



The Axiverse in 2024

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Science and
Technology
Facilities Council

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KING'S
College
LONDON

OVERVIEW



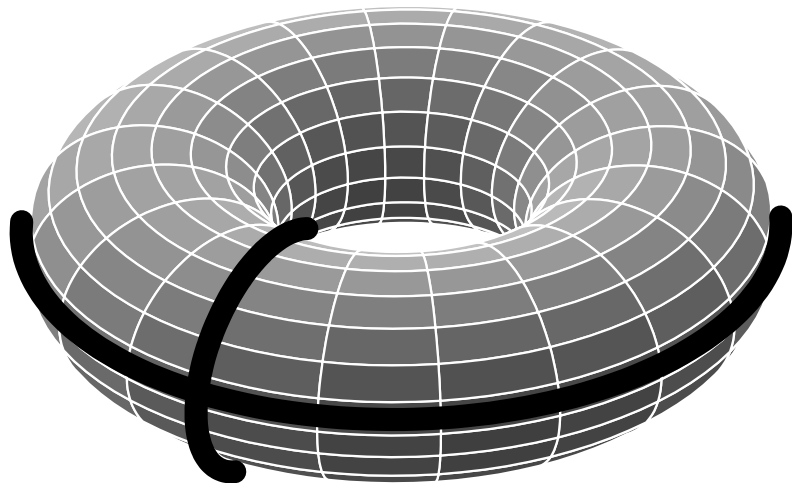
Axion Theories



Neutron observed to have EDM ~ 0 . This can be explained by the QCD axion.

$$m_a f_a = m_\pi f_\pi \Rightarrow m_a = 5.7 \mu\text{eV} (10^{12} \text{ GeV} / f_a)$$

One parameter DM model valid since 1980's



Extra dims. of string theory wrapped by flux $\rightarrow$ axion-like particles.

Number of axions given by topological invariants.

Masses spread over log scale.

Axion FAQ

Why are axions light?

→ Pseudo-Goldstone boson. Mass from non-perturbative corrections.

What defines an axion (-like particle)?

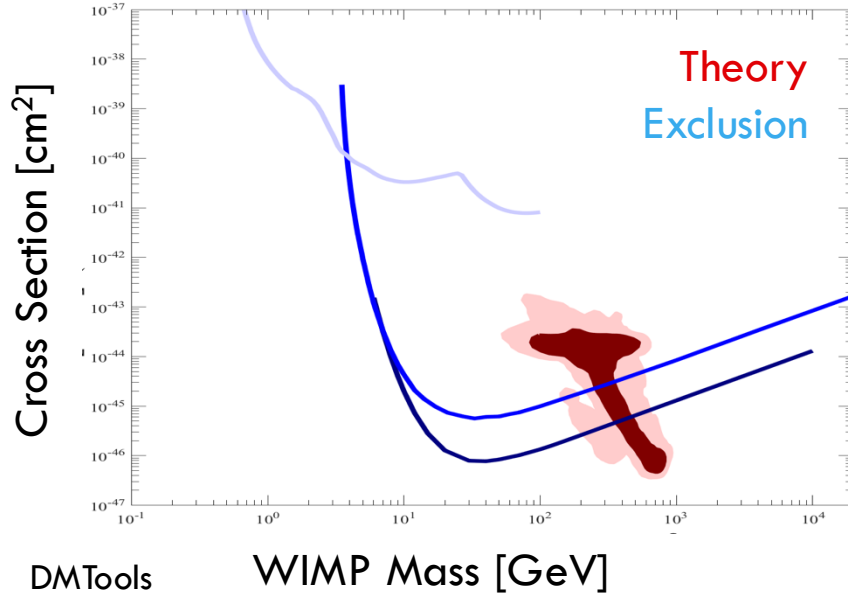
→ “light” pseudoscalar. Couples to Chern-Simons $F \sim F$ terms.

What is axion(-like) DM?

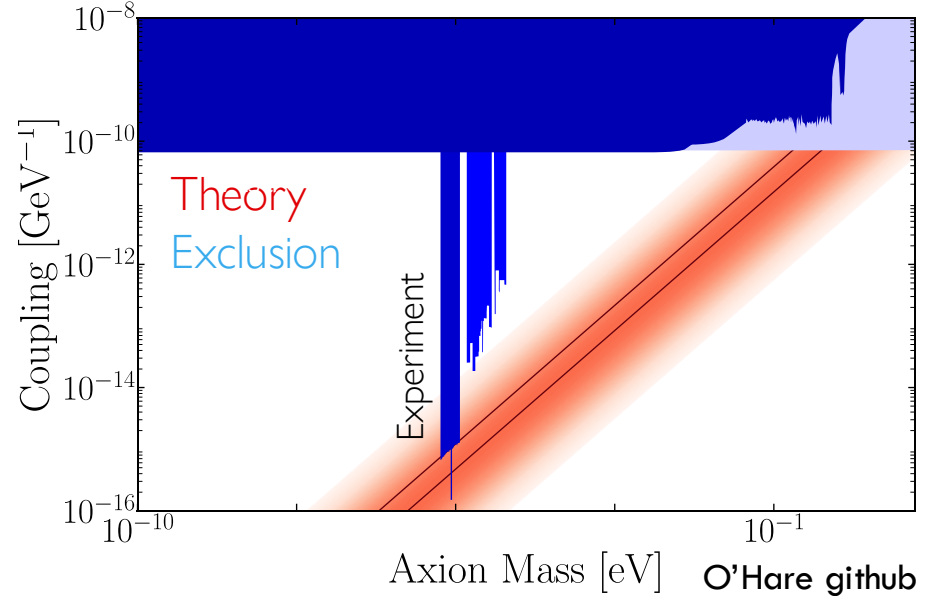
Mass $\ll 1$ eV → described as classical wave. Relic density from oscillations + potential energy.

Axions vs WIMPs

Two historical dark matter theories proposed in 70's/80's.



The Z-portal WIMP was excluded in 1987 by Homestake experiment.



The "invisible" axion of 1980 remains viable to this day for most masses.

Axion Relic Density

Relic density from solving the Klein-Gordon equation for a massive scalar field:

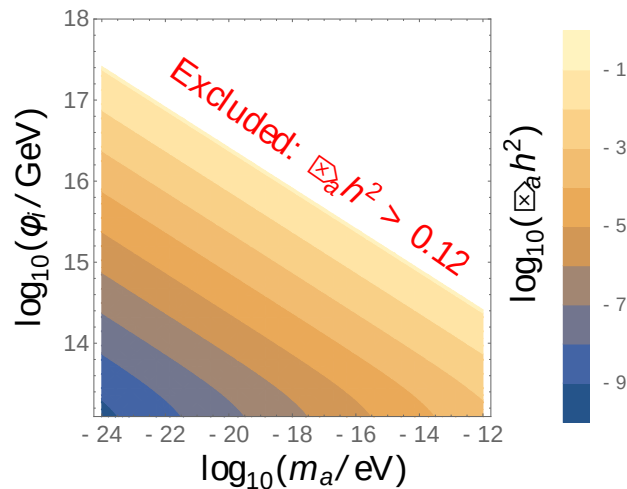
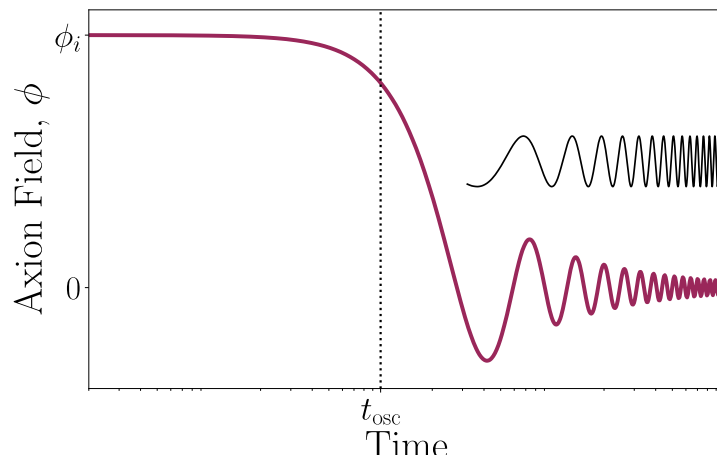
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

Damped SHM with time dependent “friction”.
Oscillates and decays when $H < m$.

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2.$$

$H \sim 1/t \rightarrow \rho \sim a^{-3}$. Harmonically oscillating scalar behaves like pressureless dust!

$$\Omega_a h^2 = 0.12 \left(\frac{\phi_i}{1.5 \times 10^{15} \text{ GeV}} \right)^2 \left(\frac{m}{10^{-15} \text{ eV}} \right)^{\frac{1}{2}}$$



Axion Direct Detection

Axions interact with electromagnetism via:

$$\mathcal{L}_{\text{int}} = -\frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g\phi\vec{E}\cdot\vec{B}$$

→ axions source Maxwell's equations:

$$\nabla\cdot\vec{E} = \rho_e - g\vec{B}\cdot\nabla\phi,$$

$$\vec{\dot{E}} - \nabla\times\vec{B} = -\vec{J}_e - g(\vec{B}\cdot\dot{\phi} - \vec{E}\times\nabla\phi)$$

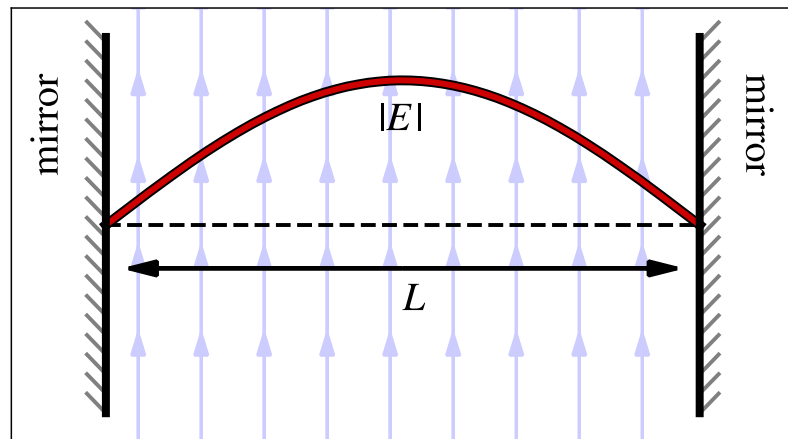
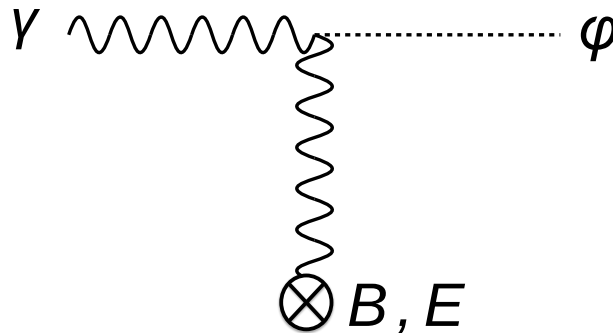
B source → linearise for E wave equation:

$$\ddot{\vec{E}} - \nabla^2\vec{E} = \frac{\omega^2}{m}\sqrt{2\rho_a}g\vec{B}\cos\omega t.$$

→ resonance via boundary conditions.

$$P = \frac{g^2 B^2 V \rho_{\text{DM}}}{m} Q. \quad \text{Power } 10^{-22} \text{ W in typical experiment}$$

The “invisible axion” was not excluded in 1987.



“Fuzzy DM”

When is an axion not a good CDM candidate?

Wavelength too large $\rightarrow$ not particle-like. Gradients in KG equation $\rightarrow$ “pressure”.

DM saturating any such bound is called “fuzzy”.

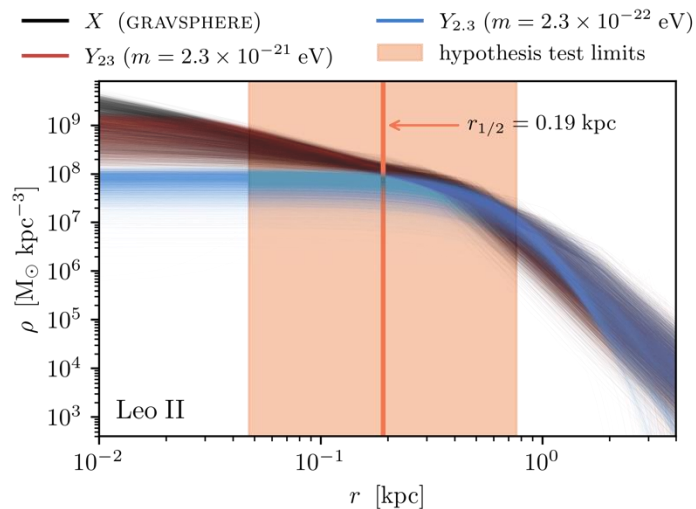
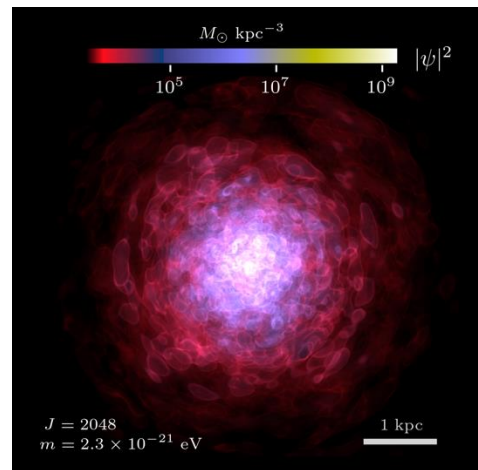
Estimate a lower bound on m from de Broglie wavelength $<$ size of dwarf galaxy:

$$R_{\text{dSph}} \approx 1 \text{ kpc}, M_{\text{dSph}} \approx 10^8 M_{\odot} \Rightarrow \sigma_v \approx 20 \text{ km s}^{-1}$$

$$\lambda_{\text{dB}} \lesssim R_{\text{dSph}} \Rightarrow m_a \gtrsim 10^{-22} \text{ eV}$$

“Bosonic Tremaine-Gunn bound”. Doing this properly is surprisingly difficult...

Zimmerman, DJEM et al.
arXiv:2405.20374



THE QCD AXION



The Strong CP Problem

A **neutron electric dipole moment** (nEDM) would **violate CP-symmetry** of QCD.

