The Axiverse in 2023

David J. E. Marsh

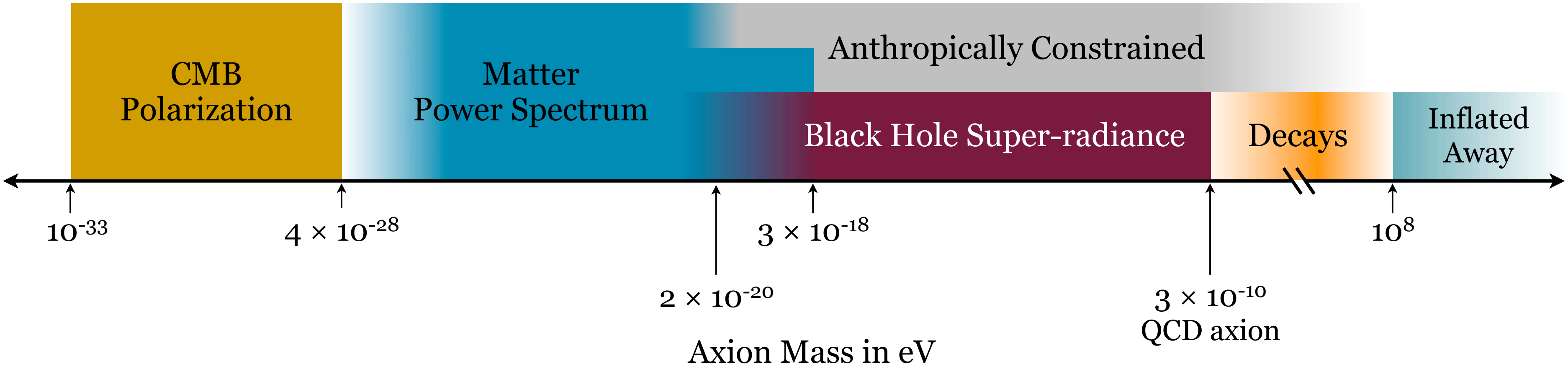
Science and Technology Facilities Council

King's College London

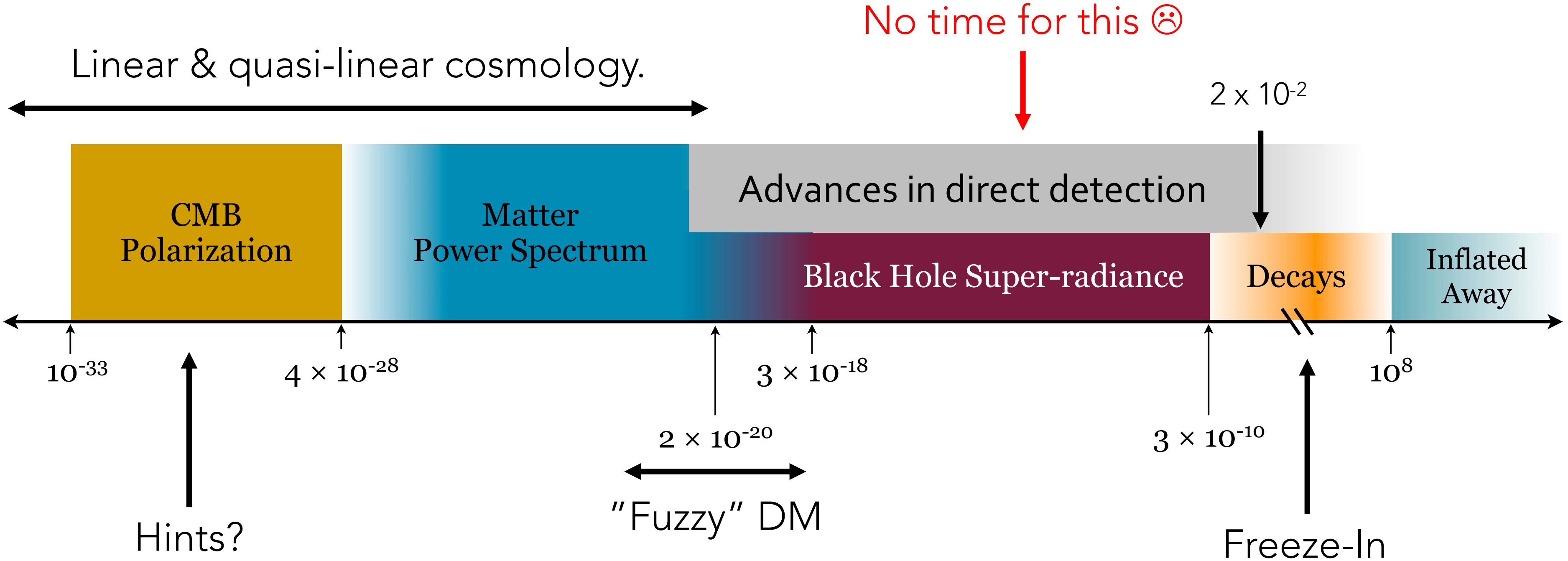
PHYSICAL REVIEW D **81**, 123530 (2010)

String axiverse

Asimina Arvanitaki,[1,2] Savas Dimopoulos,[3] Sergei Dubovsky,[3,4] Nemanja Kaloper,[5] and John March-Russell[6]



Axiverse in 2023

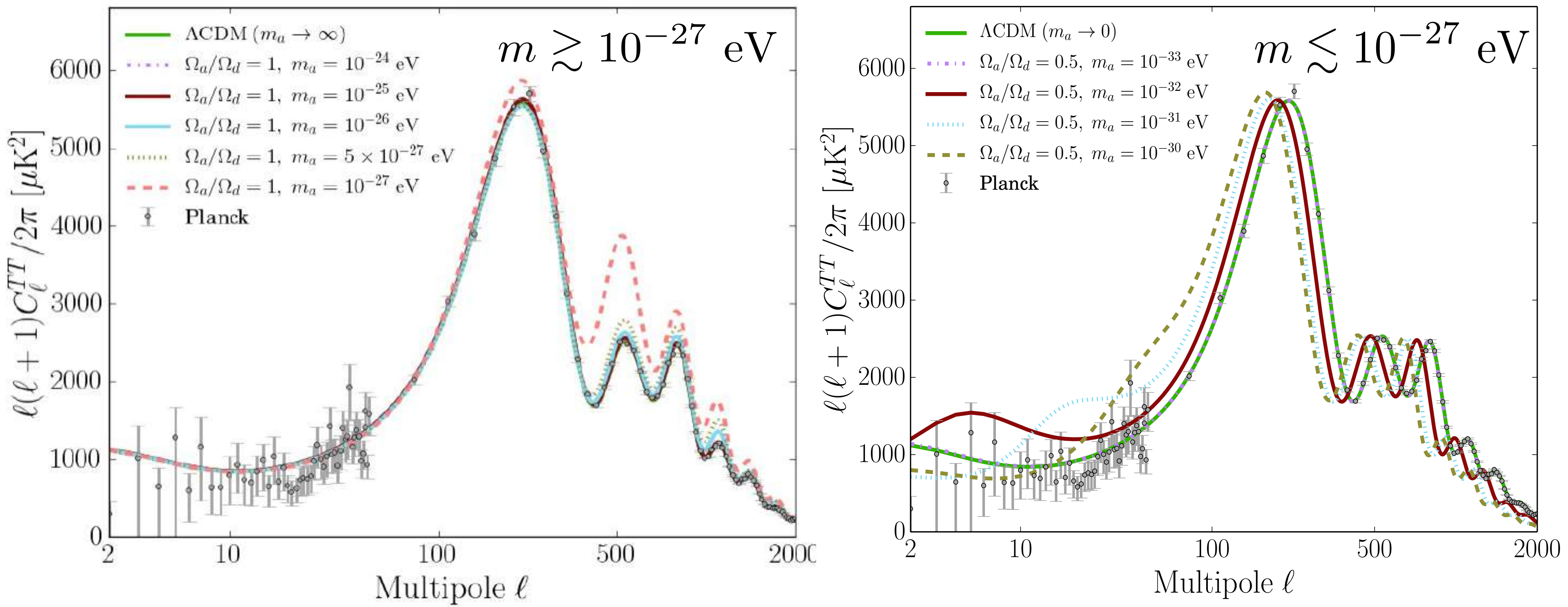


All of the suggested probes have been explored and become precise, along with some (unexpected?) new developments in cosmology and direct detection.

