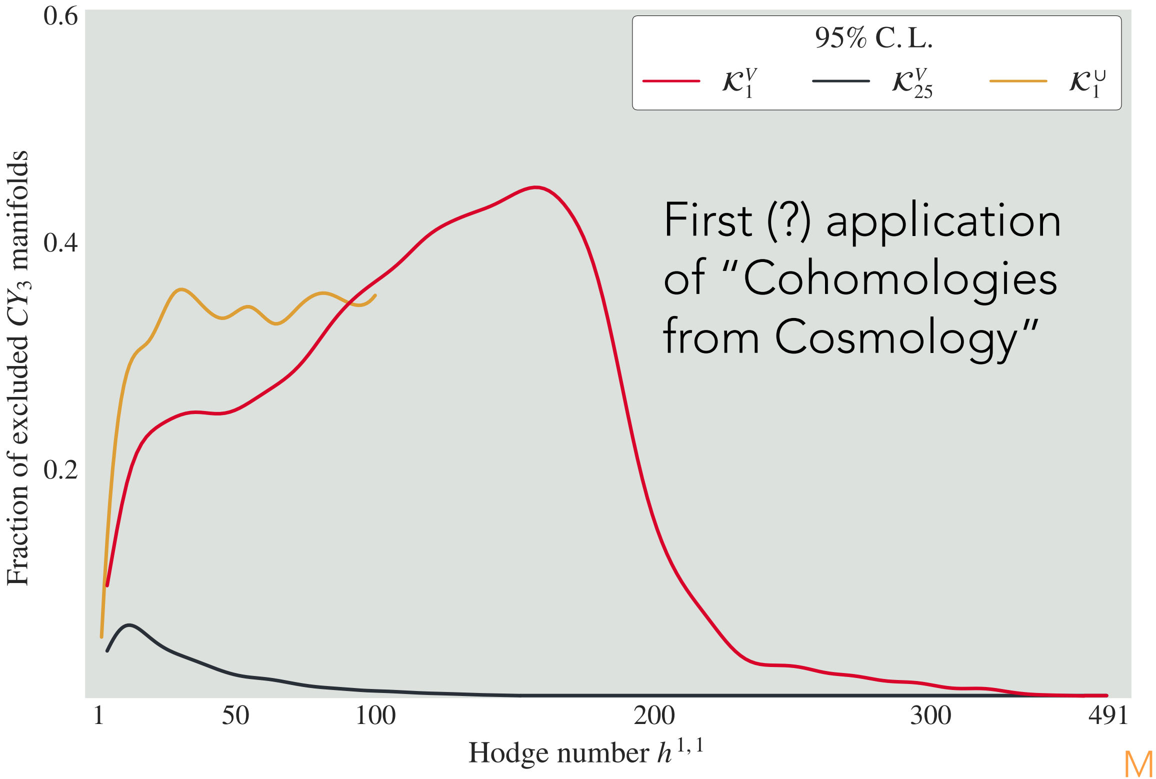
Trends: Kähler cones become very narrow at large h11 → cycles in the CY have large volumes → (ultra)light axions and smaller decay constants.

Mass spectrum “blue tilted”. Decay constants log-normal, becoming smaller at large h11.



Constraints on IIB CY Vacua

Ensemble of O(10^5) CYs. All up to h11=5. 100 per h11 up to 176. Few per h11 to 491.



Above h11~ O(few) limit driven by stellar BHs with well measured spin.

Trend easily understood from falling K eigs at large volume → Bosenova shut-off for stellar BH limits

(NB: this limit does NOT include LIGO BHs, which require different mass and spin model)

Mehta, DJEM et al (2021)

GLIMMERS FROM THE AXIVERSE

Gendler, Marsh, McAllister, Moritz arXiv:2309.13145

Axion-Photon Couplings

Recipe:

1. Choose a CY. We take 2×10^5 over h11=50, 100, 200, 491.
2. Choose a divisor to host QCD.
3. Dilate divisor to Vol=40 → QCD gauge coupling in UV.
4. Pick a divisor for QED. Same → GUT. Intersecting → non-GUT.
5. QED divisor → linear combination of axions coupling to EM.
6. Diagonalise matrices and compute couplings of eigenstates.

Consequences:

"Kinetic isolation": K matrices are sparse → suppressed kinetic mixing of all axions into EM linear comb.