Wigner-Eckhart: EDM and magnetic dipole must be parallel.

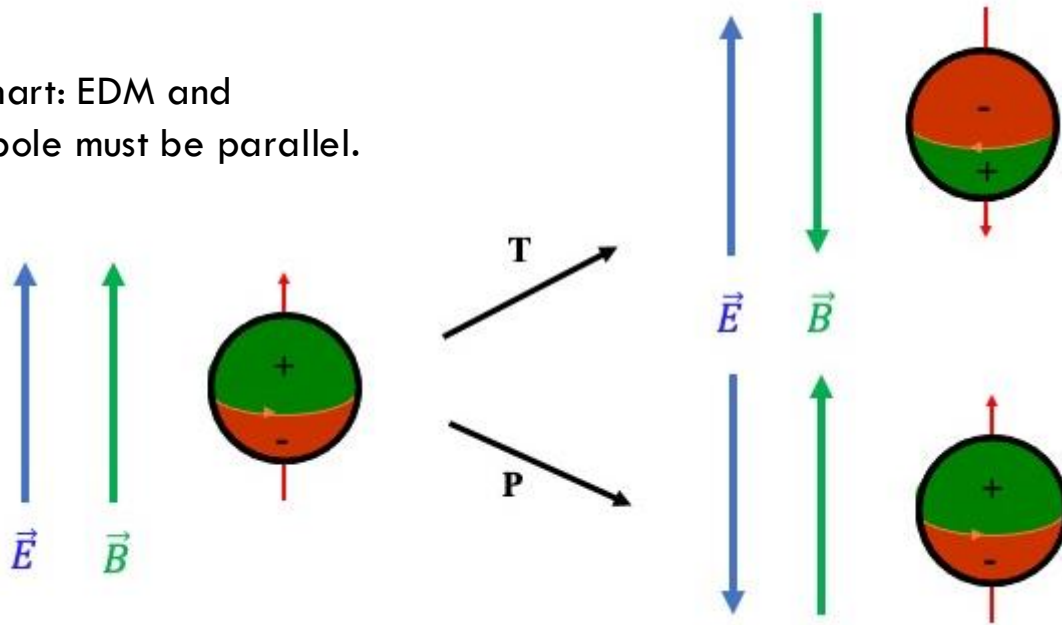


Fig: Day, Ellis DJEM (2021)

The QCD “ θ -term”

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} \text{Tr } G_{\mu\nu} \tilde{G}^{\mu\nu}$$

This is called the “Chern-Simons” term.

This term is a total derivative and classically does not affect the e.o.m’s

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - gf^{abc} A_\mu^b A_\nu^c$$

 SU(3) index. Runs over the 8 gluons (generators)

 Structure constants of the Lie algebra

$$\tilde{G}^{\mu\nu,a} = \epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}^a / 2\sqrt{-g}$$

Indices raised with $\varepsilon \rightarrow$ in the action root g measure cancels & this term does not depend on the spacetime metric, only its **topology**.

CP-violation from Chern-Simons

C = charge conjugation, P = parity, T = time inversion

QFTs must obey CPT. Therefore P and T violation $\rightarrow$ CP violation.

Consider electromagnetism:

$$F_{\mu\nu} \tilde{F}^{\mu\nu} \propto \vec{E} \cdot \vec{B}$$

E is a proper vector $\rightarrow$ odd under P

B is caused by a current of charges $\rightarrow$ odd under T

$\rightarrow$ This term violates P and T and thus CP.

The Strong CP Problem

nEDM, Abel et al (2020)

The **neutron electric dipole moment**:

$$d_n = 0 \pm 1.3 \times 10^{-26} \text{ ecm}$$

nEDM **violates CP-symmetry** of QCD.

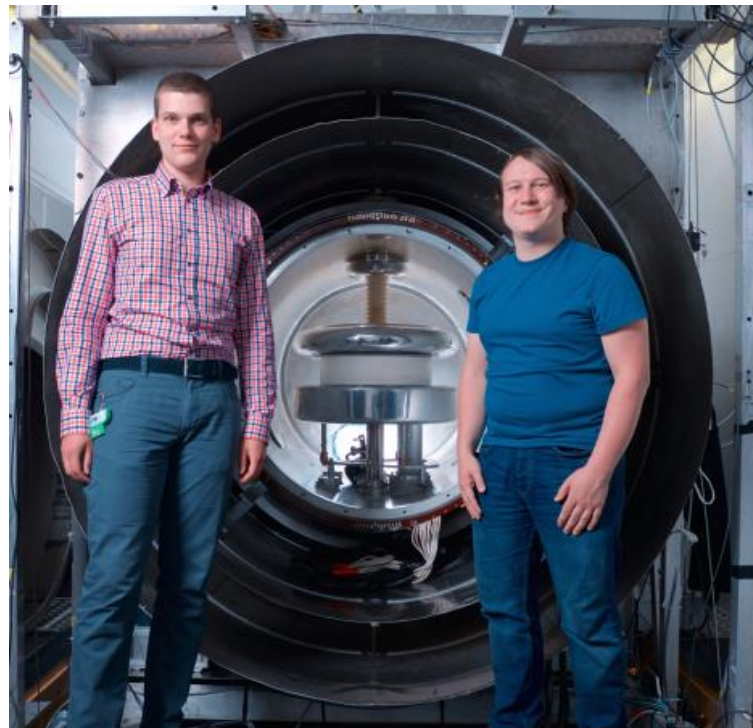
QCD
topological
term

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} \text{Tr } G_{\mu\nu} \tilde{G}^{\mu\nu}$$
$$\Rightarrow d_n = 3.6 \times 10^{-16} \theta \text{ ecm}$$

θ has a contribution from electroweak CP-violation

$$\theta = \theta_{\text{QCD}} + \arg \det M_u M_d$$

Why is $\theta < 10^{-10}$? $\theta \sim 1$ allowed by symmetry.



Rawlik & Ayres at nEDM, Switzerland (2017)

Fine tuning in theoretical Physics



$$\mathcal{L} = (\text{number}) \times (\text{operator})$$

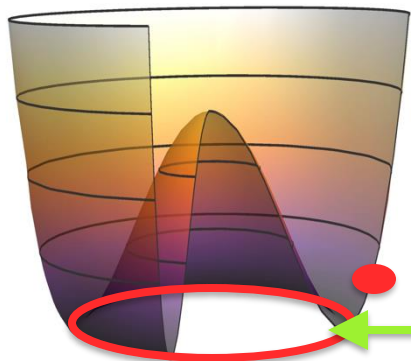
↓
=the value you measure
for the effect.

↓
=physical effect. The
neutron EDM.

$$(\text{number}) = \sum_{(\text{physics})} c_i \longrightarrow \text{Contributions from different sources. Strong and weak nuclear forces.}$$

The nEDM is measured consistent with zero. This implies a delicate cancellation at $\sim 10^{-10}$. We don't like coincidences.

Cleaning up the mess



Spontaneous symmetry breaking: a **Goldstone Boson**, θ , has a continuous “shift symmetry”, i.e. rotational symmetry.

“instantons”

Trick: couple a Goldstone to the problematic operator.

$$(\text{number}) \rightarrow (\text{number}) + \theta \rightarrow \theta$$

Now “tilt the wine bottle”: θ will now dynamically move to a fixed value = 0 by symmetry $\rightarrow$ no problematic nEDM.

Enter the Axion

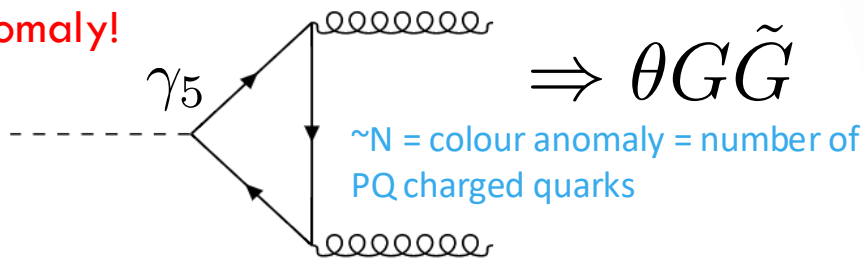
Peccei & Quinn (1977);
Weinberg, Wilczek (1978)

Make θ **dynamical**, with a potential possessing a **CP symmetric minimum**. Recipe follows...

First introduce a **U(1) symmetric** theory.

Next, **chirally charge quarks** under U(1).

Anomaly!

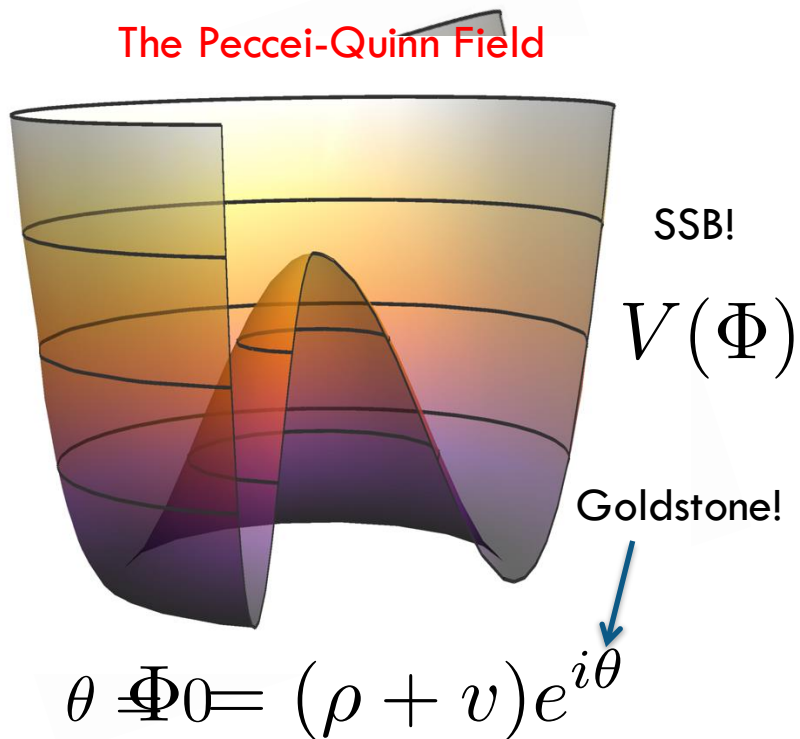


Absorb the original θ with a shift in the goldstone.

Instantons! $E_{\text{vac}} = -\cos \theta = V_{\text{eff}}(\theta)$

Minimise V: **axion θ “cleans up” the CP problem.**

The Peccei-Quinn Field





MAGNETIC
POWER
EFFECTIVE GREASE REMOVAL

AXION

TOUGH

CP CLEANER

Lime

Enter the Axion - II

Abbott & Sikivie; Dine & Fischler;
Preskill, Wise & Wilczek (1983)

$$m_a^2 f_a^2 = m_q \Lambda_{\text{QCD}}^3 \quad m_a = 5 \times 10^{-6} \text{ eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right) \quad f_a = v/N$$

Relic oscillations (“realignment”) → dark matter.

$$\omega_a = m_a + \frac{1}{2} m_a v^2 = m_a [1 + \mathcal{O}(10^{-6})]$$

$$\nu_a \approx 1 \text{ GHz} \times \left(\frac{m_a}{6 \mu\text{eV}} \right)$$

Local DM density given as a harmonic oscillator:

$$\rho_{\text{DM}} = \frac{1}{2} m_a^2 \phi_0^2 = 0.3\text{-}0.4 \text{ GeV cm}^{-3}$$

$$\phi = f_a \theta$$

A one parameter DM
model!

Axion DM is spatial/temporal variations in the nEDM/ θ angle + instanton potential energy.

IMPROVED...

BETTER DETERGENT
BOOSTER THAN EVER!

AXION

**NOW WITH DARK
MATTER!**

Safe whitening brightening power
for all your wash...**pre-soaks** too!

CAUTION: EYE IRRITANT
READ IMPORTANT INFORMATION ON SIDE PANEL

NET WT. 25 OZS.
(1 LB. 9 OZS.)

What is the Axion Mass?

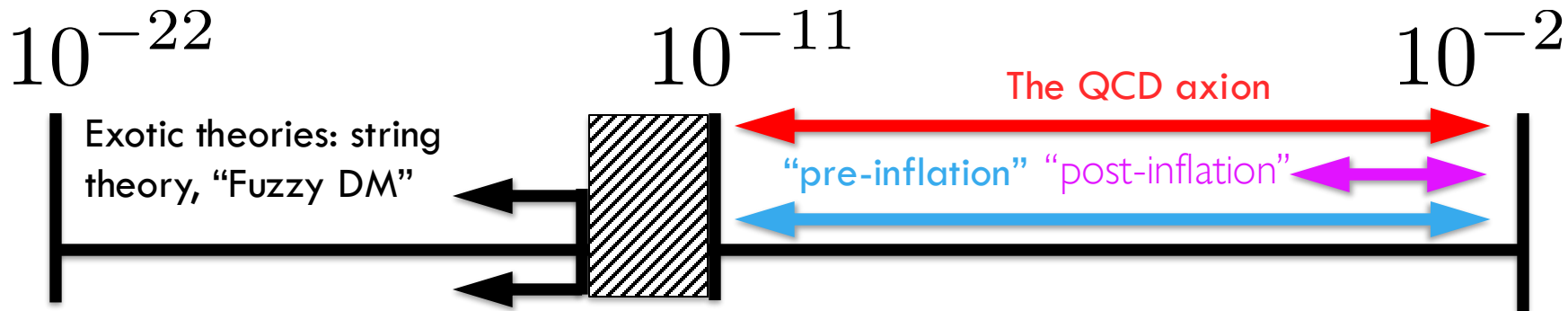
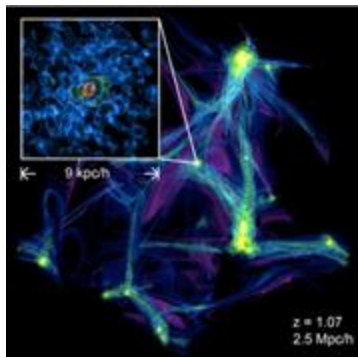
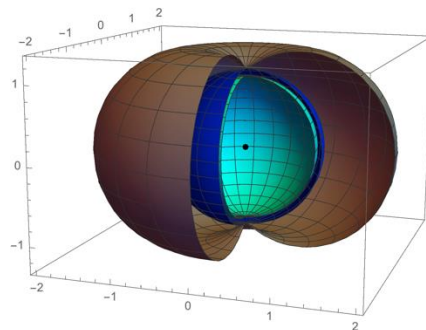