LINEAR++ COSMOLOGY

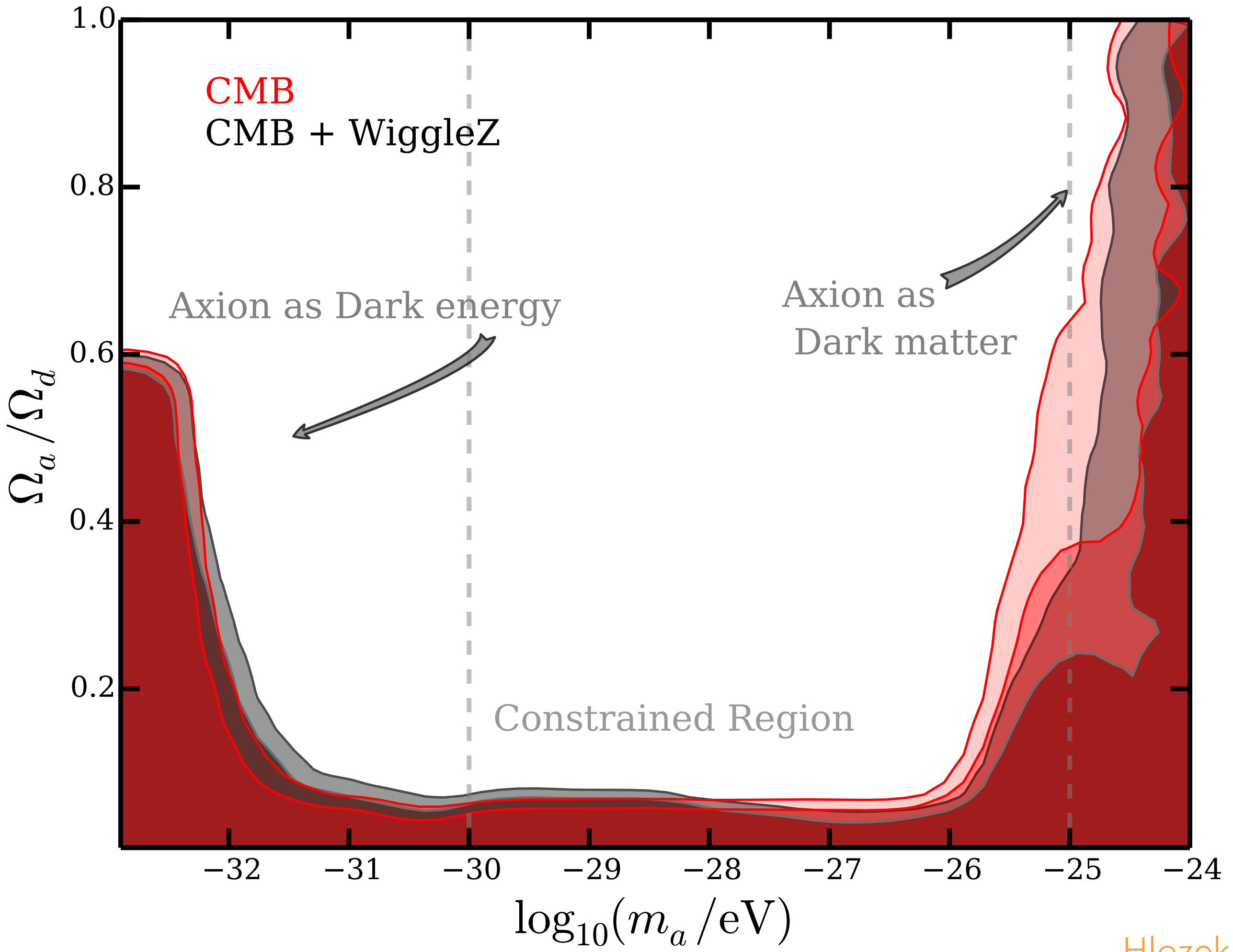
Matter Power Spectrum

Light axions making up just a few percent of the DM show up in CMB anisotropies.



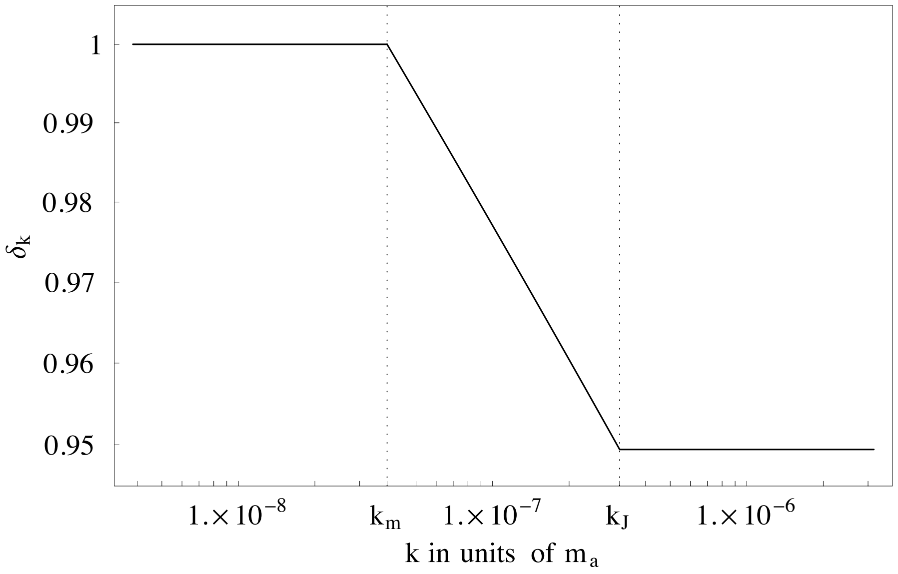
Hlozek, DJEM et al (2014)

Physics: damped motion of the axion field behaves as dark energy at early times.
Expansion rate differs from LCDM → change Silk damping and Sachs Wolfe.

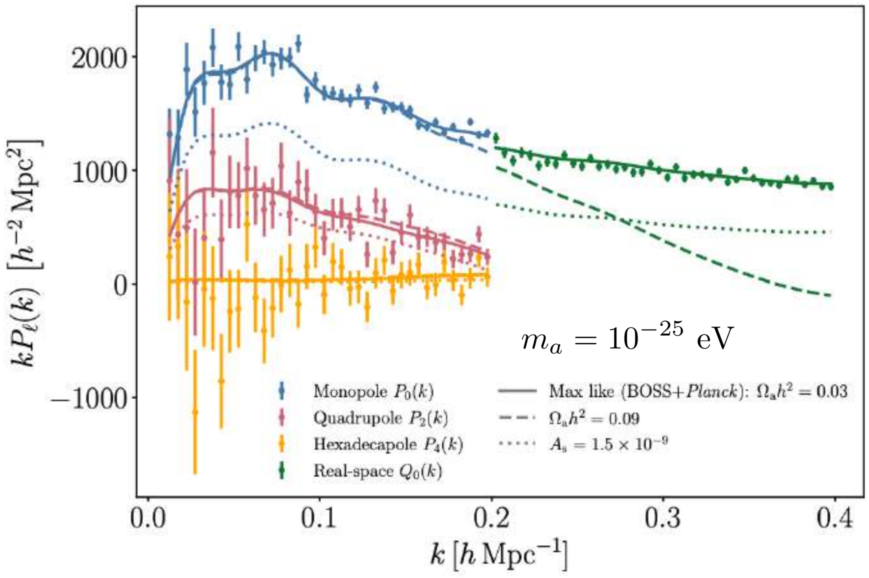


Hlozek, DJEM et al (2014)

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)".

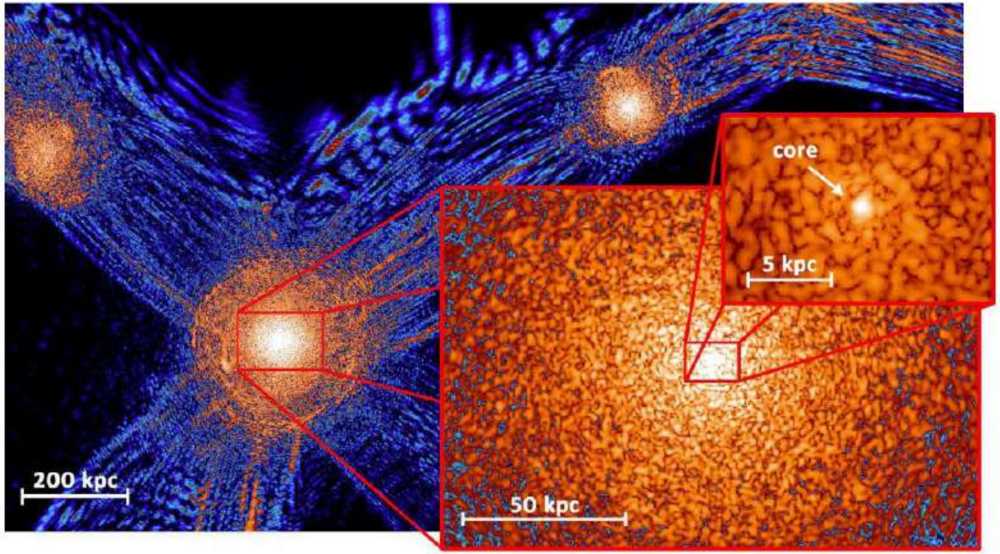


Axiverse 2023: EFTofLSS in the BOSS DR12 P(k) multipoles.

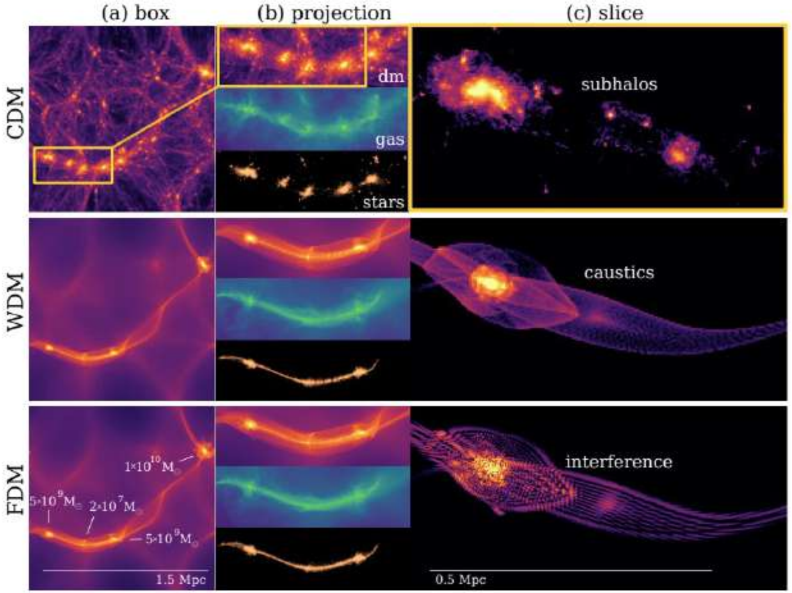
Lague DJEM et al (2021); Rogers, DJEM et al (2023).
Codes: axionCAMB, multinest, cosmosis, PeakPatch, CLASS-PT

Simulating Light Axions

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



Schive et al (2014)



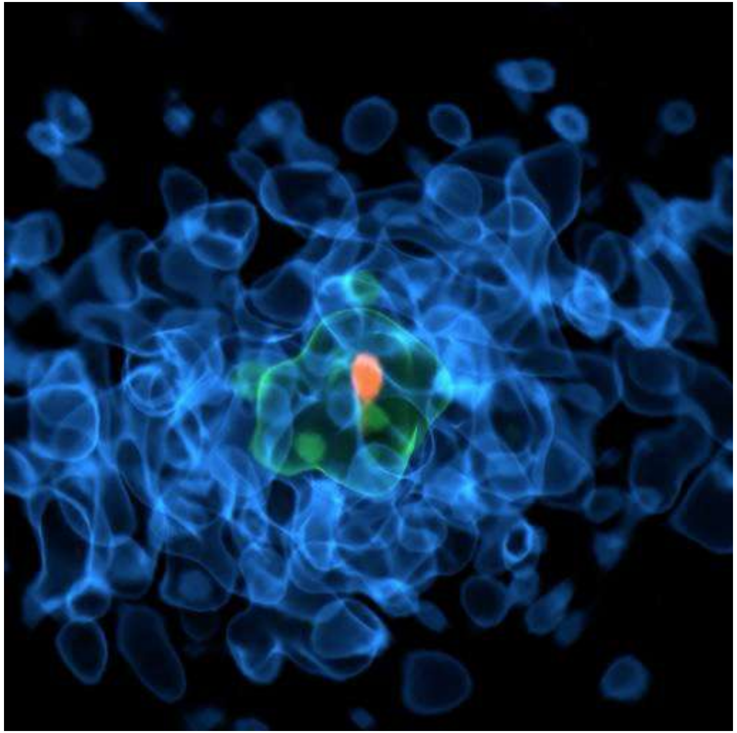
Mocz et al (2019)

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

Tour of Constraints

Assuming ultralight axions are all of DM, a wide variety of astrophysics sets limits. To test the axiverse fully, understanding non-linear models of mixed DM needed.