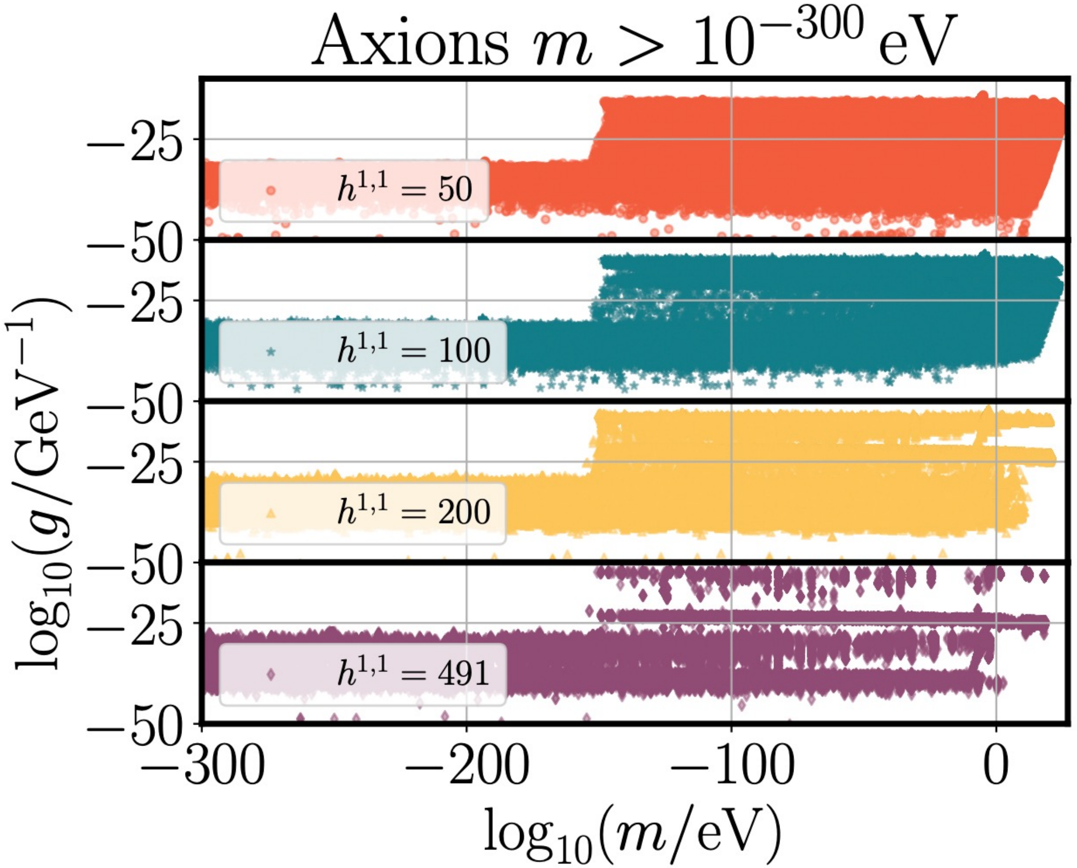
"Light threshold": mass scale generated by ED3 branes on divisor → hierarchically suppressed coupling of axions lighter than this.

c.f. similar effect in GUTs found by Agrawal et al.