Fig: Veltmaat et al (2018)

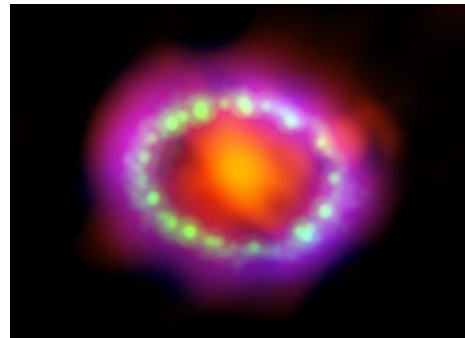


Galaxy formation
e.g. DJEM (2016)



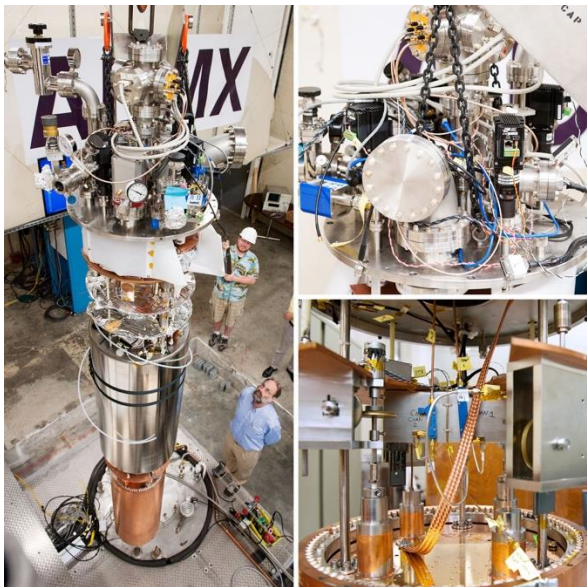
"Black Hole Superradiance"
e.g. DJEM & Stott (2018)

Fig: Physics World

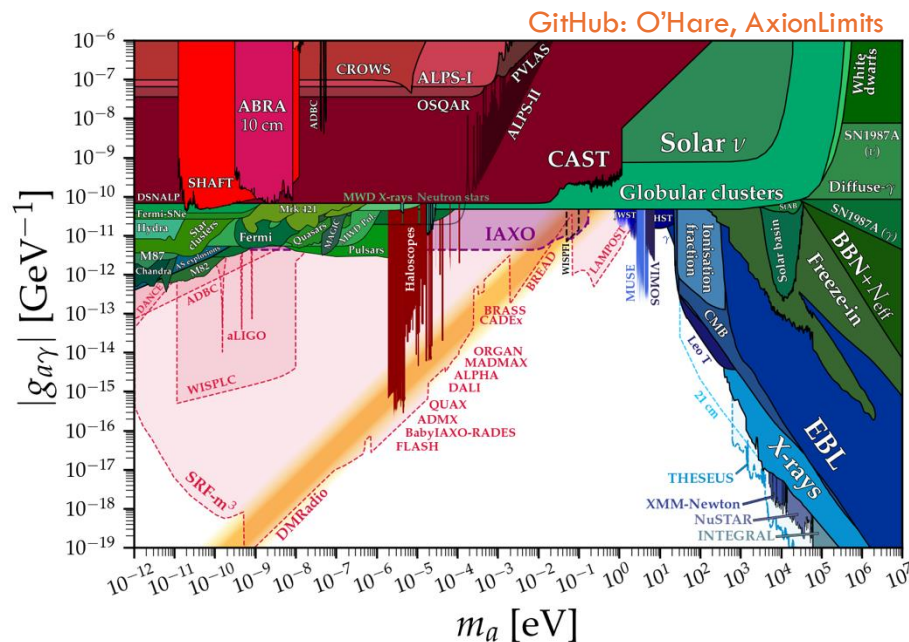


SN1987A Neutrino Burst
e.g. Chang et al (2018)

Direct Detection Present & Future

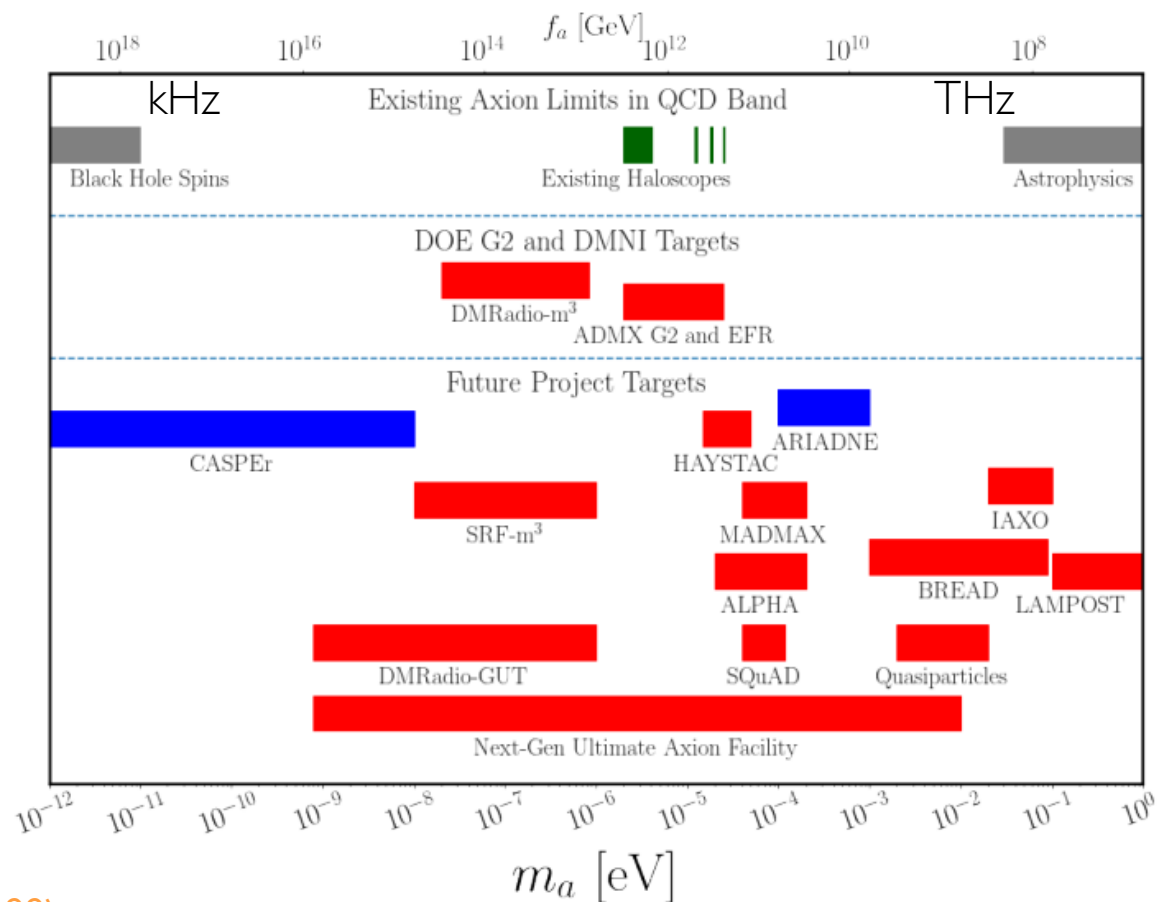


Microwave cavities exist all over the world and are a mature axion detection strategy. This one is ADMX.



Planned cavities and other tech. could discover QCD axion across whole mass range in 10-20 years.

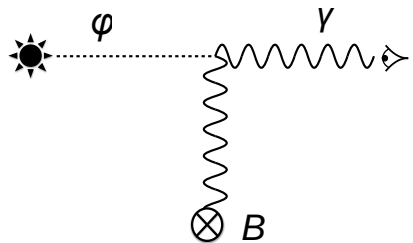
A simpler picture: how can we detect the QCD axion?



Axion Indirect Detection

CAST collab. (2017)
Walters, DJEM et al (2024)

Axions produced inside stars (not DM) provide a key constraint and search channel.



Non-observation of X-rays by
Cern “heliscope”:

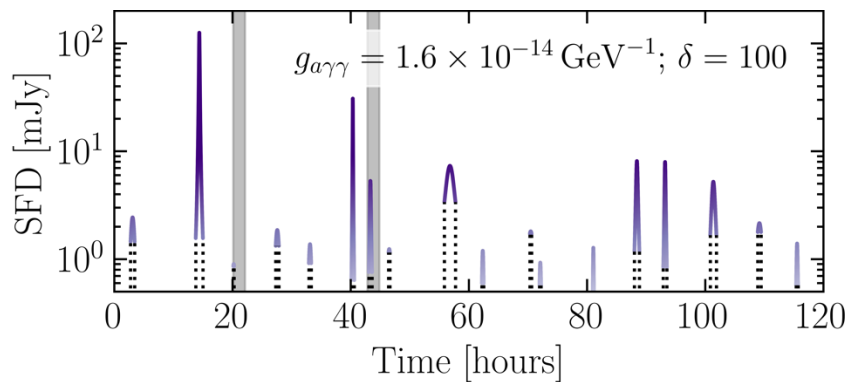
$$g < 6 \times 10^{-11} \text{ GeV}^{-1}$$

Indirect det. of axion DM needs B fields and
resonant plasmas → **neutron stars**.

$$\omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \quad P_{a \rightarrow \gamma} \sim B^2 g^2 L^2$$

P = conversion.
probability
L = size of
resonant region

“Miniclusters” → bright **radio (low m)** transients.
Need dedicated telescope.



STRING AXIVERSE

Specifically, type IIB on CY3's.



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

$$S = -\frac{1}{2} \int F_5 \wedge \star F_5, \quad F_5 = dC_4$$

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
h^{1,1} Hodge number =
topological

Compactify → massless fields in 4D:

$$S = -\frac{1}{8} \int da_i \mathcal{K}_{ij} \wedge \star da_j,$$

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

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:

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

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

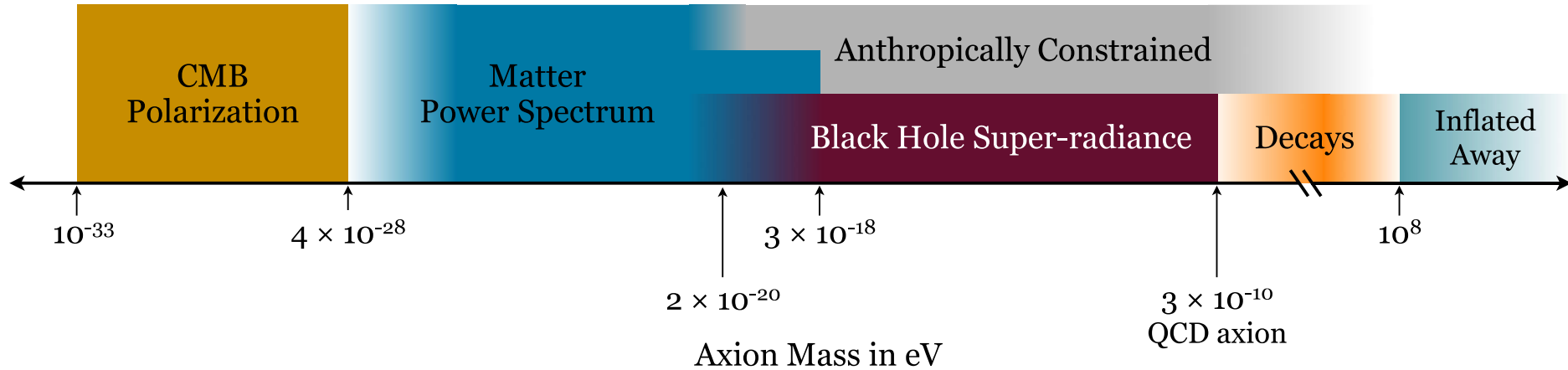
$$\Lambda_j \sim M_{pl}^3 m_{\text{SUSY}} \exp[-\text{Vol} D_i]$$

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

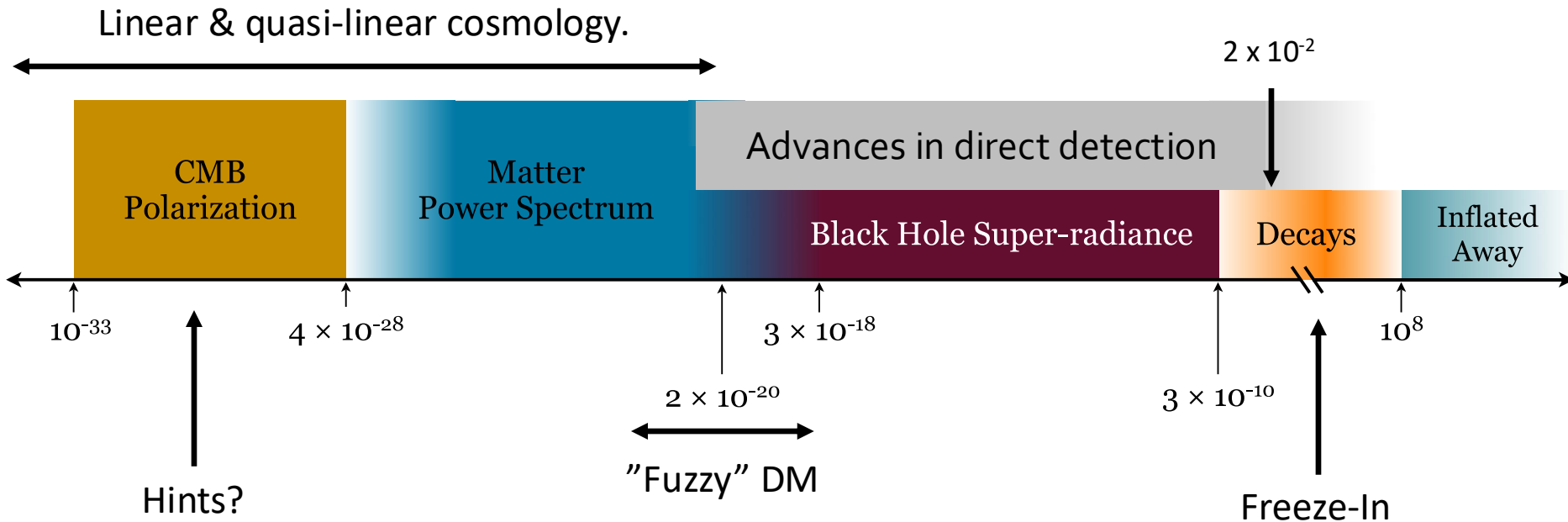
PHYSICAL REVIEW D **81**, 123530 (2010)