- Dark Energy Survey weak lensing → $m>10^{-23}$ eV. Dentler, DJEM et al (2021)
- Relaxation in the Milky Way → $m>10^{-22}$ eV. Hui et al (2016)+
- High-z galaxies → $m>10^{-22}$ eV.
- Milky Way satellites → $m>10^{-21}$ eV.
- Lyman alpha forest P(k) → $m>2 \times 10^{-20}$ eV. Rogers & Peiris (2020)
- Survival of Eridanus-II star cluster → $m>10^{-19}$ eV. DJEM & Niemyer (2019); Dalal & Kravtsov (2022)



FREEZE-IN AXIONS

Decays

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

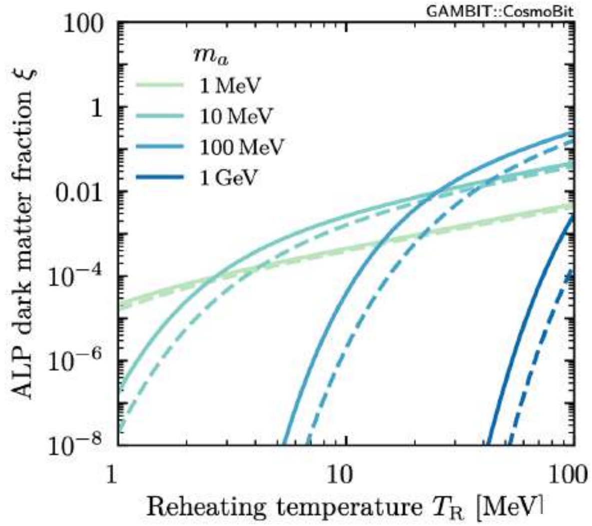
Cosmological constraints on decaying axion-like particles: a global analysis

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)

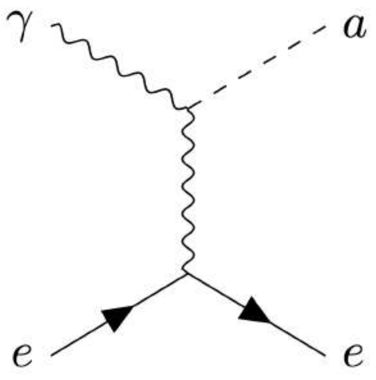
Irreducible Axion Background

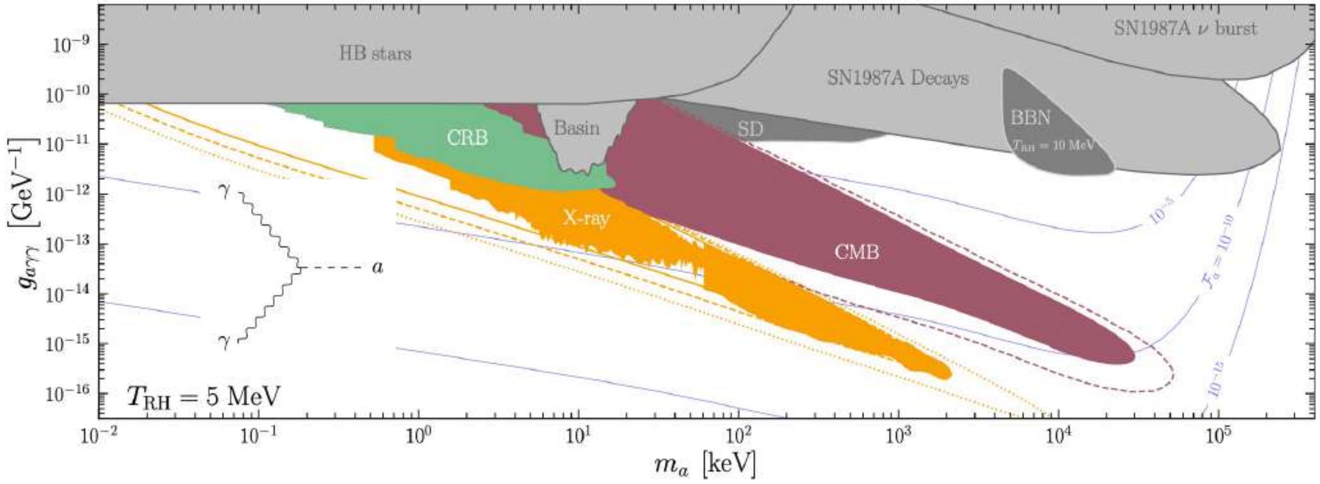
Kevin Langhoff,[1,2] Nadav Joseph Outmezguine,[1,2] and Nicholas L. Rodd[3]



- 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 $\tau > 10^{10}$ 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 (ω<0):

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

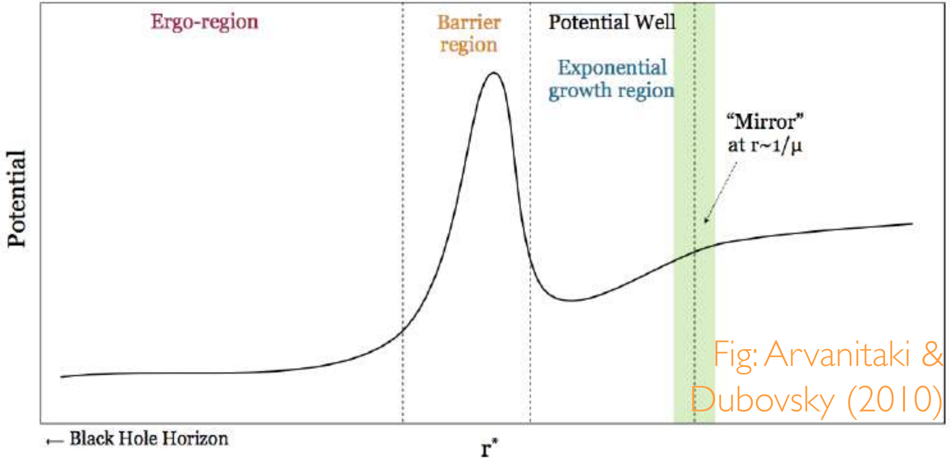
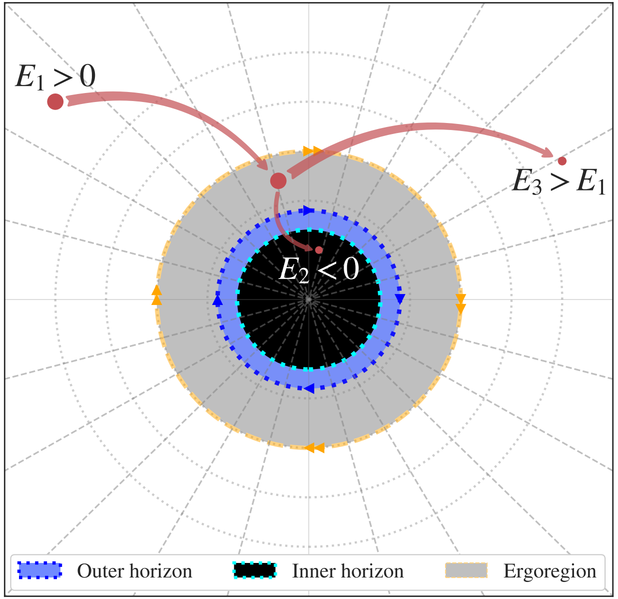


Fig: Arvanitaki & Dubovsky (2010)

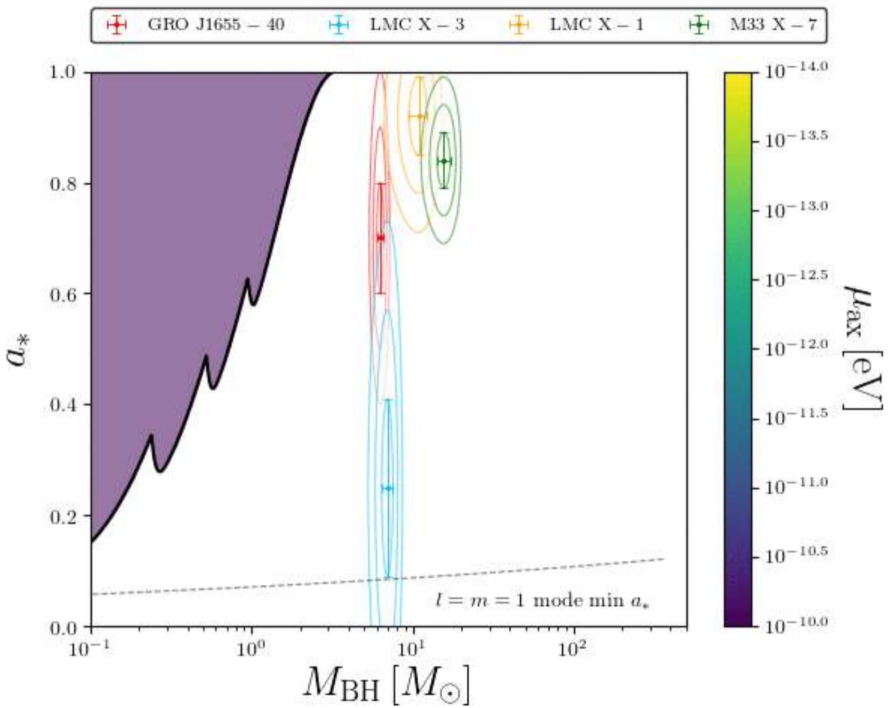
Physical picture: "Penrose process/ black hole bomb"