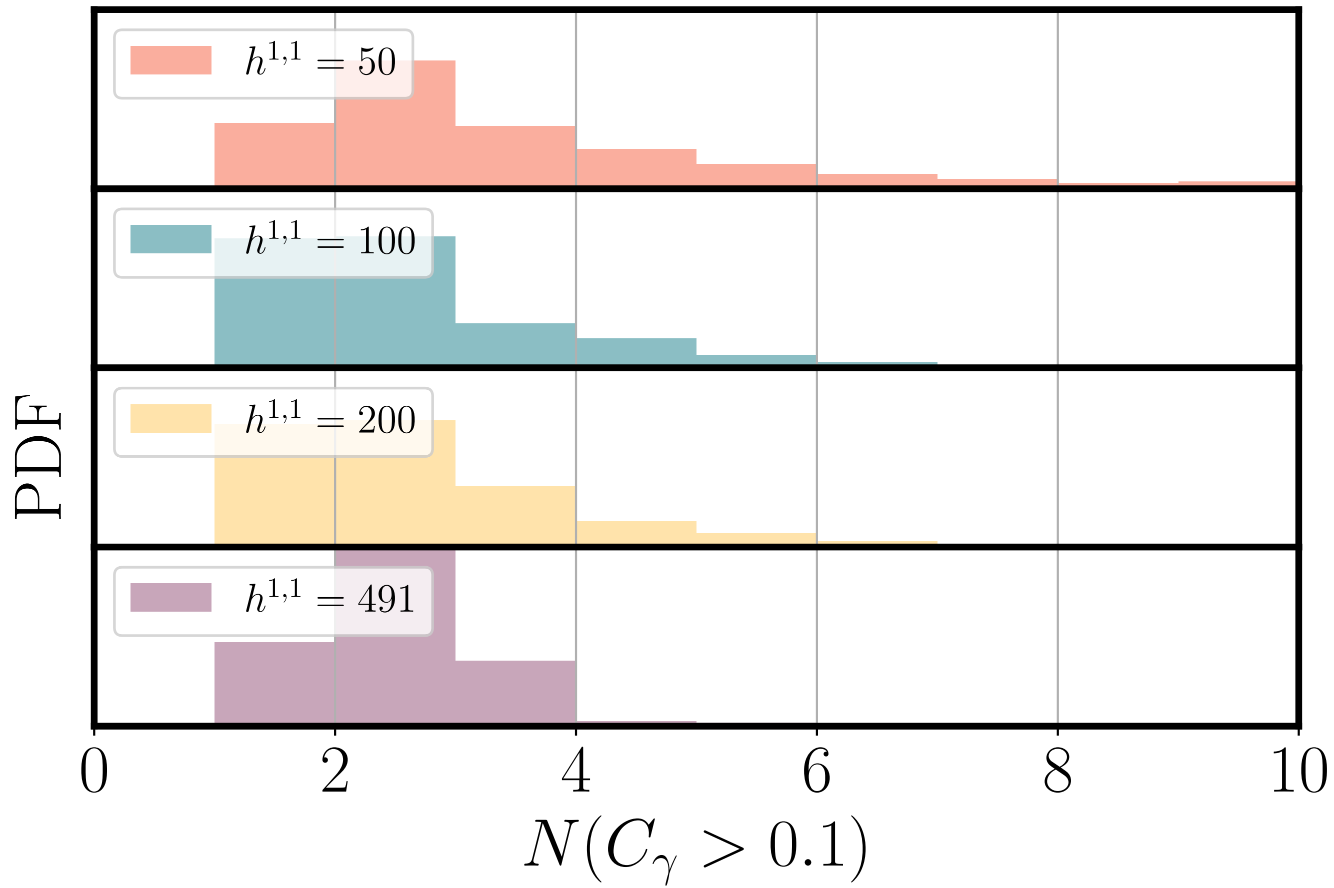
Stringy effects! Need CY to get K matrix. No "U(1) instantons" in field theory.

Restricting QED gauge coupling running decouples $m<10^{-150}$ eV → not all axions couple.