String axiverse

Asimina Arvanitaki,^{1,2} Savas Dimopoulos,³ Sergei Dubovsky,^{3,4} Nemanja Kaloper,⁵ and John March-Russell⁶



Axiverse in 2024



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

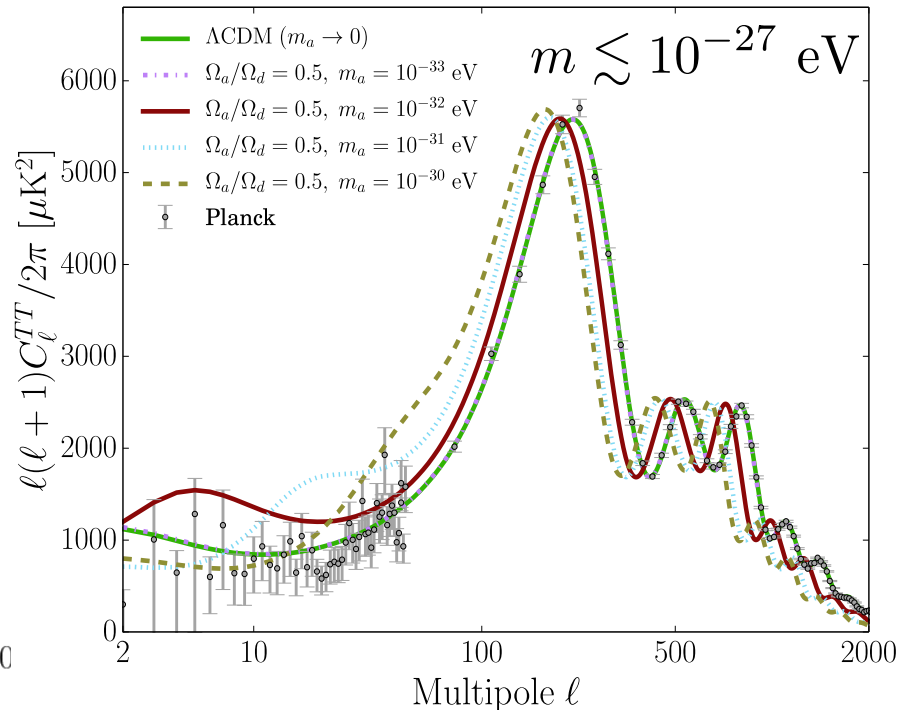
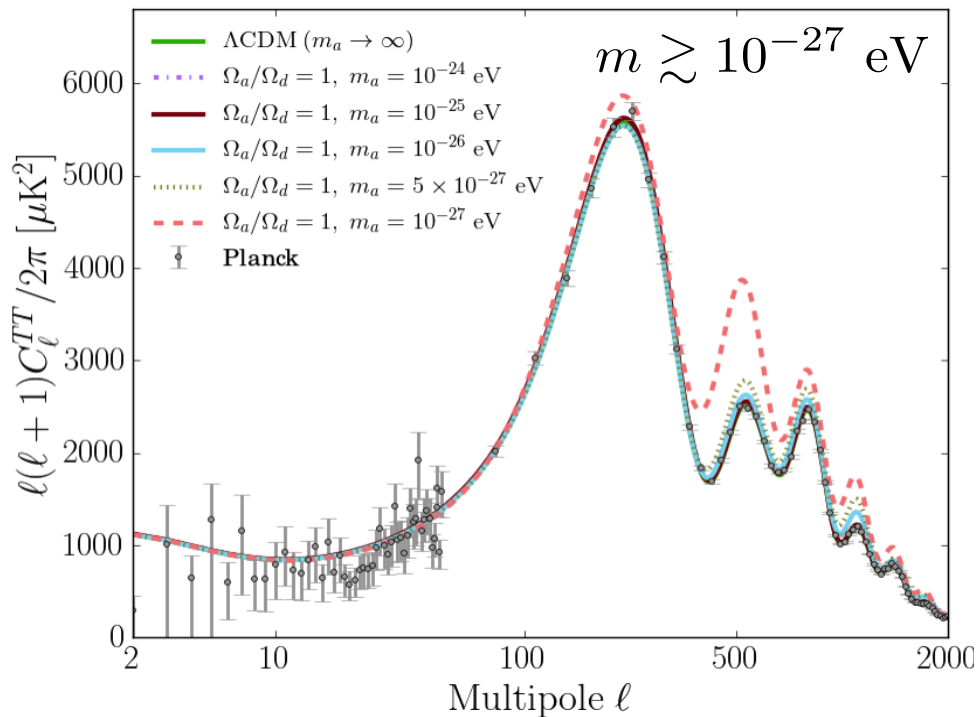
LINEAR++ COSMOLOGY

i.e. fuzzy dark matter and its relatives



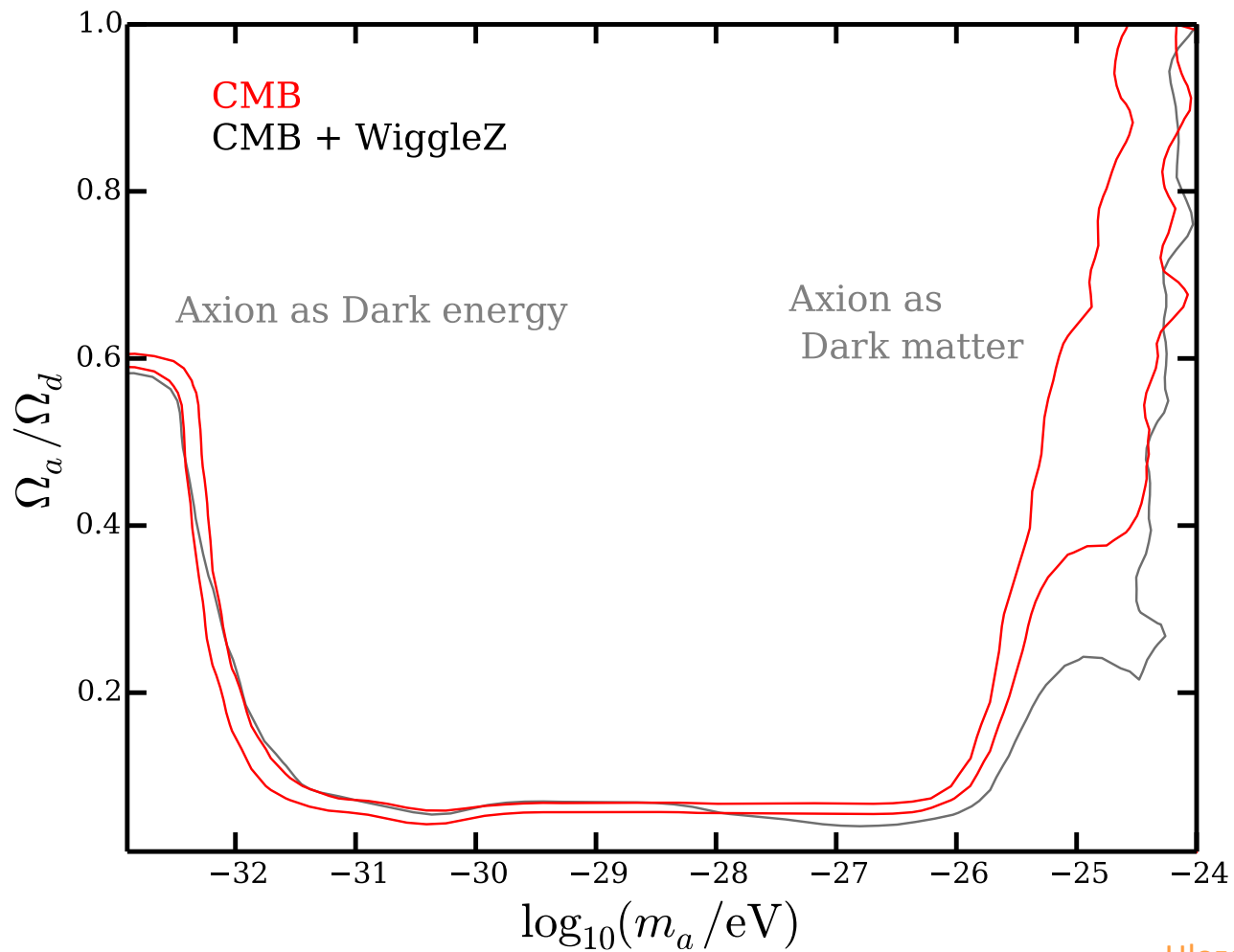
Matter
Power Spectrum

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

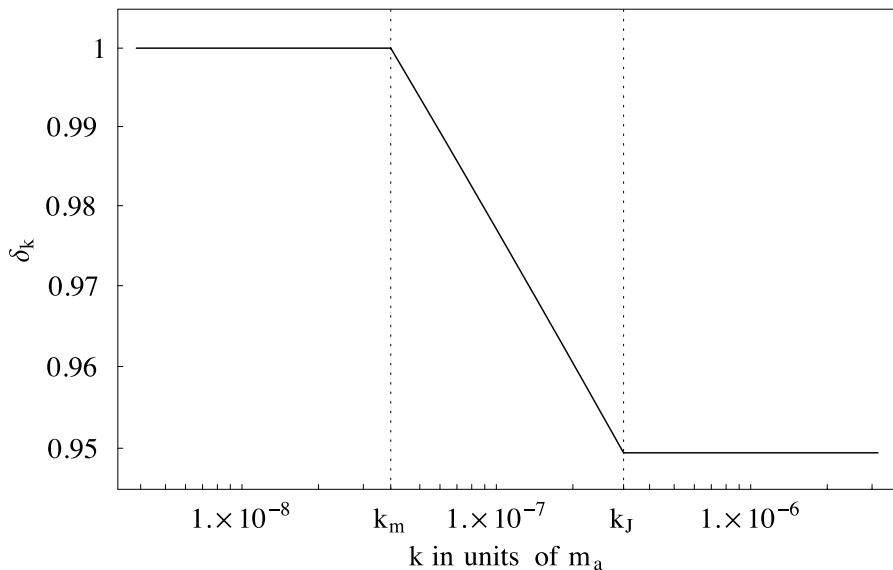


Hlozek, DJEM et al (2014)

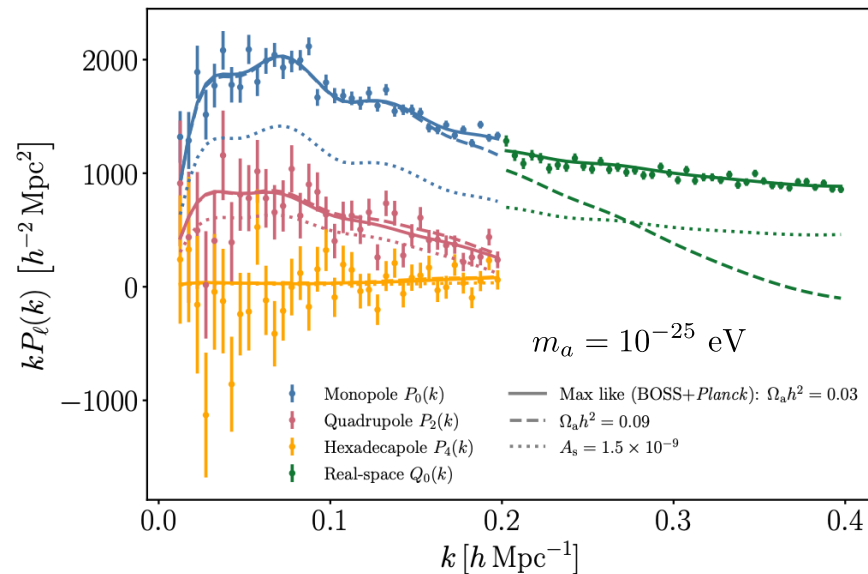
Physics: **damped motion of the axion field** behaves as **dark energy** at early times.
Expansion rate differs from LCDM $\rightarrow$ change Silk damping and Sachs Wolfe.



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

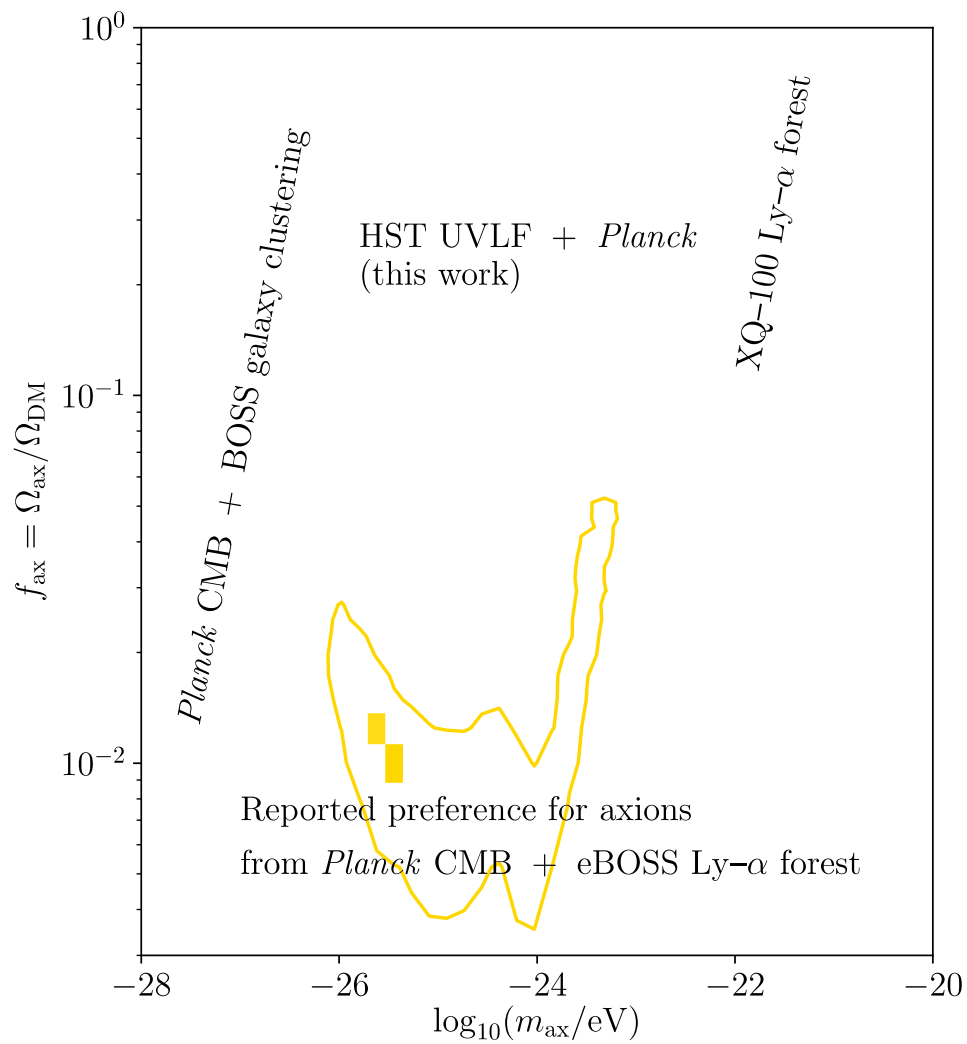


Axiverse 2009: “step in $P(k)$ ”.