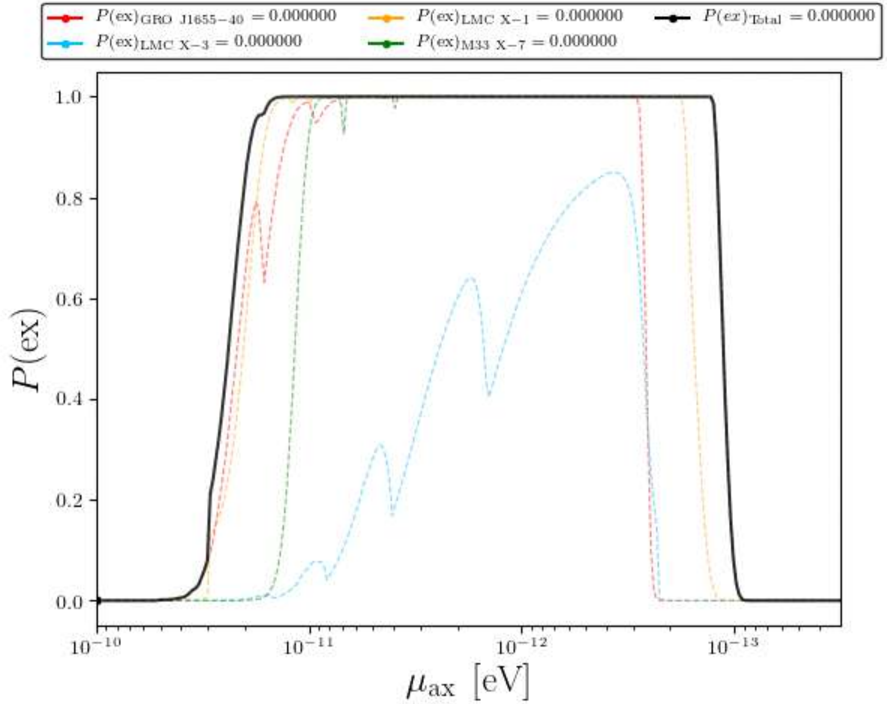


Resonant bosons extract spin from astrophysical BHs, if $\Gamma_{SR} > \Gamma_{others}$

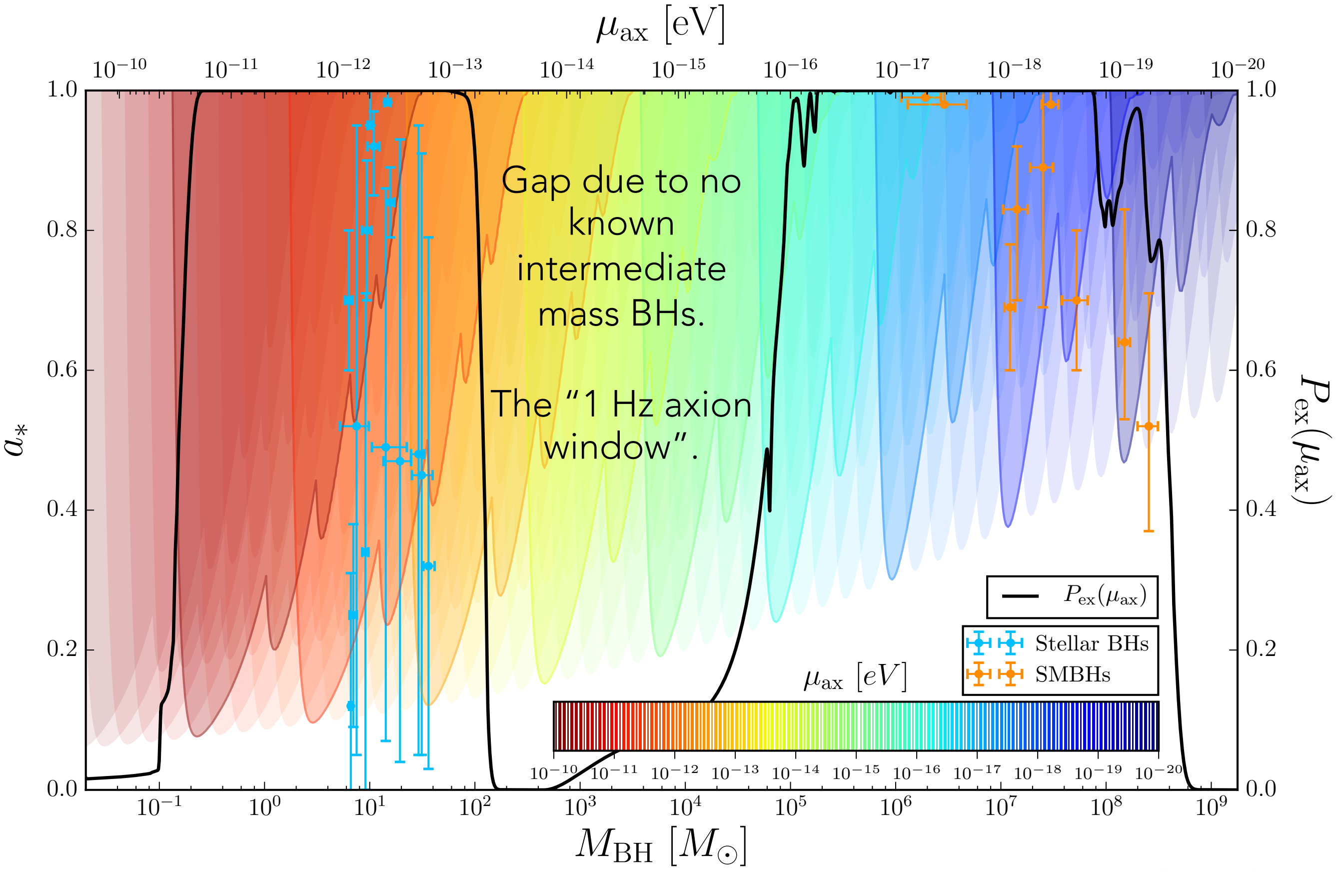
Exclude axion masses where known BHs exist in the superradiant forbidden region.
This sample: X-ray stellar BHs. Gaussian composite likelihood.

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.)

ϕ^4 Instability: "Bosenova"

Yoshino & Kodama (2012); Arvanitaki+(2014); Stott (2018)

Bose enhanced 2-2 scattering in superradiant cloud can have a rate $\Gamma_4 > \Gamma_{SR}$.
Shuts off SR by cloud collapse above critical value of $\lambda\phi^4$ coupling, $\lambda = m^2/f^2_{pert}$.

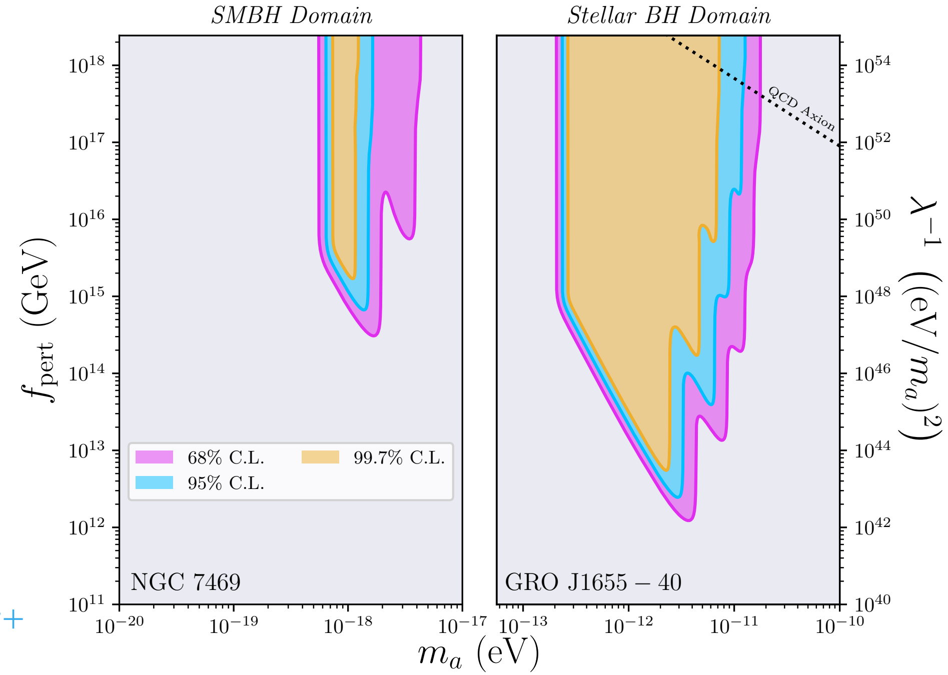
Approximate excluded regions:

Stellar BHs:

$$m_a \in [1 \times 10^{-13}\ \mathrm{eV}, 2 \times 10^{-11}\ \mathrm{eV}]$$
$$f_{\rm pert} \gtrsim 10^{14}\ \mathrm{GeV}$$

Supermassive (SM) BHs:

$$m_a \in [8 \times 10^{-20}\ \mathrm{eV}, 1 \times 10^{-16}\ \mathrm{eV}]$$
$$f_{\rm pert} \gtrsim 10^{16}\ \mathrm{GeV}$$

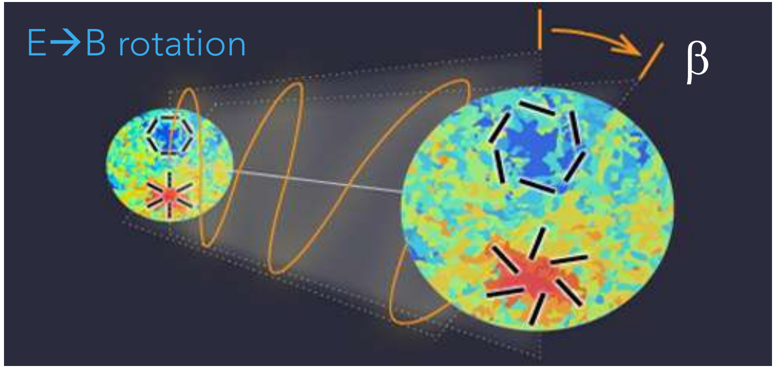


Implemented with a simple cut-off. See Baryakhtar+ for advanced rate calcs. Quantitatively similar.