$$\alpha(\Lambda_{\rm UV}) > 1/128$$

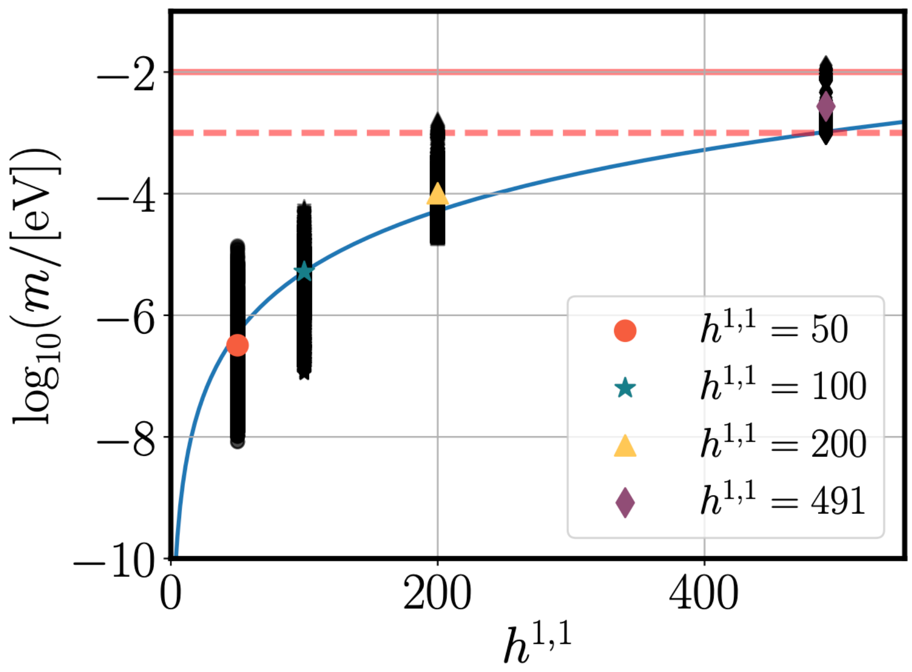


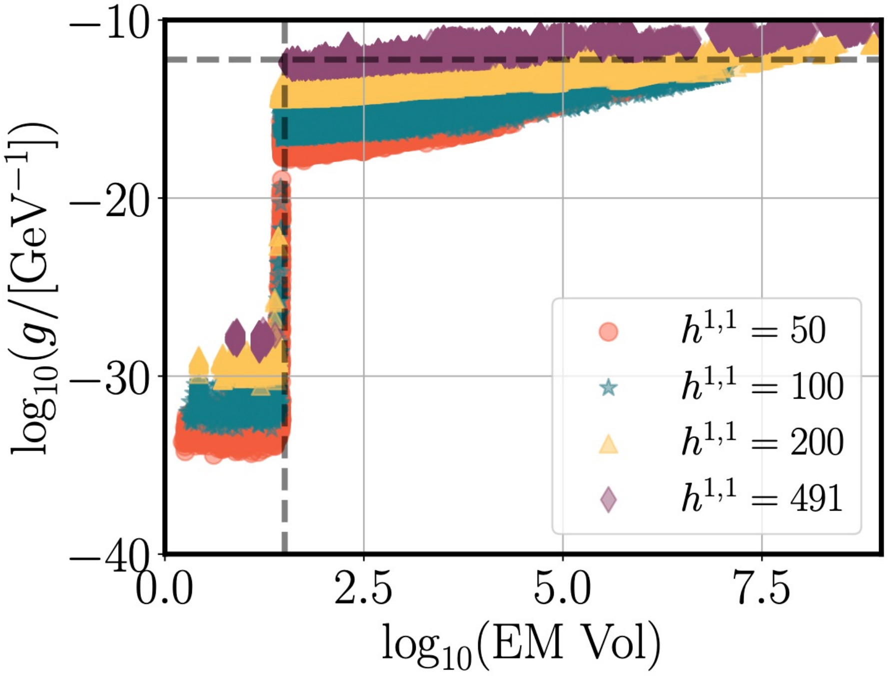
Number of axions with O(1) coupling to photons is small. $g = C_\gamma \frac{\alpha}{2\pi f_a}$



QCD axion mass strongly correlated with the Hodge number → discover QCD axion and measure topology of CY (!).

Light threshold at Vol~30 → X-ray spectra probe non-GUTs. May exclude some models with large h11





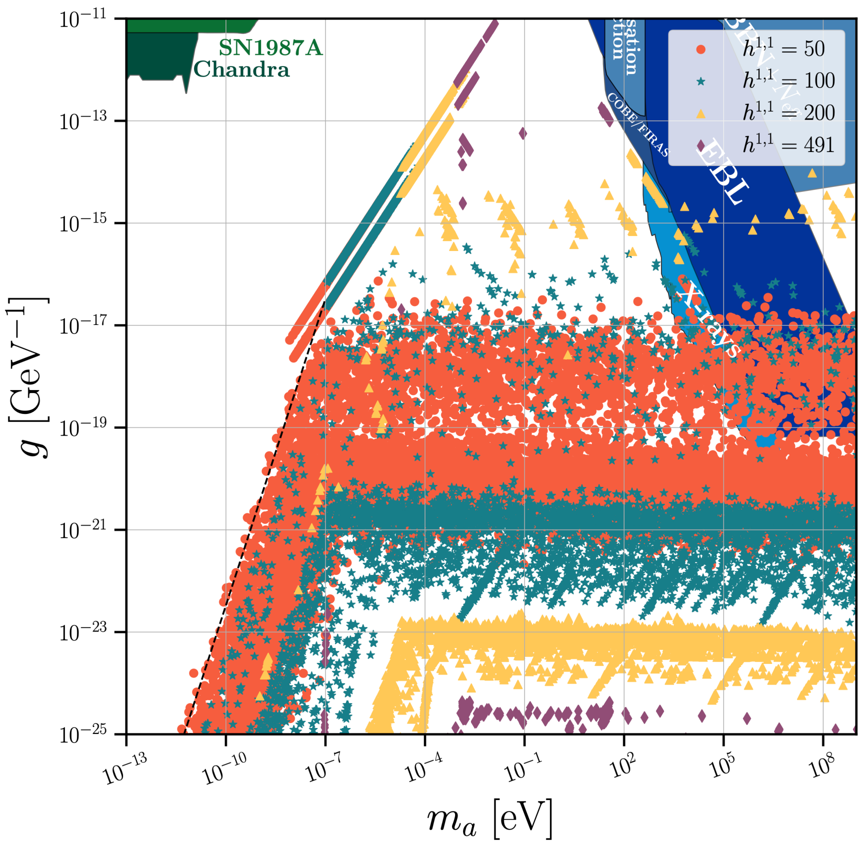
GUTs vs non-GUTs

GUT: fix cycle volume for group containing EM and QCD at $1/\alpha_{GUT}$

→ The QCD induced mass is bigger than the ED3 one.