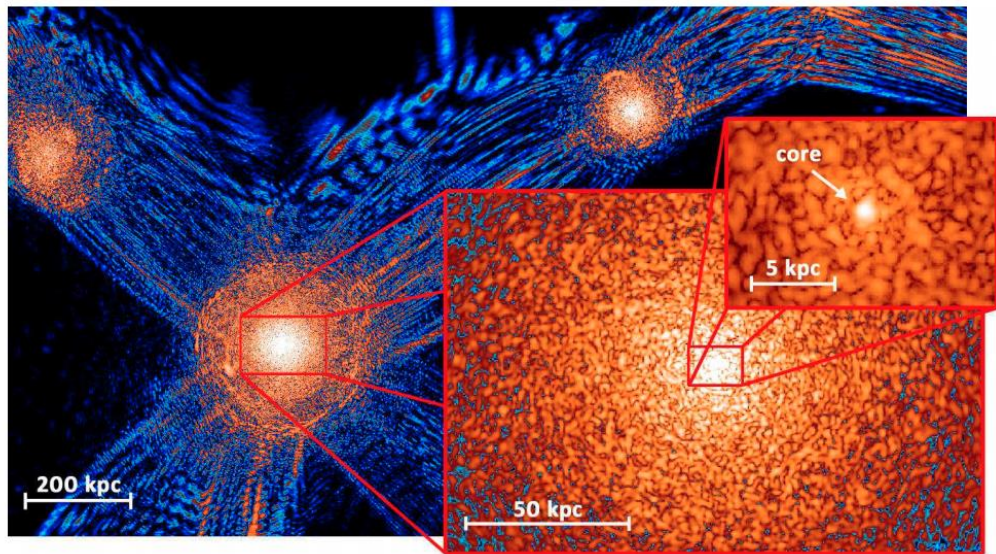
Axiverse 2023: EFTofLSS in the BOSS DR12 $P(k)$ multipoles.

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

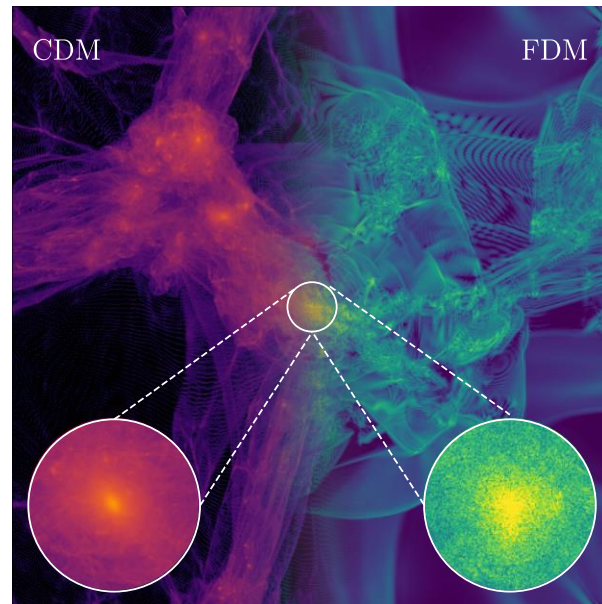


Simulating Light Axions

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



Schive et al (2014)



Laguerre, Djem et al (2023)

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

SUPERRADIANCE!



Black Hole Super-radiance

Black Hole Superradiance

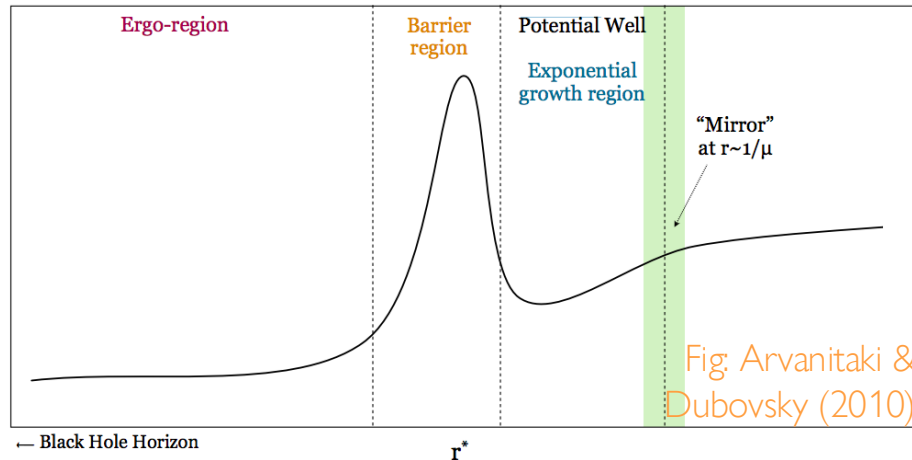
Review: Brito et al (2015)

Solve for instabilities of KG equation on

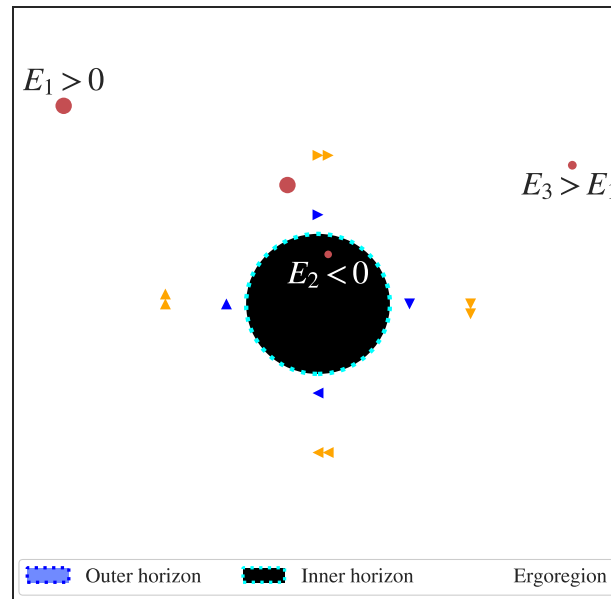
Kerr: $\square\phi - \partial_\phi V(\phi) = 0$

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

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



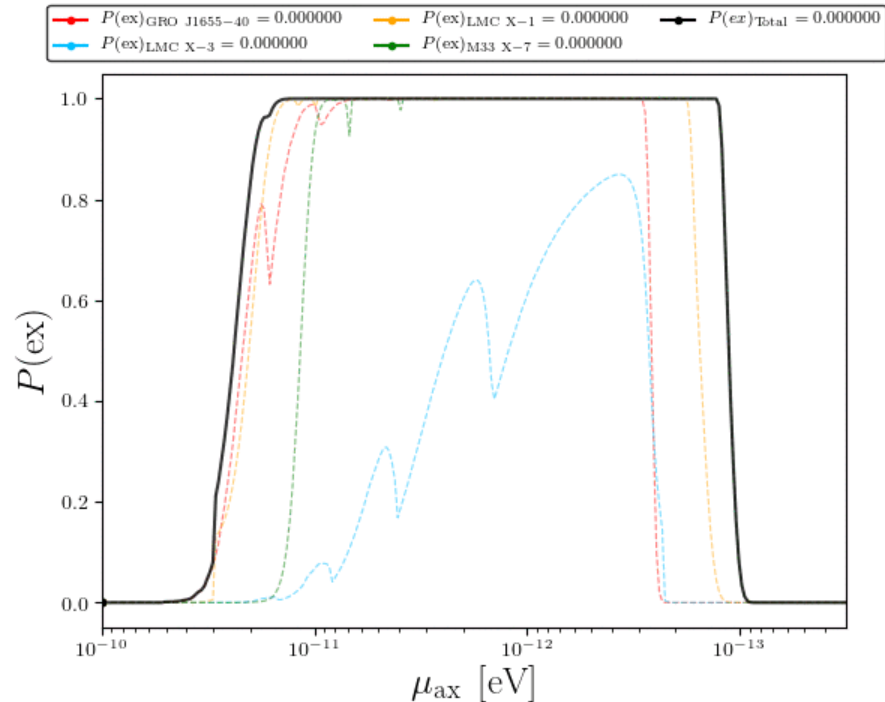
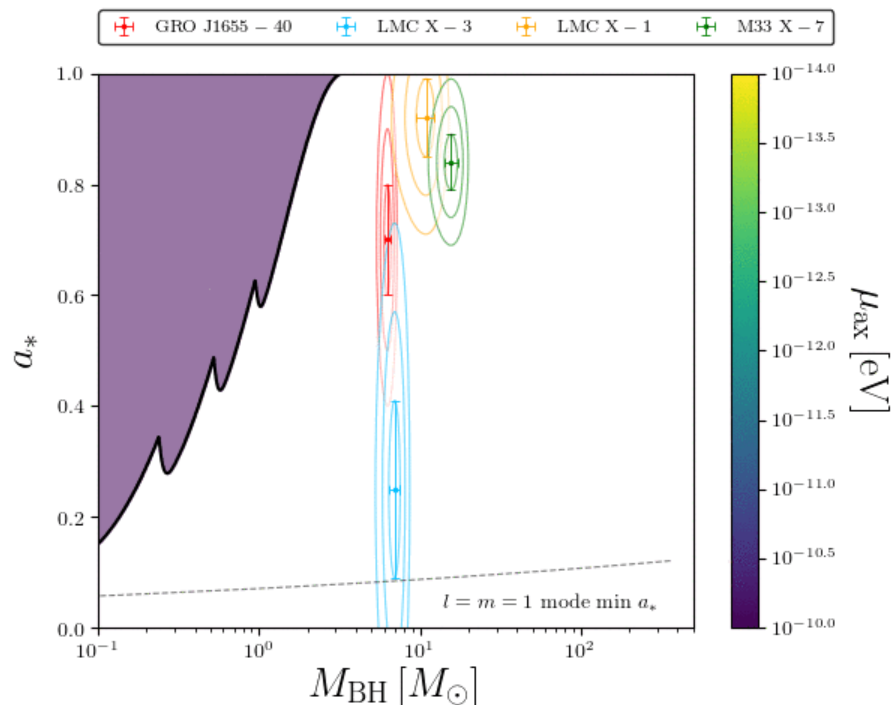
Physical picture: “Penrose process/ black hole bomb”



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

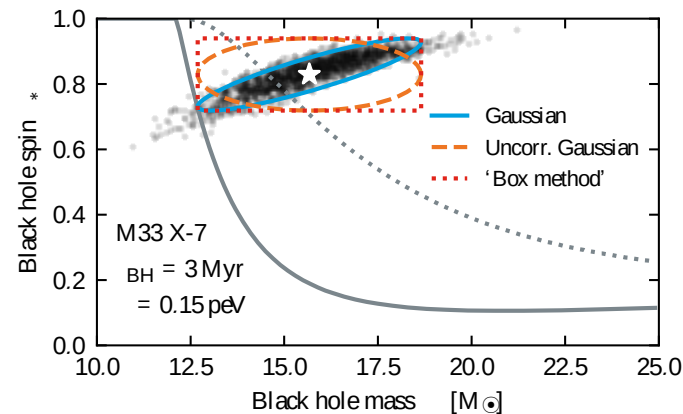
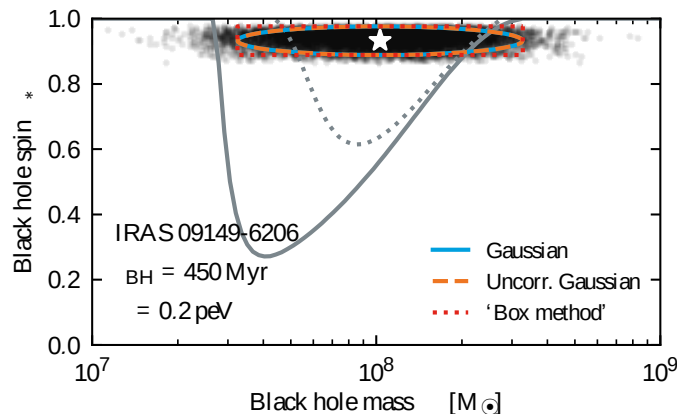
Exclude axion masses where known BHs exist in the superradiant forbidden region.
 This sample: X-ray stellar BHs. Gaussian composite likelihood.