COSMIC BIREFRINGENCE

CMB
Polarization

Birefringence



E, B are CMB polarization states (Stokes)

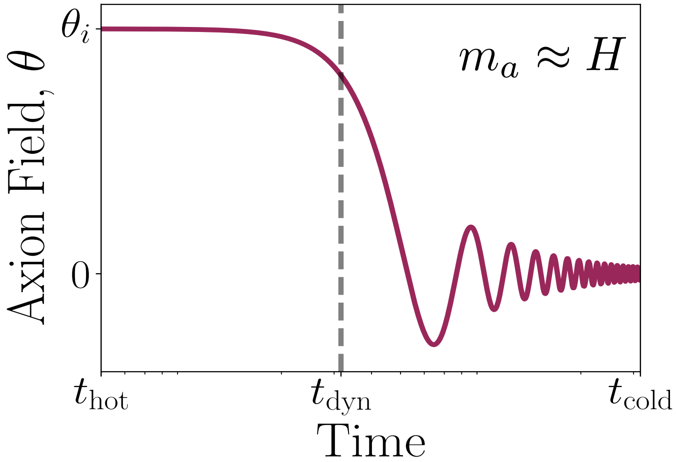
$$\beta = 5.2 \pm 1.9 \times 10^{-3}$$

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:

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

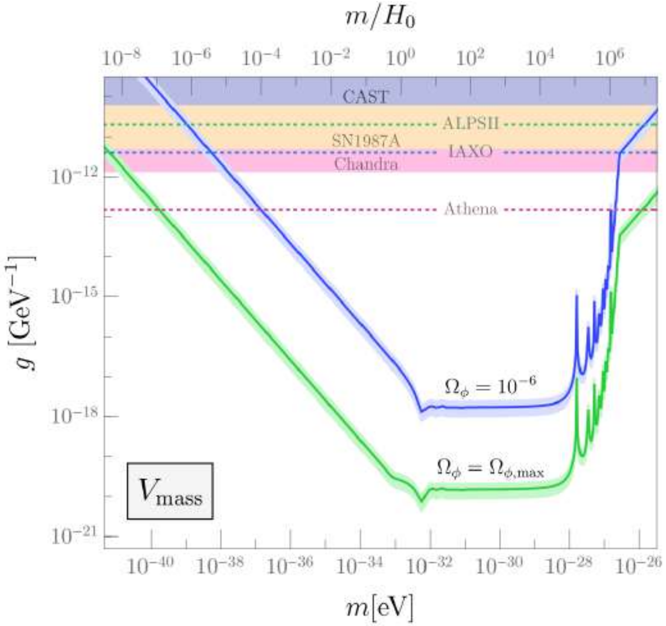


Fixes the axion mass:

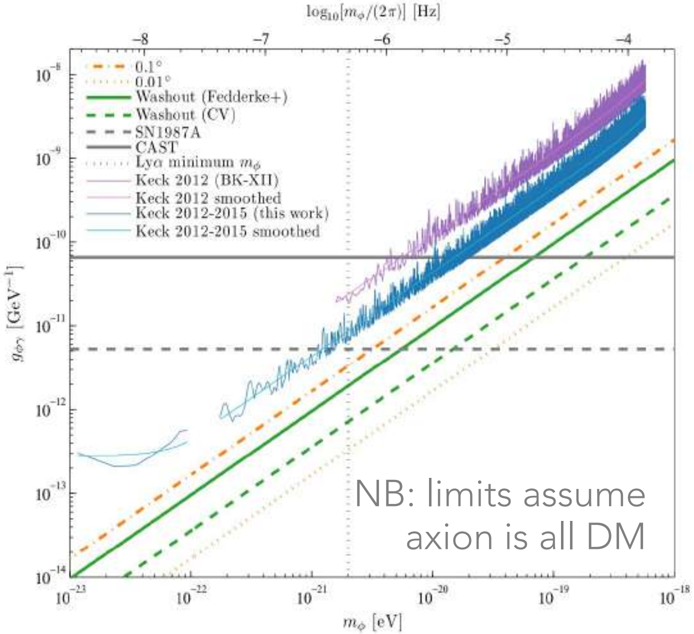
$$10^{-33}\ {\rm eV} \lesssim m \lesssim 10^{-28}\ {\rm eV}$$

H_0 $H_{\rm CMB}$

Birefringence can be highly complementary/ synergistic to direct searches for axions.



Enforcing β=0.3 → preferred region depending on Ω. Fujita et al (2021)



Polarisation "washout" also caused by heavier axions. Keck collab. (2022)

Isocurvature in the ultralight axion also induces anisotropic birefringence and large angle BB with amplitude fixed by scale of inflation, c.f. tensor modes.

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

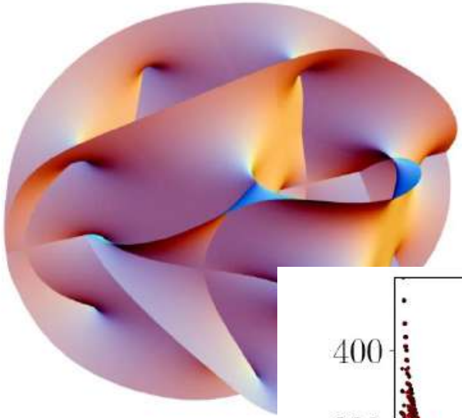
$$\Lambda_j \sim M_{pl}^3 m_{\mathrm{SUSY}} \exp[-\mathrm{Vol}\, D_i]$$

→ 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 $M_{\rm GUT} \simeq 2 \times 10^{16}$ 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

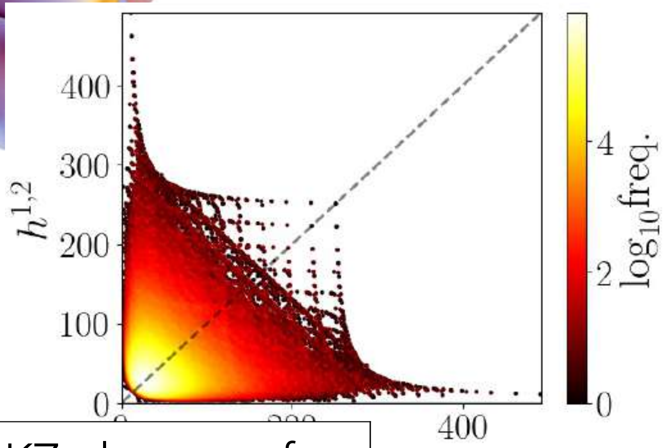
KS Axiverse

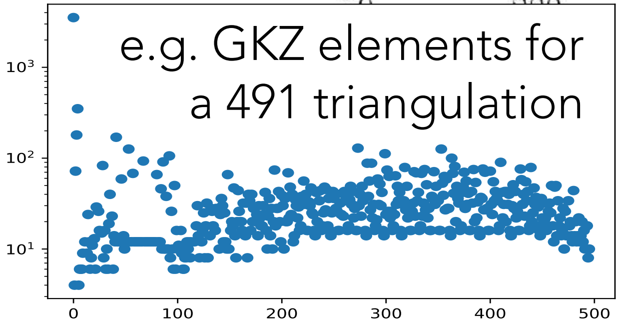
- CY3s constructed as hypersurfaces in "ambient toric varieties". E.g. Fermat quintic in CP4.
- KS database gives all 4d reflexive polytopes ~4 x 10^8.
- Triangulation of these gives ambient toric varieties. Unique polynomial → CY with h11 Kähler moduli.
- Automated fun with CY-Tools!
- Axions: Q unique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



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





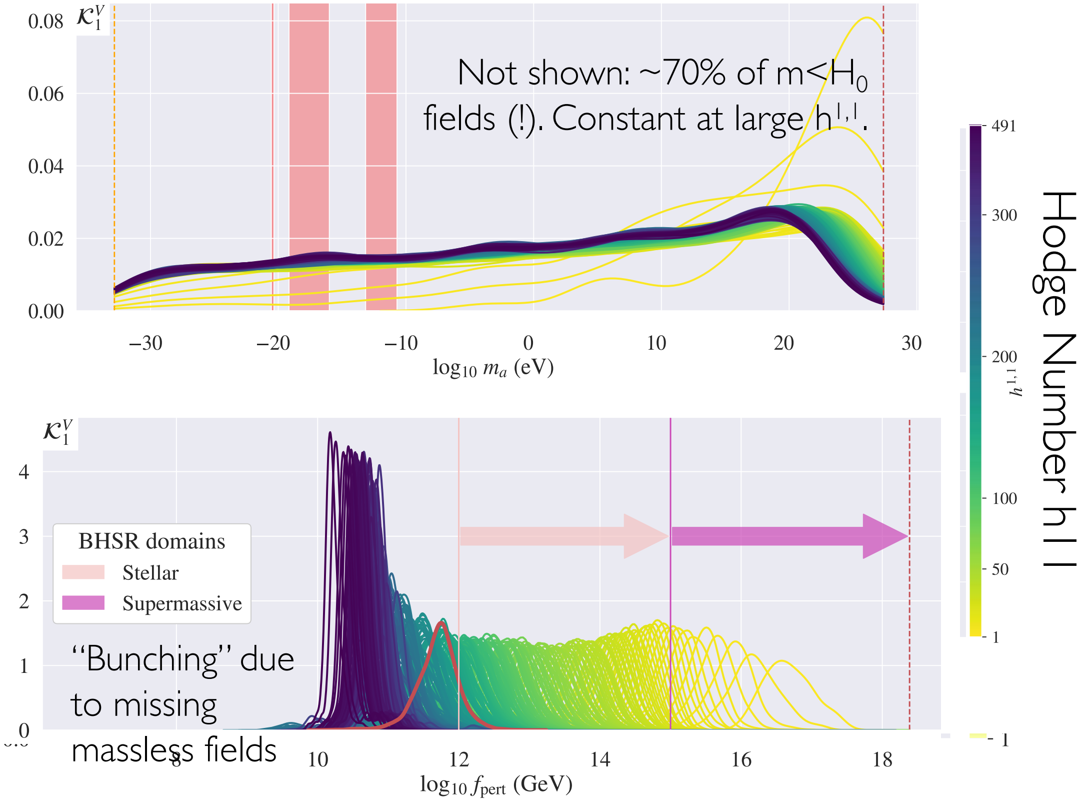
Axion Spectra from KS

Mehta, DJEM et al (2021)