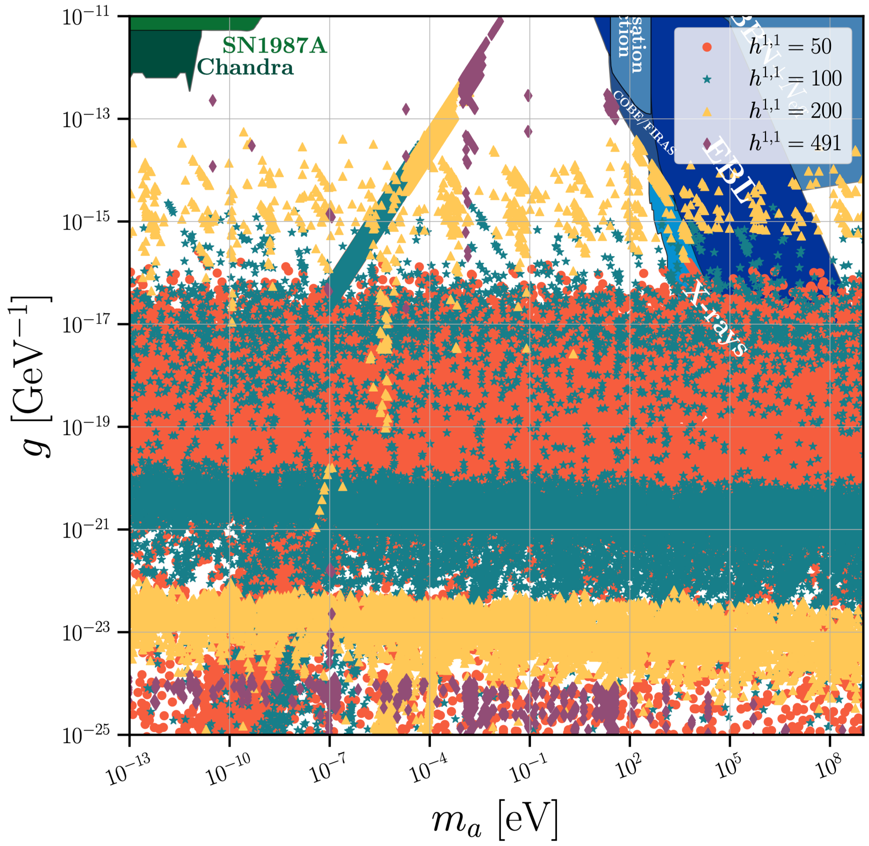
→ QCD axion provides the light threshold.

→ No axions above the QCD line (as Agrawal et al in field theory).