GIF by Matthew J. Stott

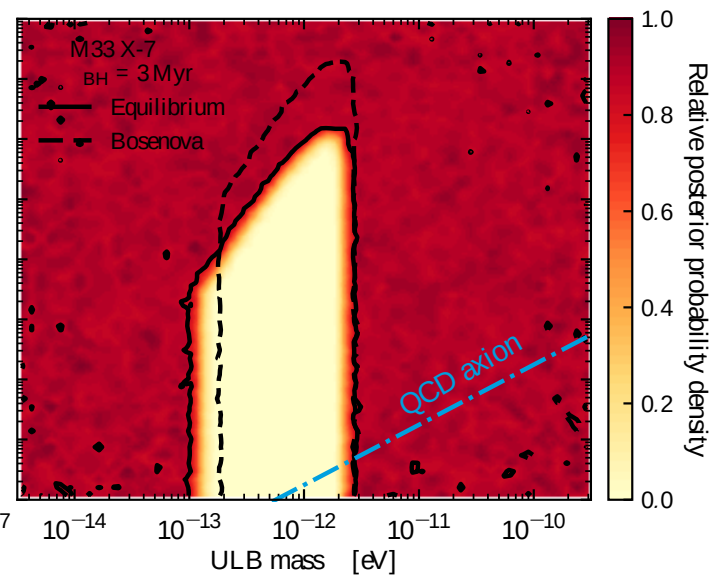
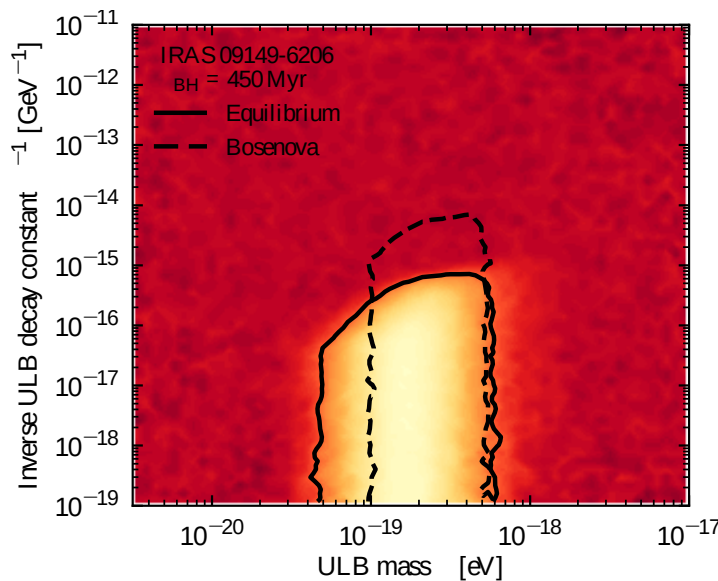


“Exclusion probability” is marginal likelihood. Statistically robust constraints.

Rigorous
treatment of BH
stats.



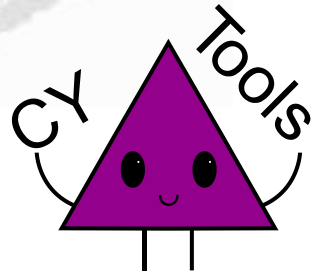
Minimum value of
decay constant for
SR imposed by 2-2
scattering.



STRING THEORY PROGRESS

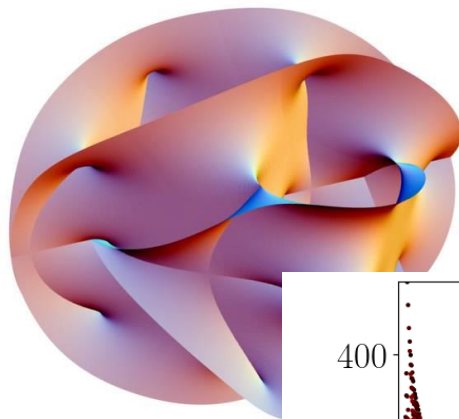
Easy to use computational geometry

Demirtas, Rios-Tascon, McAllister



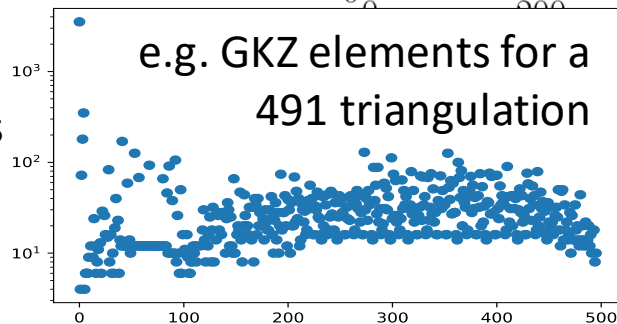
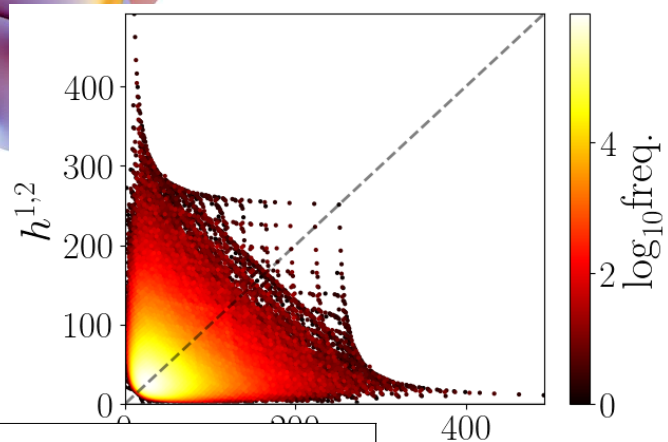
“KS Axiverse”

- CY3s constructed as hypersurfaces in “ambient toric varieties”. E.g. Fermat quintic in $\mathbb{CP}^4$.
- KS database gives **all** 4d “reflexive polytopes” $\sim 4 \times 10^8$ with “Hodge numbers h_{11}, h_{21} ”.
- “Triangulation” of these gives ambient toric varieties. Unique polynomial $\rightarrow$ CY with h_{11} axions.
- Automated fun with CY-Tools!
- Compute axion properties for different sizes and shapes and shapes of any CY! 10^5 in laptop time!



$h_{11}=27$: most polytopes
 $h_{11}=491$: most CYs $< 10^{428}$

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



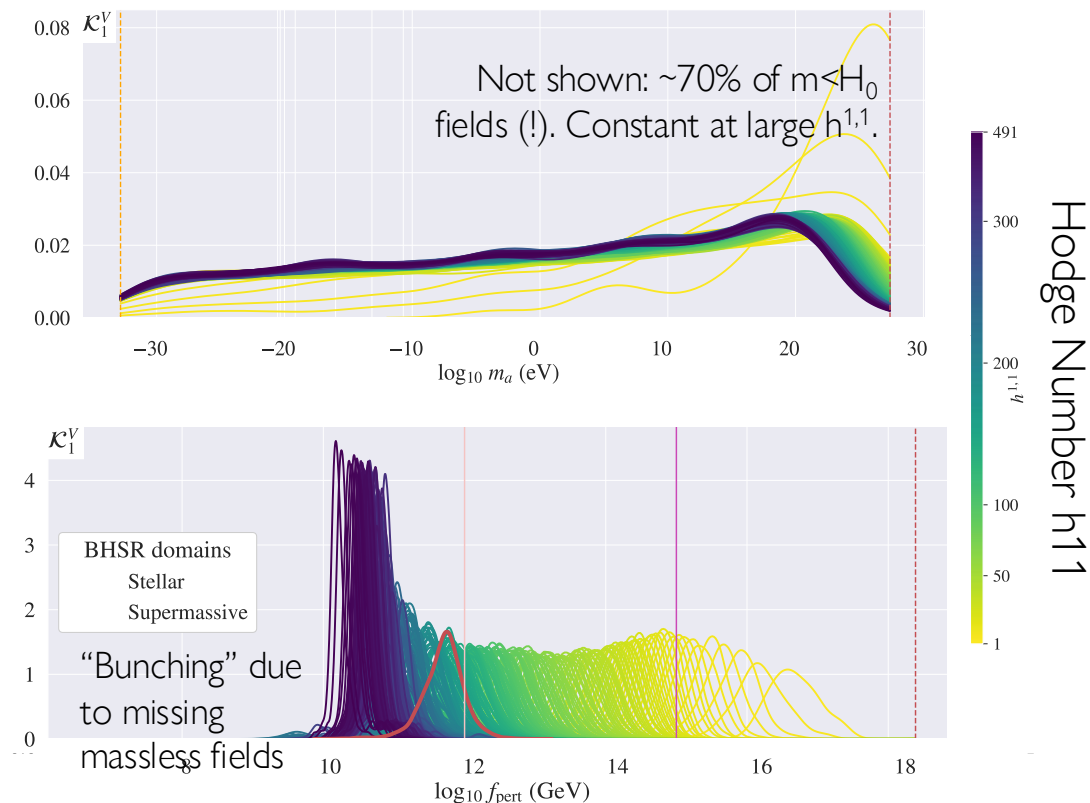
Axion Spectra from KS

Mehta, DJEM et al (2021)

Expand V to quartic order,
diagonalise $\rightarrow$ masses + quartics
("fpert").

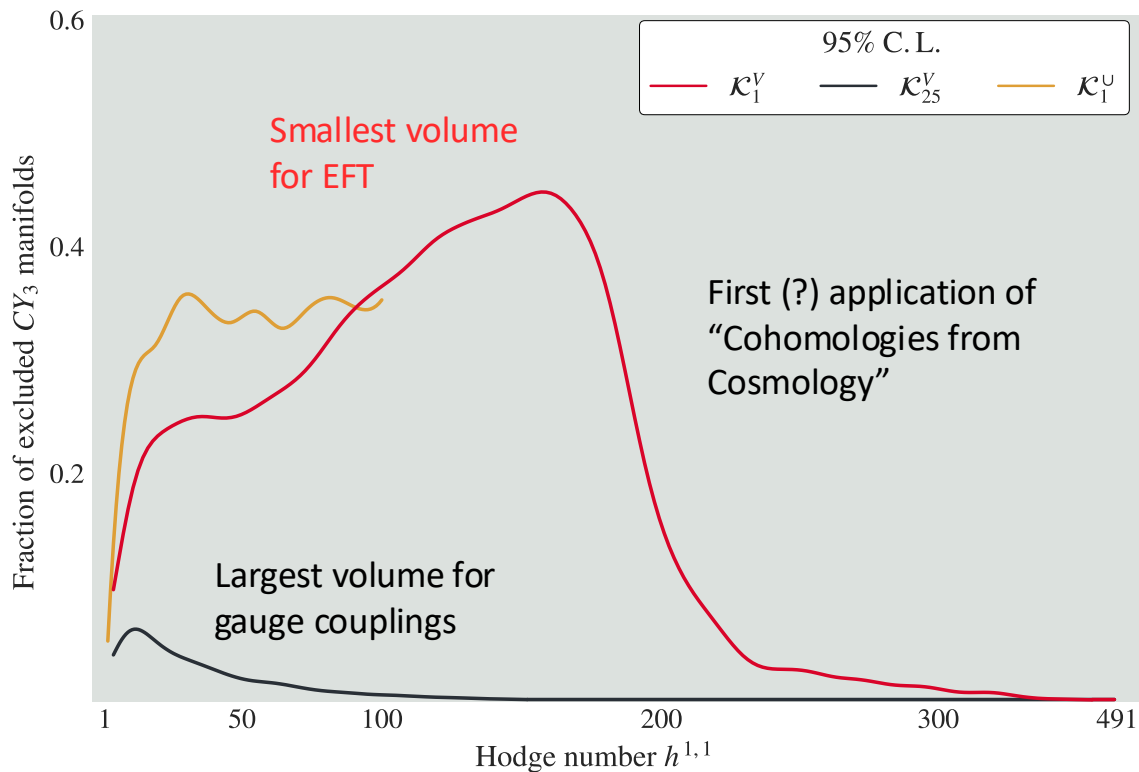
Trends: at large $h_{11} \rightarrow$ cycles in the
CY have large volumes $\rightarrow$ (ultra)light
axions and smaller decay constants.

Mass spectrum "blue tilted".
Decay constants log-normal,
becoming smaller at large h_{11} .



Constraints on IIB CY Vacua

Ensemble of $O(10^5)$ CYs. All up to $h^{1,1}=5$. 100 per $h^{1,1}$ up to 176. Few per $h^{1,1}$ to 491.



Above $h^{1,1} \sim O(\text{few})$ limit driven by stellar BHs with well measured properties.

Cut-off understood from volume increase with $h^{1,1} \rightarrow$ smaller $f \rightarrow 2$ -2 scattering shut-off for stellar BHs.

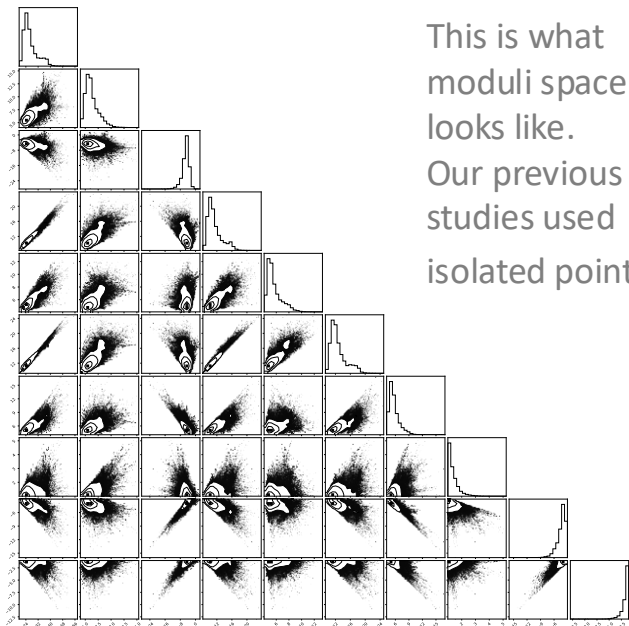
THE FUTURE OF THE AXIVERSE



Go big on statistics...

Topology from Cosmology Axion Collab.
DJEM, He, Halverson, McAllister groups

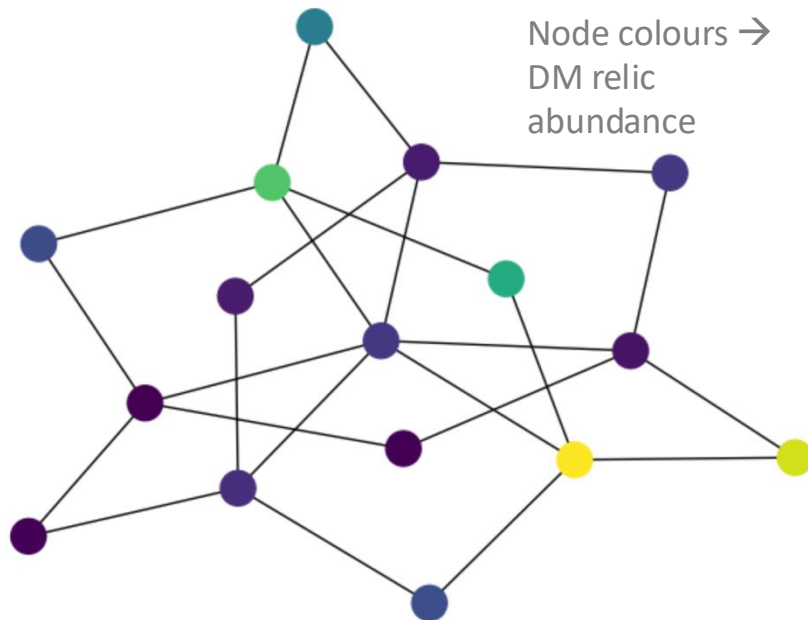
Axion EFT defined by a CY plus h11 Kahler parameters, t . Do an MCMC.