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

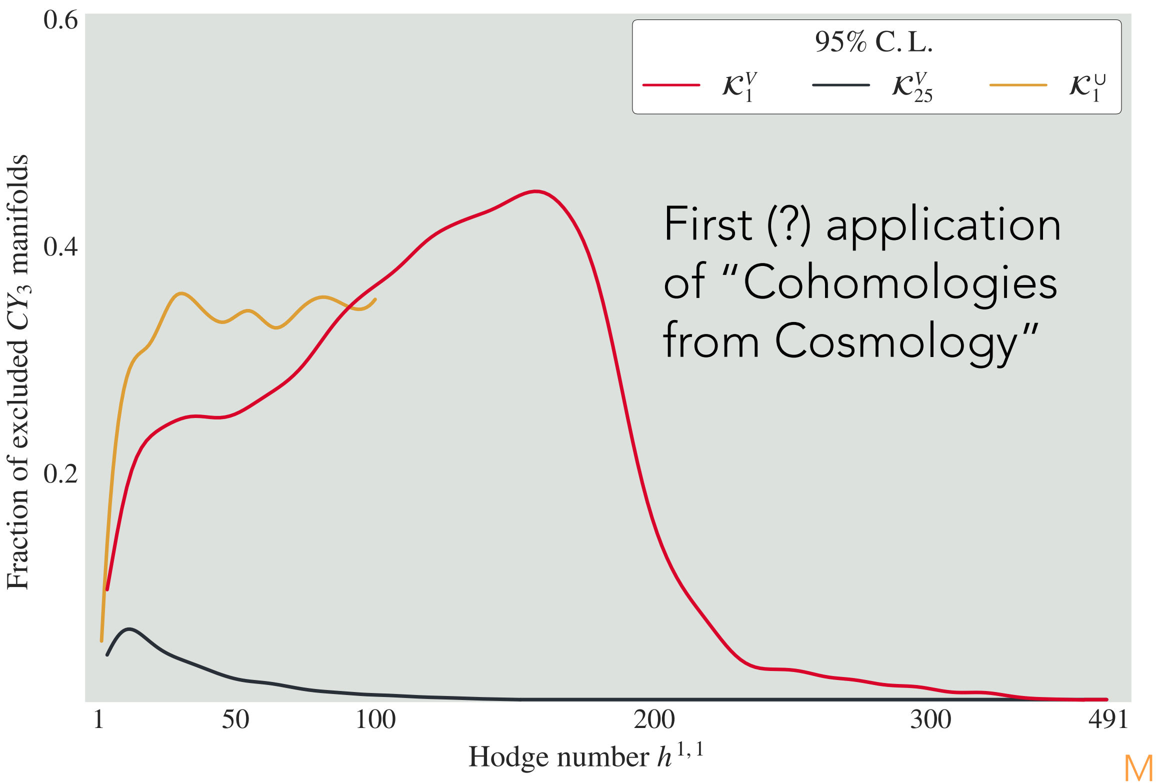
Trends: Kähler cones become very narrow at large h11 → cycles in the CY have large volumes → (ultra)light axions and smaller decay constants.

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

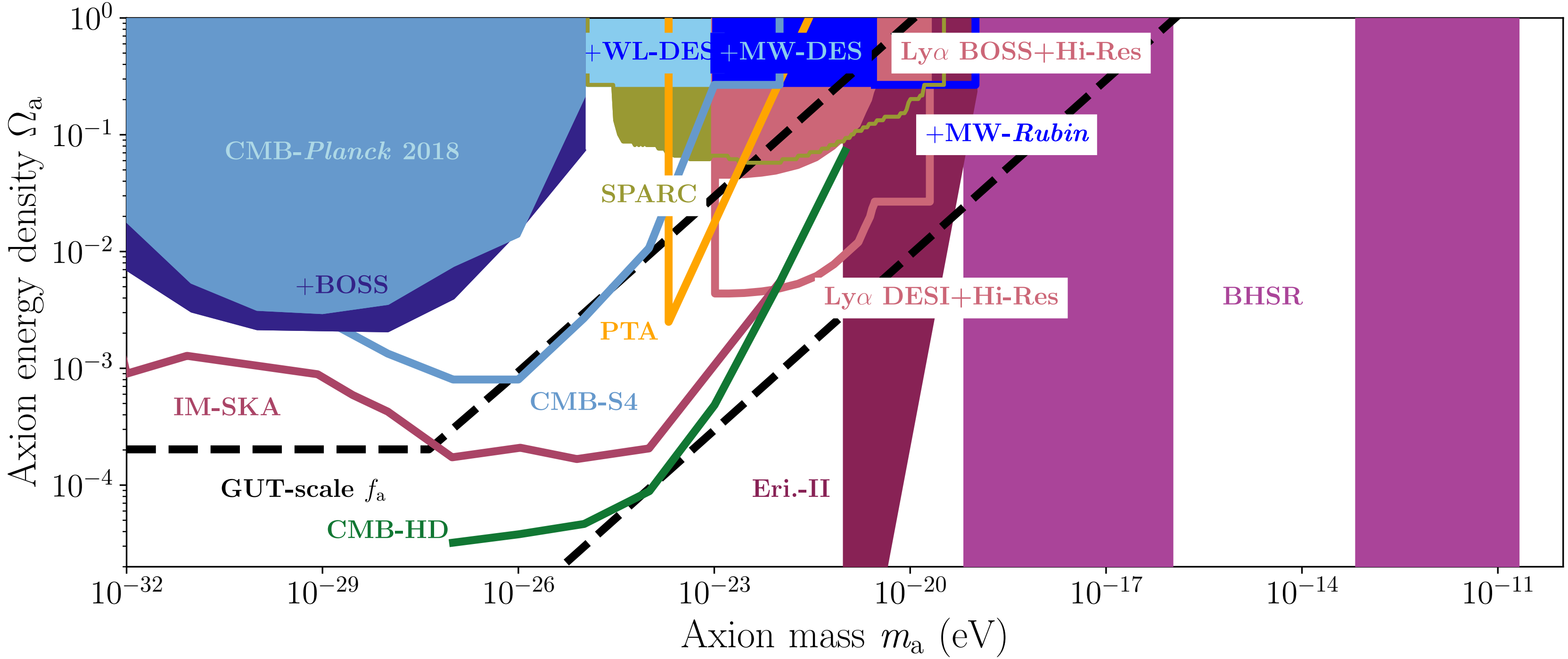
(NB: this limit does NOT include LIGO BHs, which require different mass and spin model)

Mehta, DJEM et al (2021)

THE FUTURE OF THE AXIVERSE

Cosmological Probes

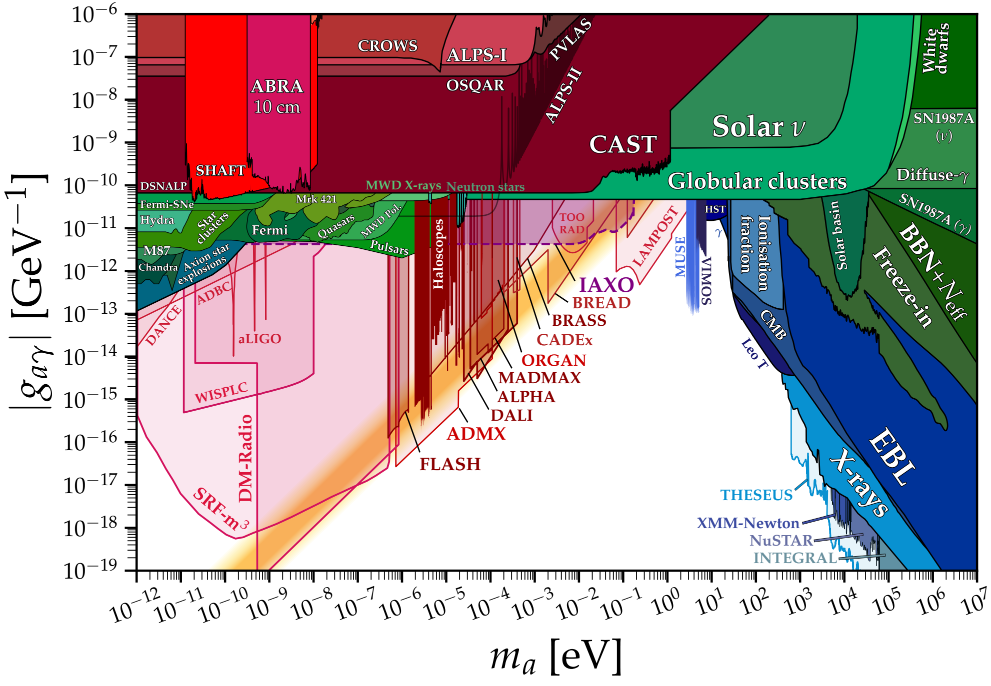
Rogers, DJEM et al (2023)



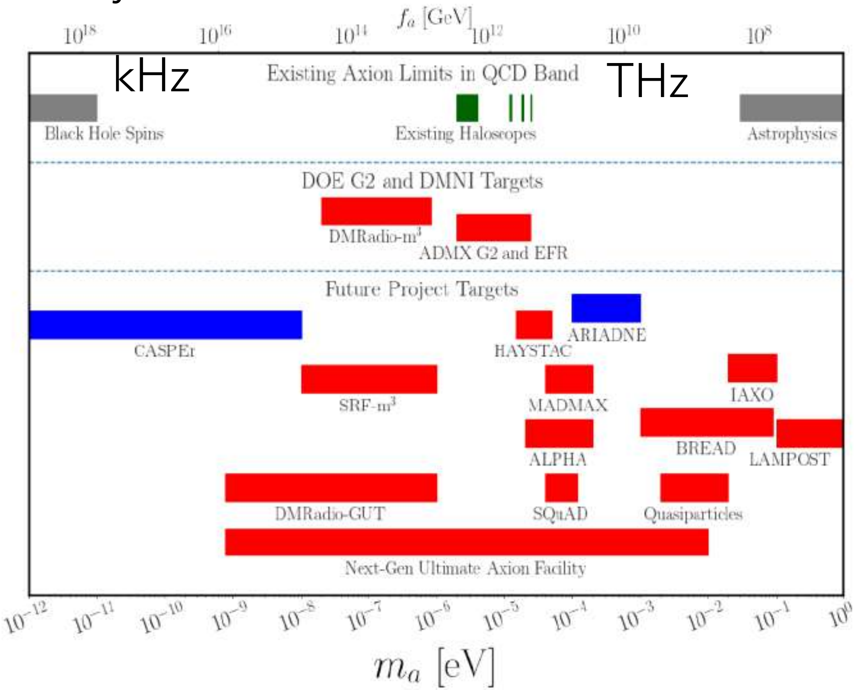
Upcoming surveys will reach sensitivity to probe sub-dominant axion DM predicted by GUT scale decay constants from 10^{-28} to 10^{-20} eV. Original axiverse "matter power".

The QCD axion will be found

For string theory: fixes the overall scale of the decay constants → ~h11.