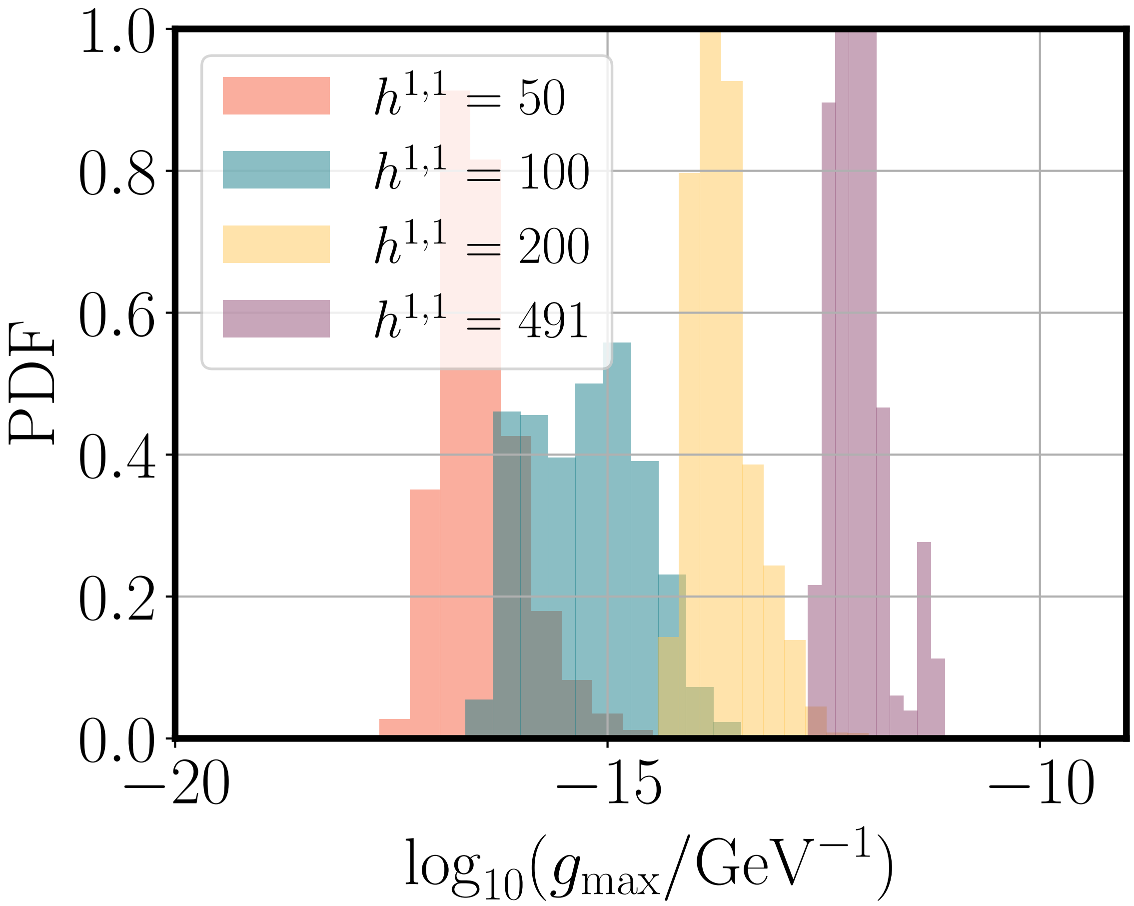


GUTs vs non-GUTs

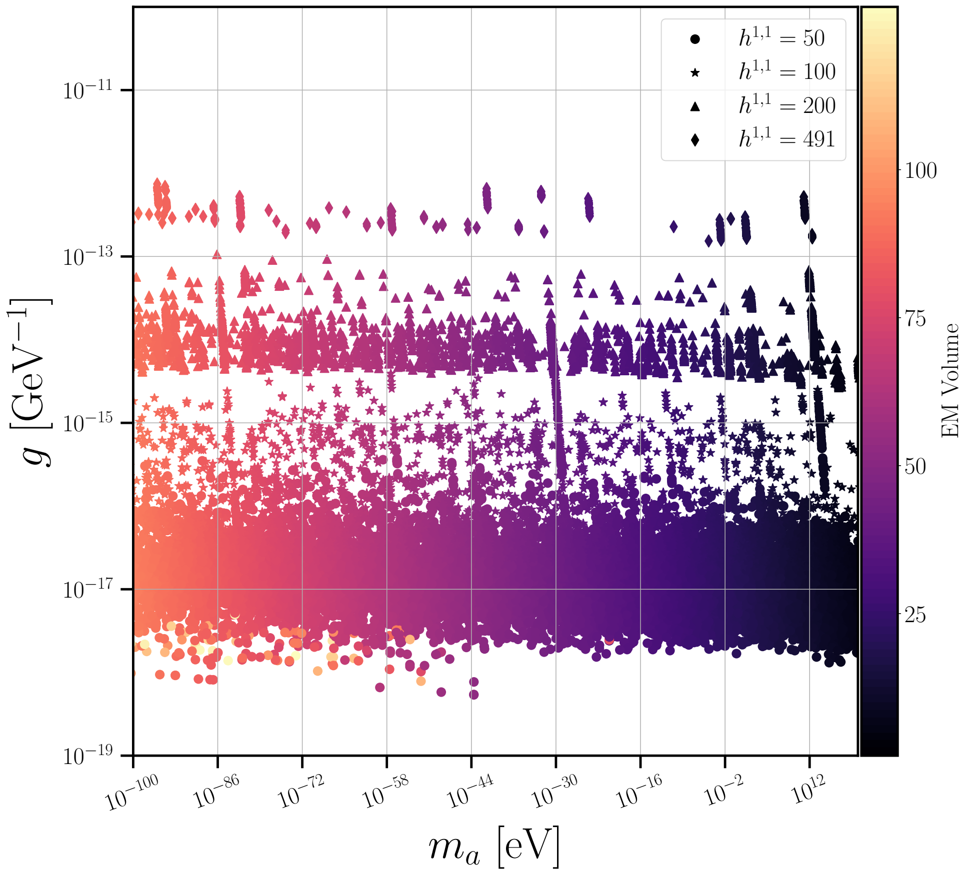
Non-GUTs: (almost) anything goes.