This is what
moduli space
looks like.
Our previous
studies used
isolated points.

Laptop time for h11~10's!

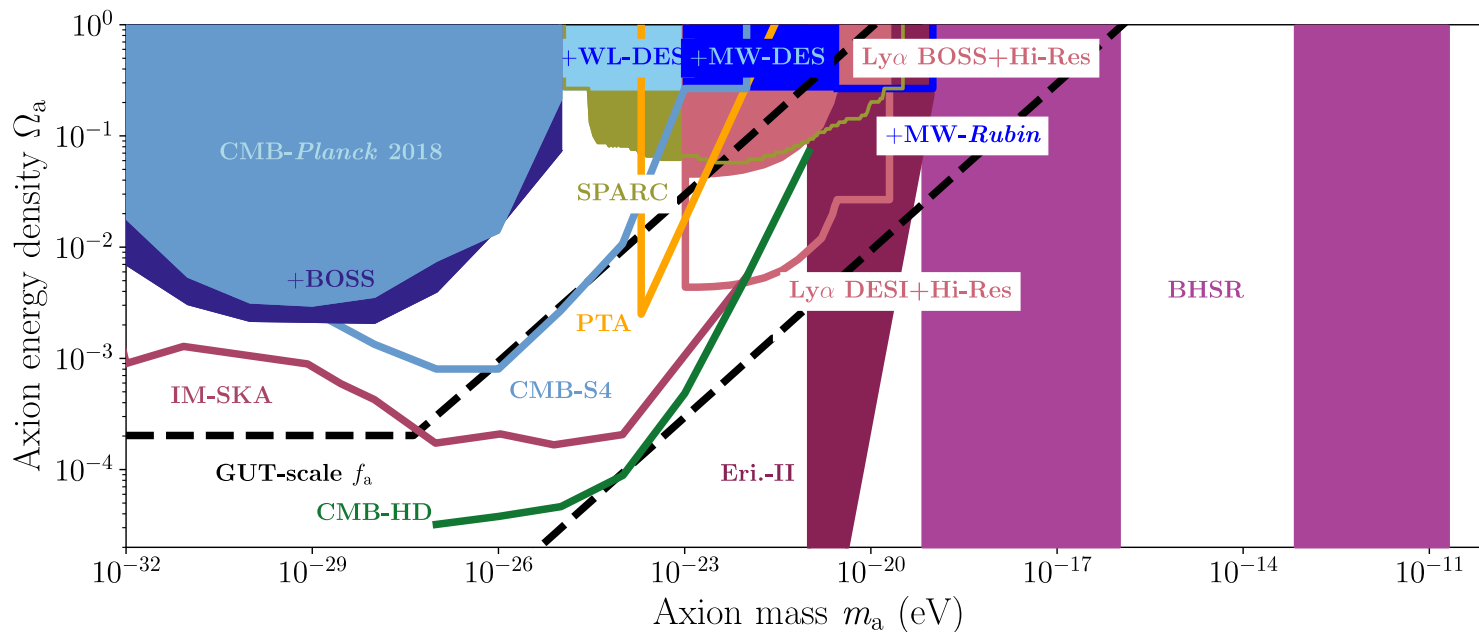
Explore CYs using graph neural nets?



“Flip graph” for small polytope.

Cosmological Probes

Rogers, DJEM et al (2023)

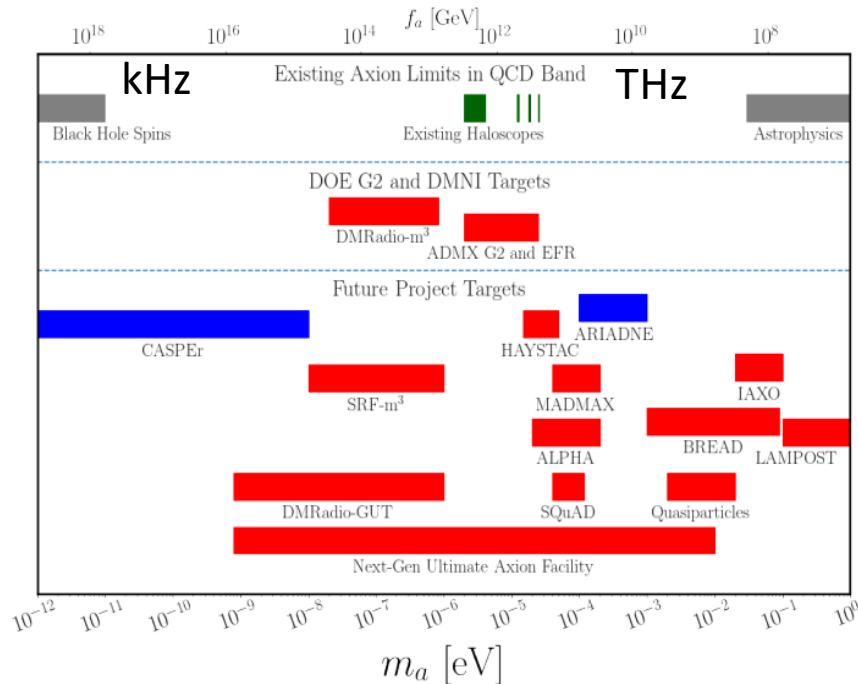
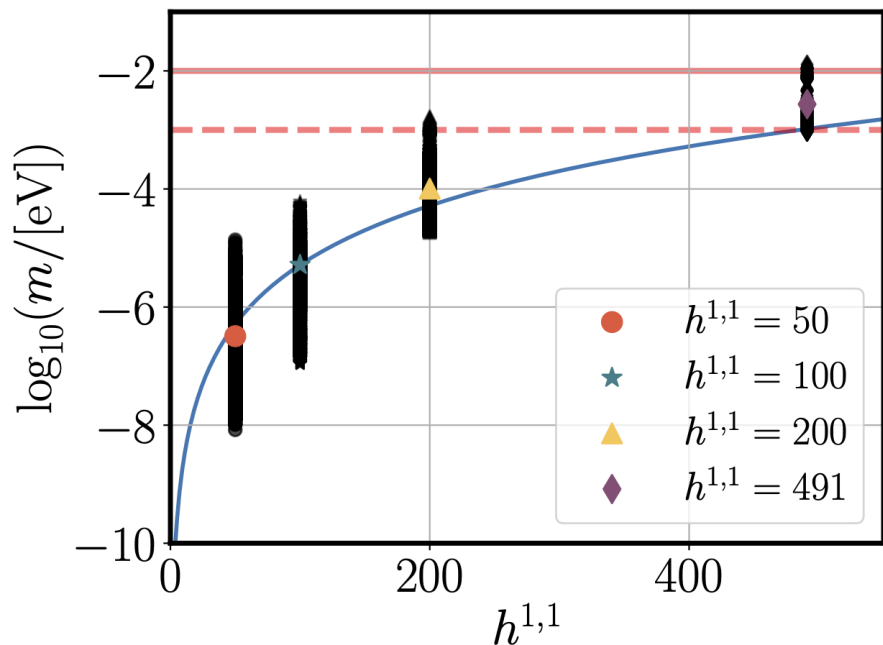


Upcoming surveys will reach sensitivity to probe sub-dominant axion DM predicted by **GUT scale decay constants from 10^{-28} to 10^{-20} eV**. Original axiverse "matter power".

In prep: construct fuzzy DM models at low $h_{11} \rightarrow$ constrain Kahler params.

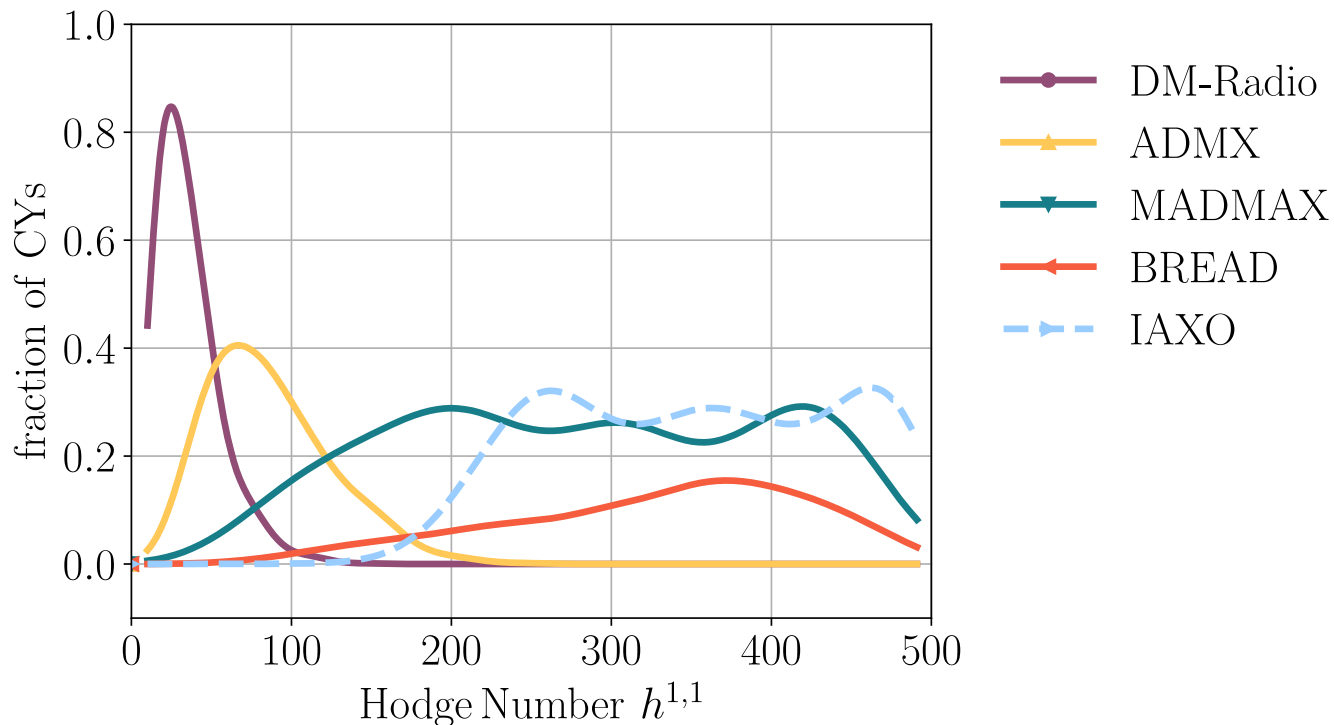
The QCD axion will be found

For string theory: fixes the overall scale of the decay constants $\rightarrow$ topology of CY.

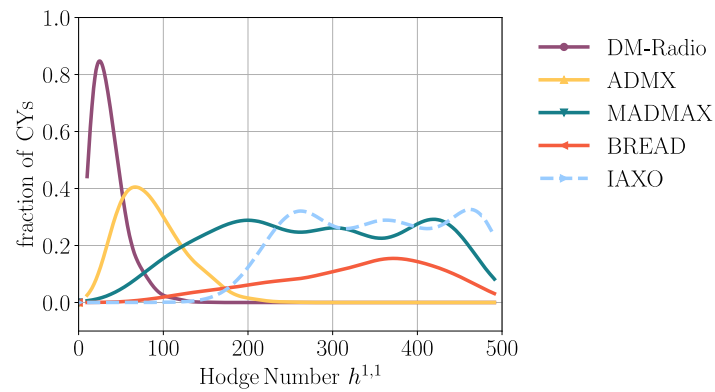
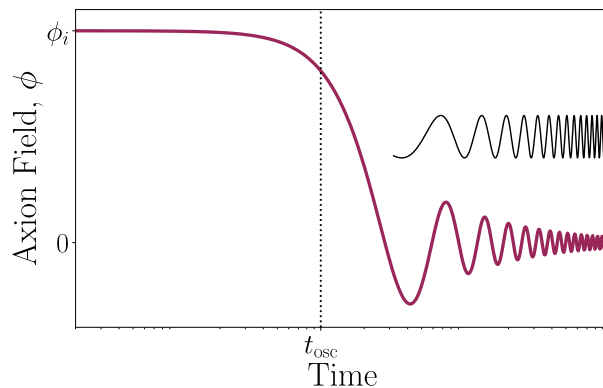
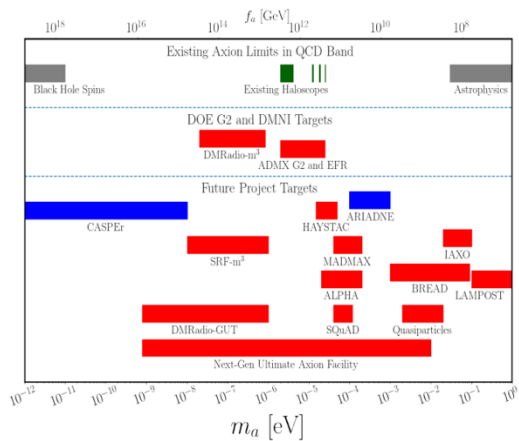
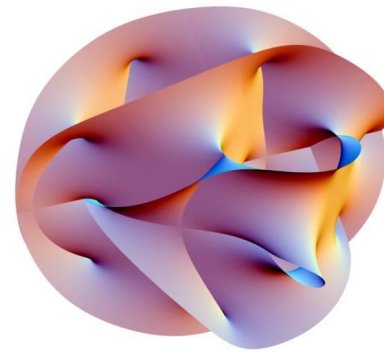
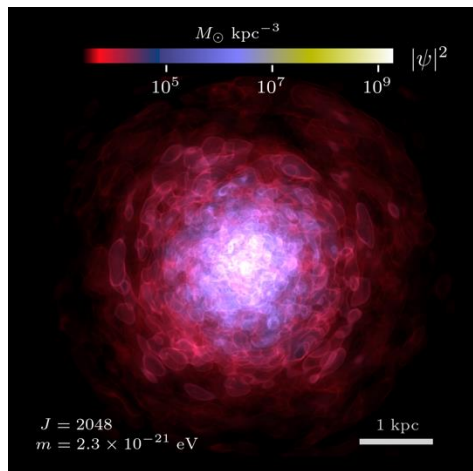


The QCD axion will be found

Different experiments probe very different regions of the string landscape.