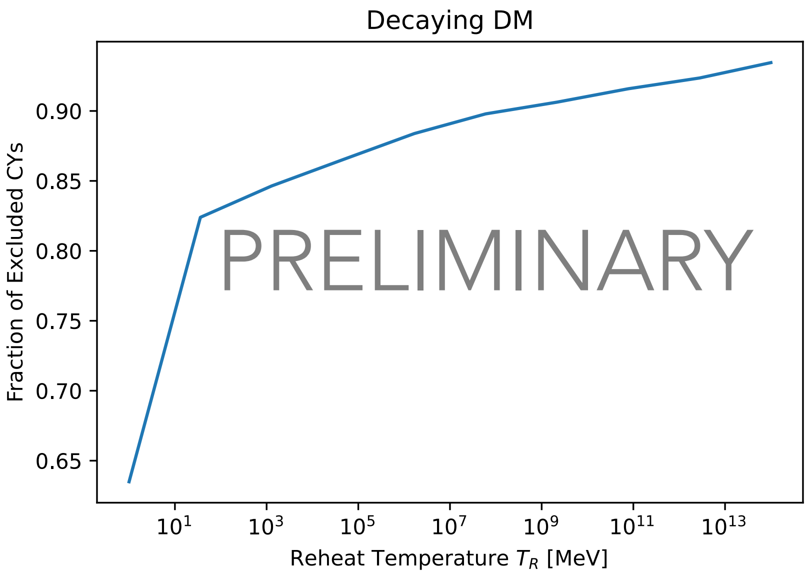


AxionLimits: Ciaran O'Hare



Snowmass white paper "Axion Dark Matter" (inc DJEM)

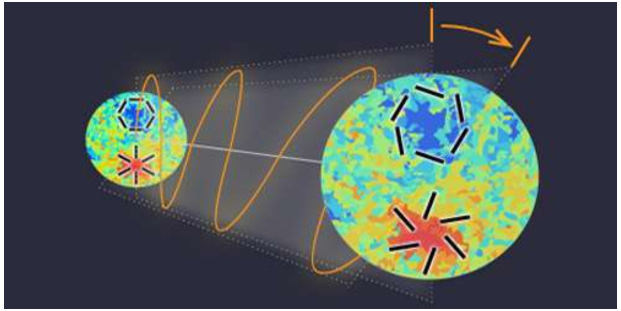
The Visible Sector on CYs



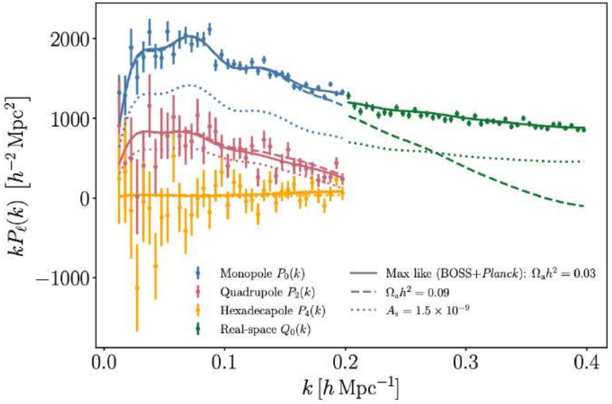
Some preliminary observations:

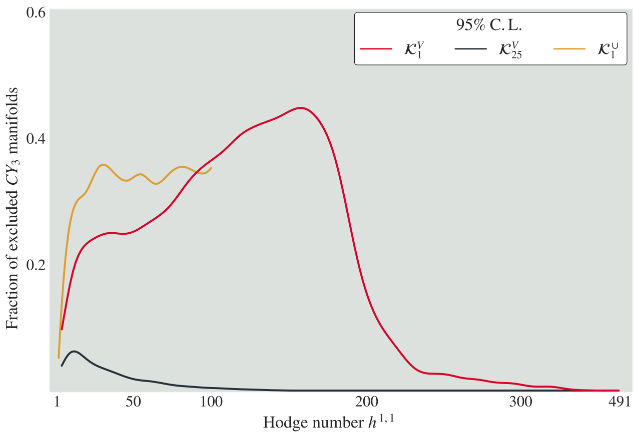
- Axions "above QCD" require U(1) on large divisor → complete into asymptot. free non-GUT group → extra instanton.
- Birefringence happens, but $\beta \sim 2 \times 10^{-4}$ is slightly small to explain Planck.
- Freeze-in + decay → strong limits if reheating is at high T>>BBN.
- Possible axion reheating ("moduli problem").
- Laundry list: dark sectors, explicit orientifolds (see Moritz 2023) …

Gendler, DJEM, McAllister, Moritz (summer 2023)



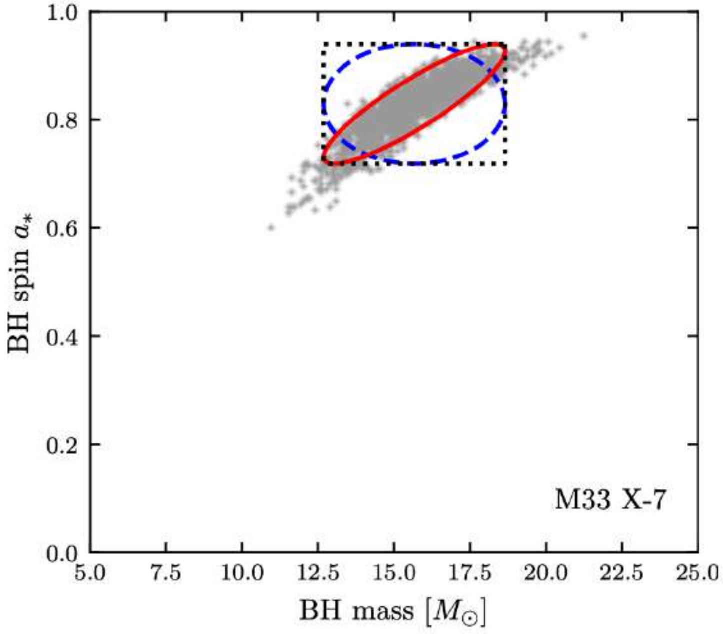
- Birefringence has a hint from Planck: have we seen evidence of the axiverse already?
- Cosmological probes have matured in precision, and in the next decades will test GUT scale axions.
- Superradiance has been used to test the axiverse up to h11~200 in explicit constructions on CYs.
- Advances in constructing the visible sector in Type-IIB offer promise to probe h11 = 491 due to low f's.

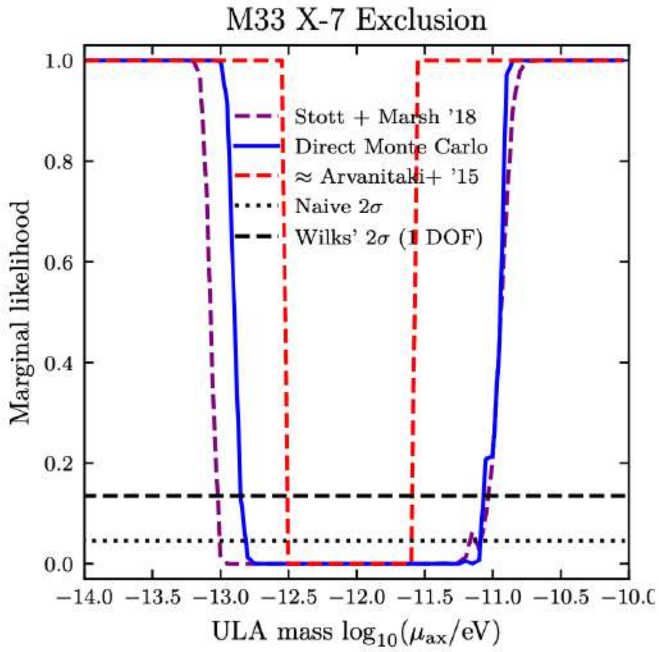




BACKUP SLIDES

Superradiance Methods I

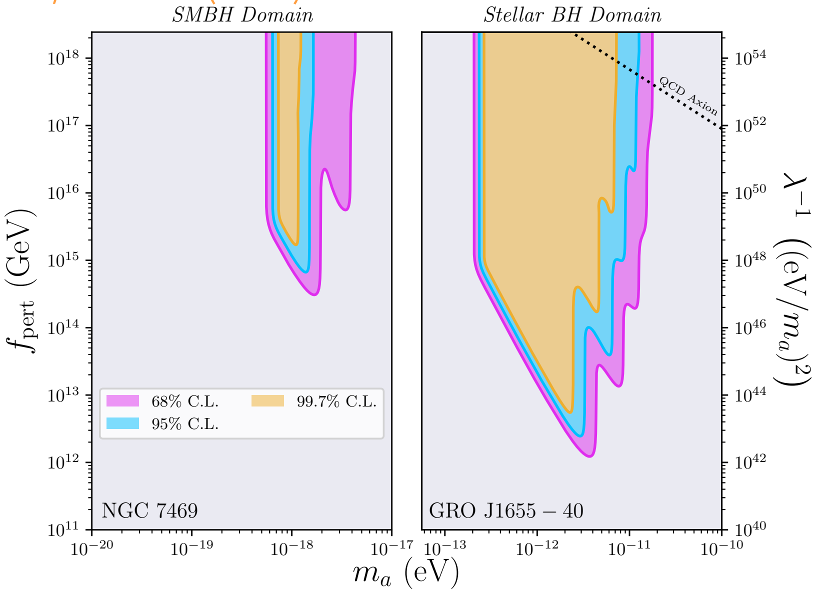




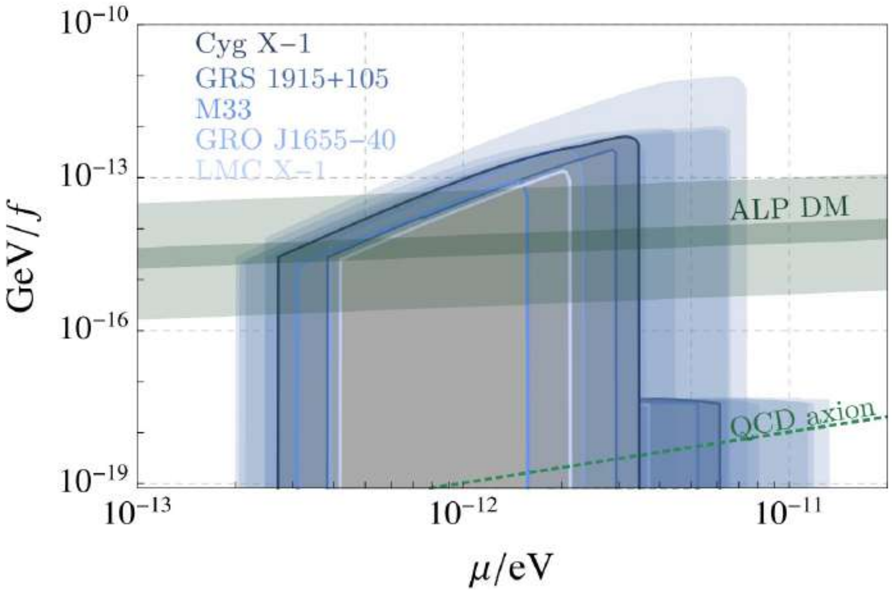
Arvanitaki+ take a conservative "box" approach to exclusion.
Gaussian approximation reproduces the full Monte-Carlo well for M33-X7.
CY exclusions dominated by width of mass bound due to just a few BHs like this.