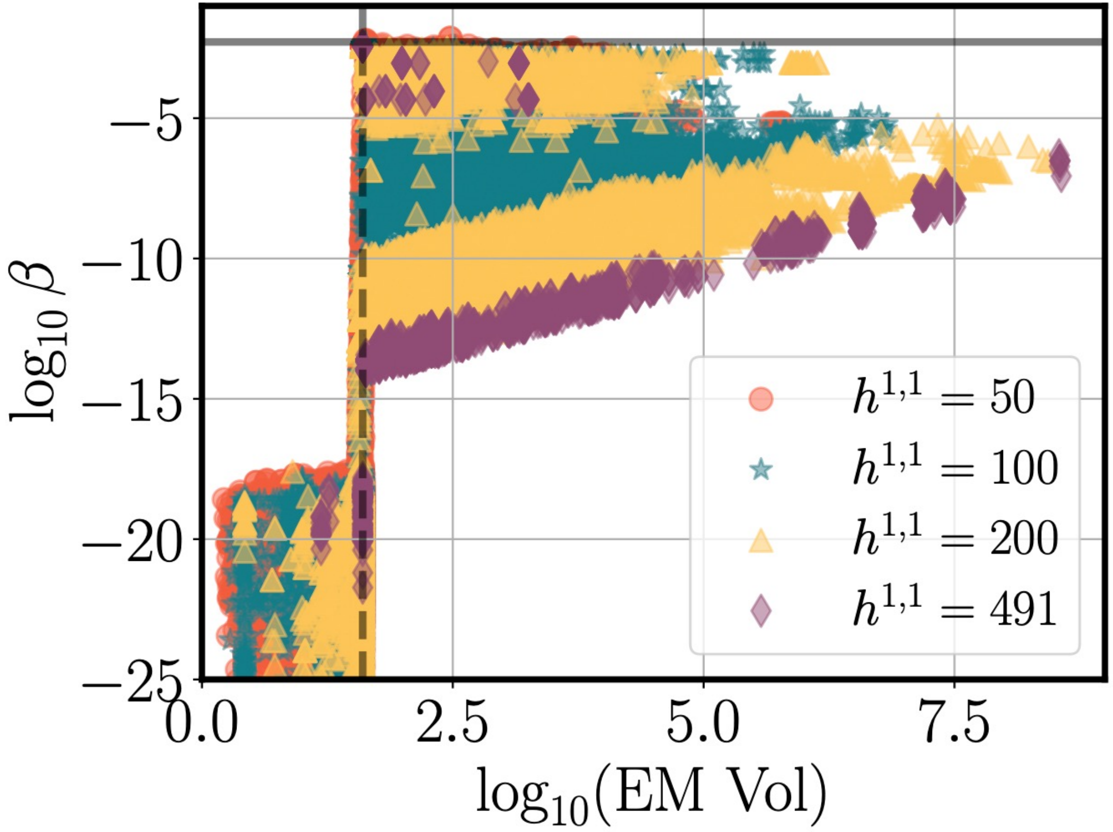
The maximum value of g increases with h11 due to increasing cycle volumes.



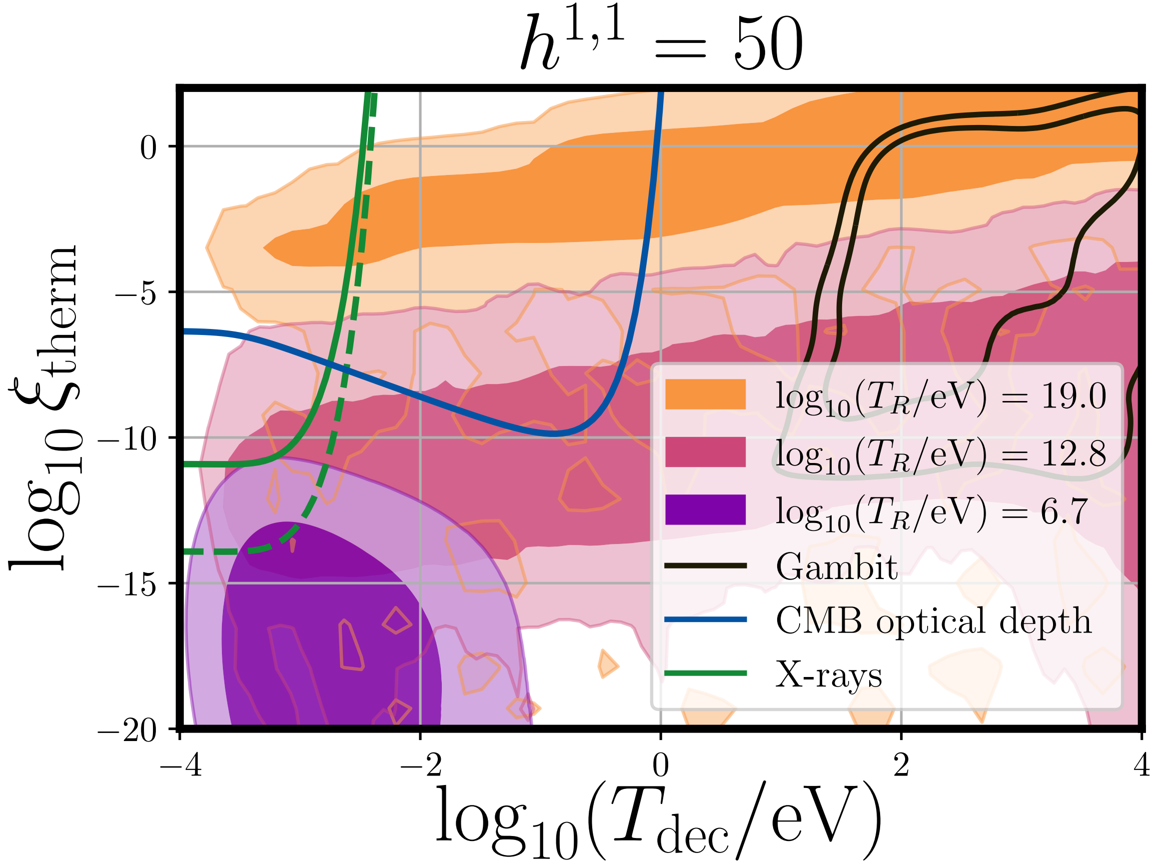
Which axions couple O(1) to EM depends on the cycle volume → UV info.

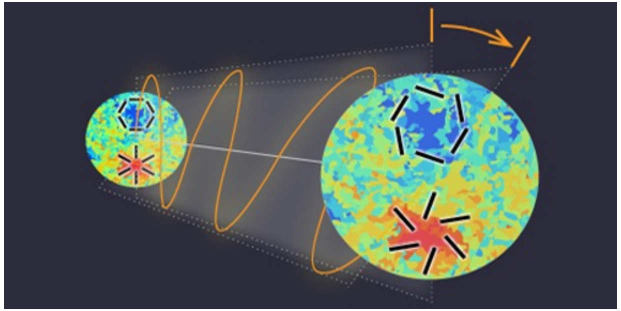


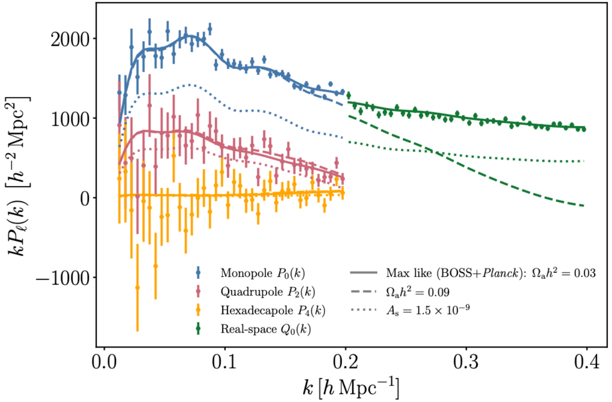
Birefringence possible but non-generic. Only get the right value if Vol~40 (H_{CMB} light threshold). Interesting coincidence?



keV – GeV axions Primakoff freeze-in then decay. Disfavours reheating T>10^{10} GeV → upper limit on SUSY?







- Birefringence has a hint from Planck: have we seen evidence of the axiverse already?
- Cosmological probes have matured in precision, and in the next decades will test GUT scale axions.
- Superradiance has been used to test the axiverse up to h11~200 in explicit constructions on CYs.
- Advances in constructing the visible sector in type IIB offer promise to discover the axiverse.