Superradiance Methods II

Mehta, DJEM+ (2021)



Baryakhtar+ (2020)

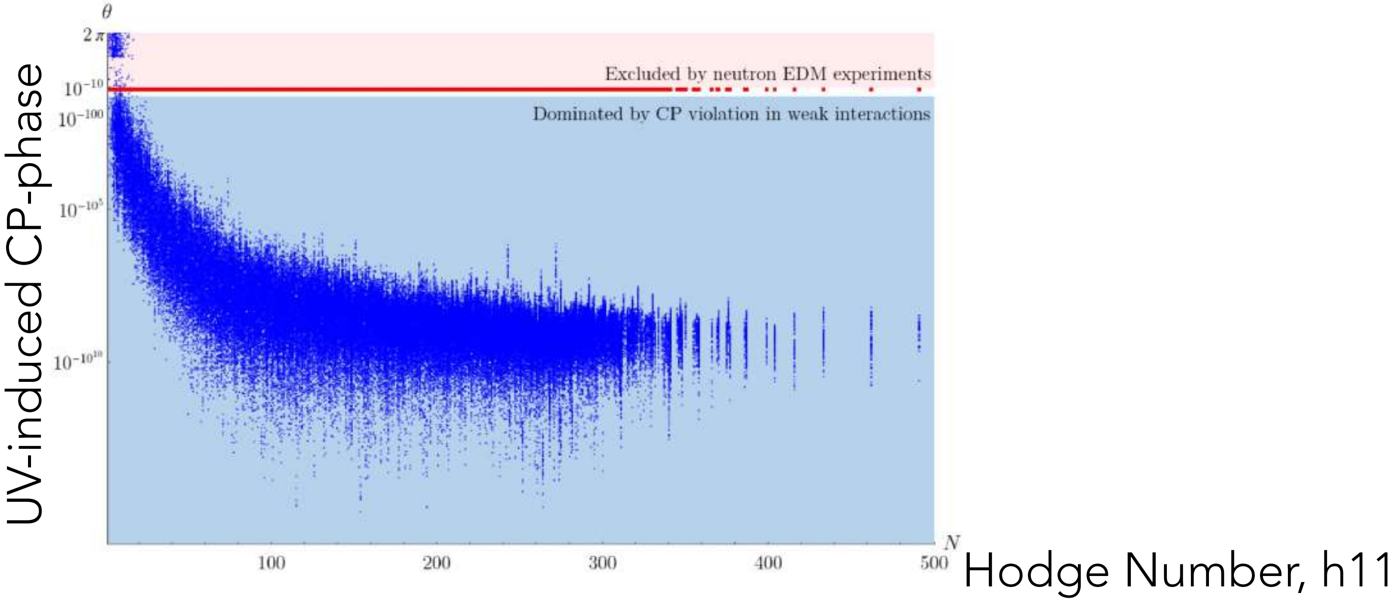


Improved treatment of 2-level system scattering in Baryakhtar+ leads to O(1) change in upper limit on fa for superradiance. Will not change h11 CY limits (log-normal fa).

Strong-CP Problem

Demirtas et al (2021)

Choose divisor to host QCD at tip of SKC. Dilate to GUT coupling.
QCD instanton + ED3 on h11+4 prime toric divisors. Random phases → CP breaking.

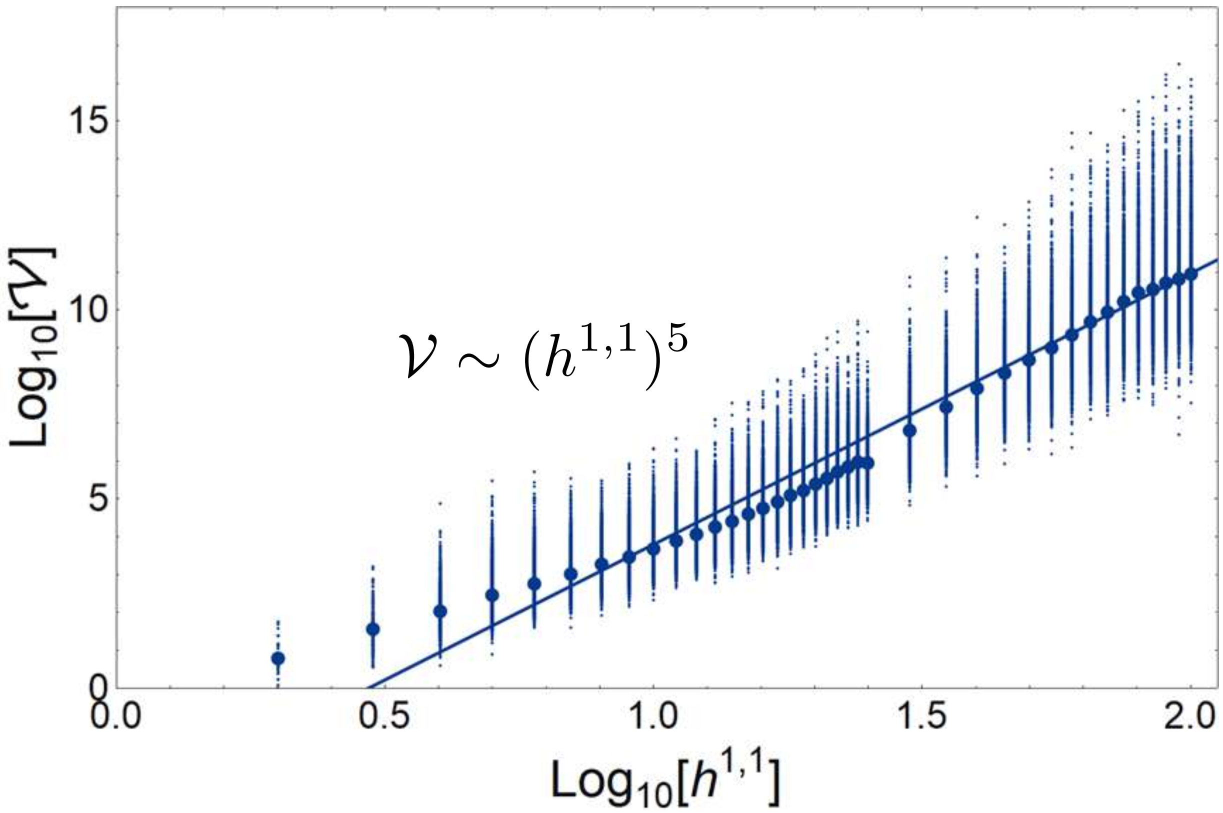


h11 shift symmetries → absorb some phases. PQ quality problem from misalignment of mass basis and prime toric. No quality problem if QCD axion relatively heavy.

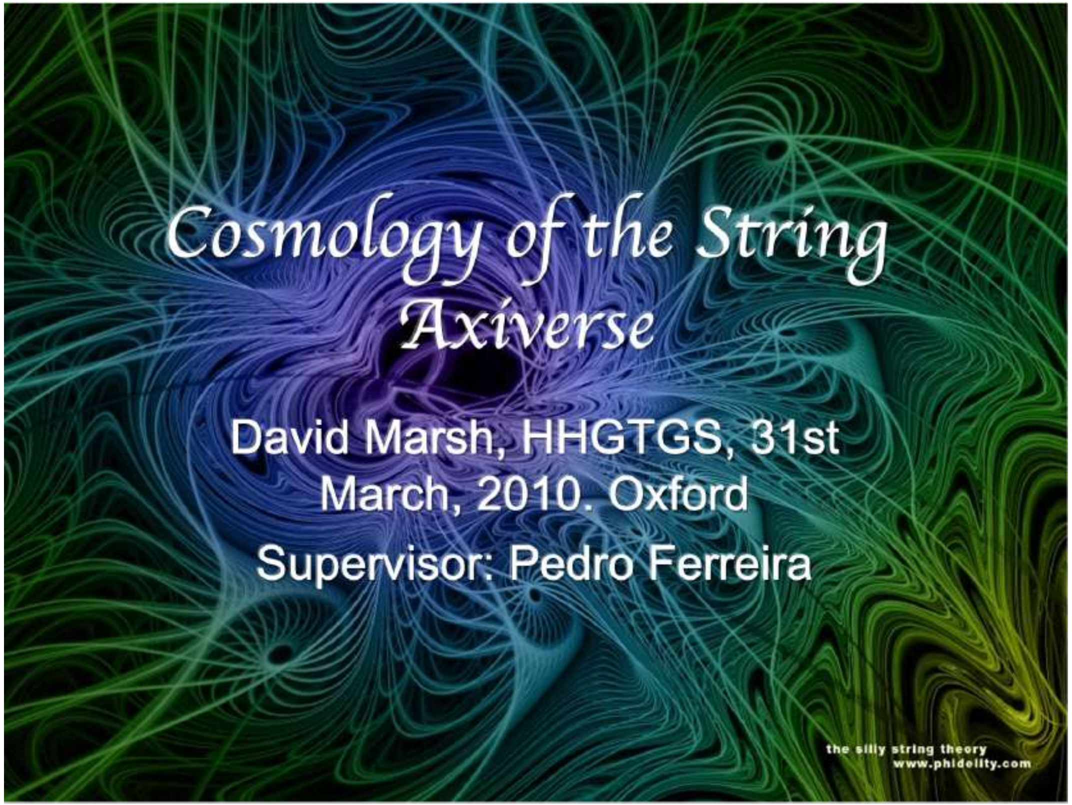
Volume Trend with h11 in KS

Volume computed at tip of SKC → location in moduli space with smallest volume still under control.

$$\langle f_a \rangle \sim \frac{M_{pl}}{\mathcal{V}^{2/3}}$$



My very first seminar, 31st March 2010, “Hitch Hikers Guide to Grad School”.



Terrible slide design… great subject! Cosmological perturbation theory of light axions.

String Axiverse

Asimina Arvanitaki (UC, Berkeley and LBL, Berkeley), Savas Dimopoulos (Stanford U., Phys. Dept.), Sergei Dubovsky (Stanford U., Phys. Dept. and Moscow, INR), Nemanja Kaloper (UC, Davis), John March-Russell (Oxford U., Theor. Phys.)

May, 2009

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