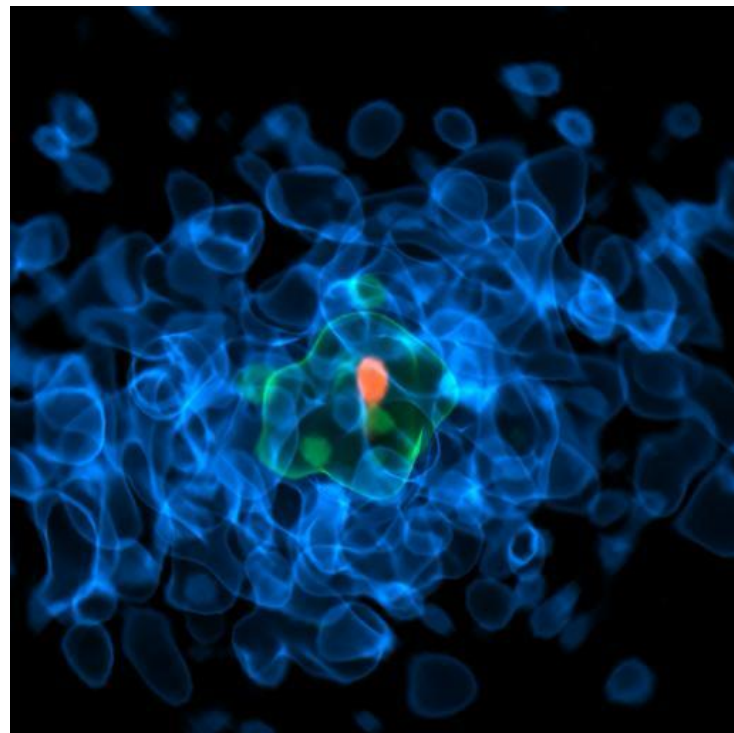
Summary

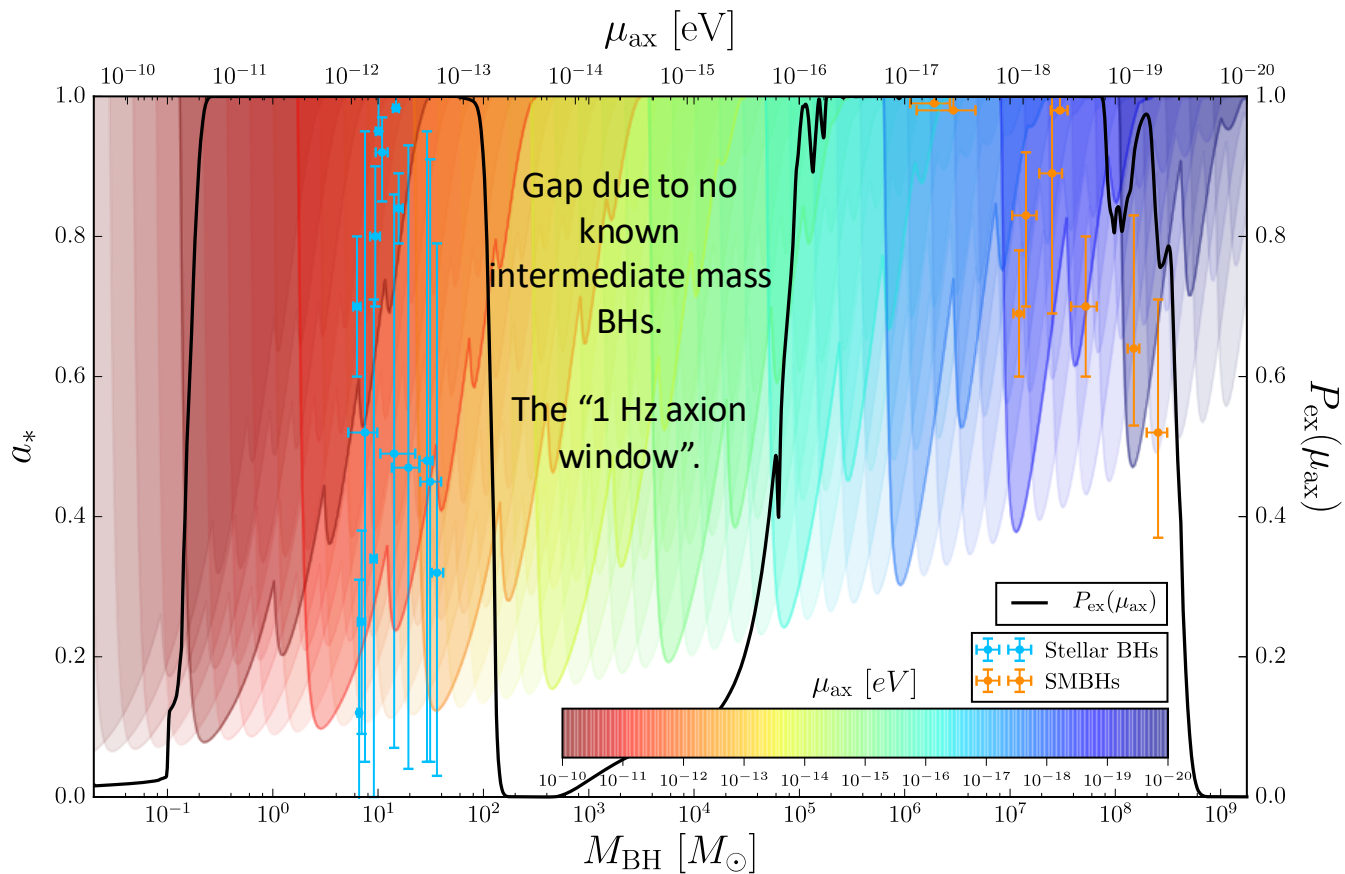


Tour of Constraints

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)





Stott & DJEM (2018)

FREEZE-IN AXIONS



Decays

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

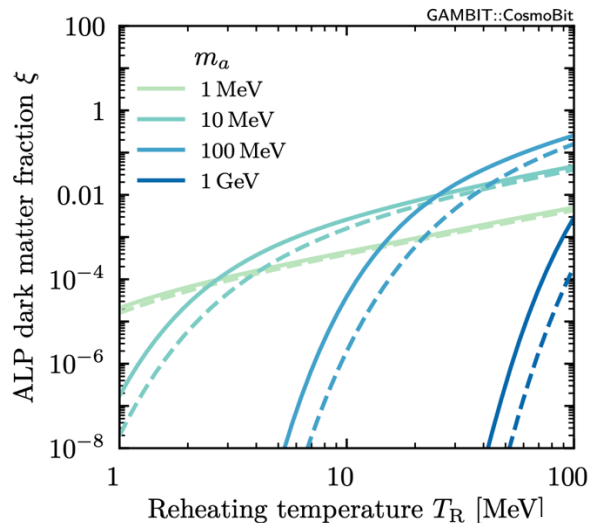
Csaba Balázs,^a Sanjay Bloor,^b Tomás E. Gonzalo,^{c,d}
Will Handley,^{e,f} Sebastian Hoof,^{d,g} Felix Kahlhoefer,^{c,d}
Marie Lecroq,^{a,h} David J.E. Marsh,ⁱ Janina J. Renk,^{b,j,k}
Pat Scott^{b,k} and Patrick Stöcker^{c,l}



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

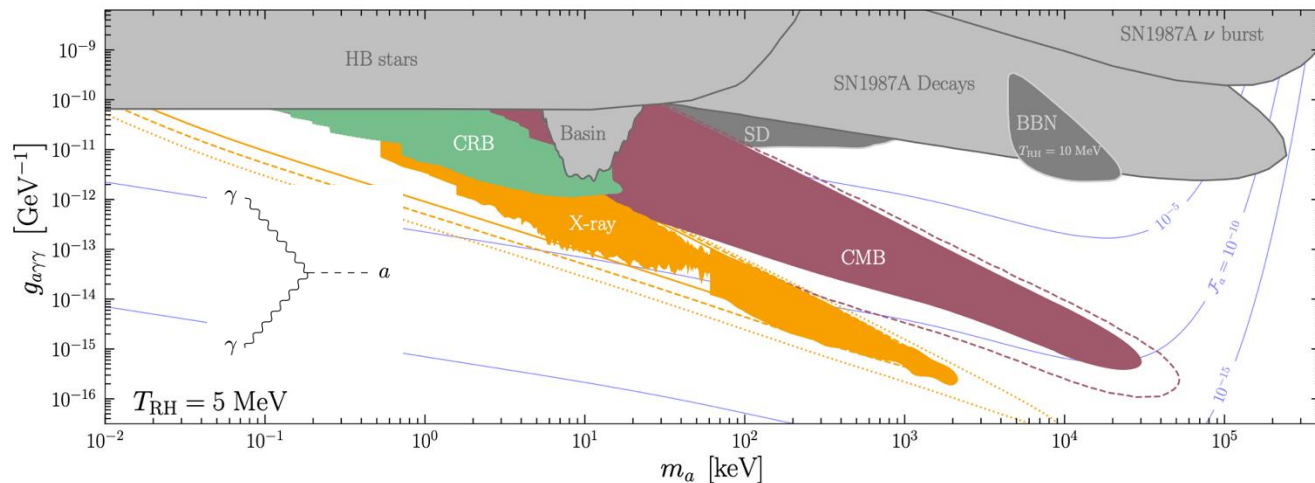
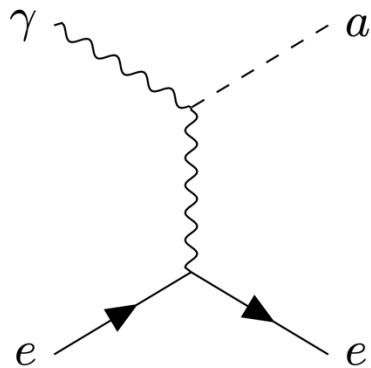
Irreducible Axion Background

Kevin Langhoff,^{1,2} Nadav Joseph Outmezguine^{1,2} and Nicholas L. Rodd³



- Primakoff process produces axions from $\gamma + e^-$ with zero initial state $\rightarrow$ **freeze-in axions**.
- Minimal contribution reheating to BBN, $T_R = 5$ MeV.
- keV -GeV axions subsequently **decay** $\rightarrow$ limits for DM fractions as low as 10^{-10} and $\tau > 10^{10}$ yrs!

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

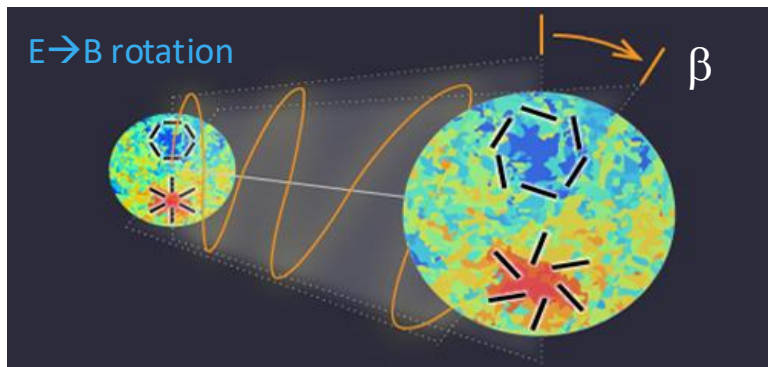


COSMIC BIREFRINGENCE



CMB
Polarization

Birefringence



E, B are CMB polarization states (Stokes)

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

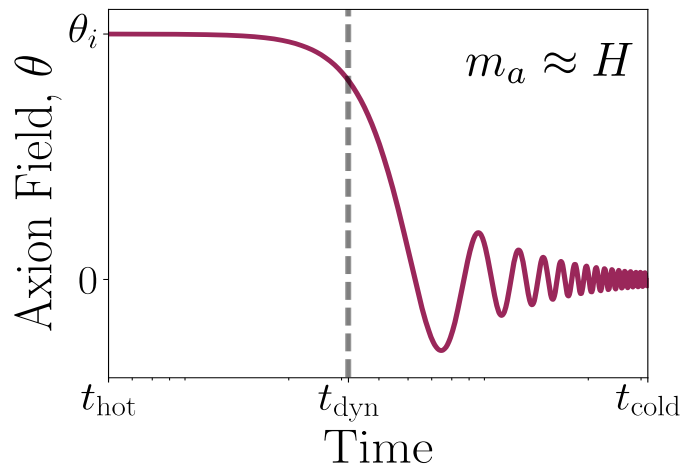
Minami & Komatsu (2020)

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:

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



Fixes axion mass:

$$H_0 \cdot 10^{-33} \text{ eV} \lesssim m \lesssim 10^{-28} \text{ eV} \cdot H_{\text{CMB}}$$

$$g = \frac{\alpha}{2\pi f_a}, \quad \phi = \theta f_a \Rightarrow \beta = 10^{-3} \theta$$

GLIMMERS FROM THE AXIVERSE

Gendler, Marsh, McAllister, Moritz arXiv:2309.13145

Jakob told you all about this a few weeks back...



Axion-Photon Couplings

Recipe:

1. Choose a CY. We take 2×10^5 at $h_{11}=50, 100, 200, 491$.
2. Choose a divisor to host QCD.
3. Dilate divisor to $\text{Vol}=40 \rightarrow$ QCD gauge coupling in UV.
4. Pick a divisor for QED. Same $\rightarrow$ GUT. Intersecting $\rightarrow$ non-GUT.
5. QED divisor $\rightarrow$ linear combination of axions coupling to EM.
6. Diagonalise matrices and compute couplings of eigenstates.

Consequences:

“Kinetic isolation”: K matrices are sparse $\rightarrow$ suppressed kinetic mixing of all axions into EM linear comb.

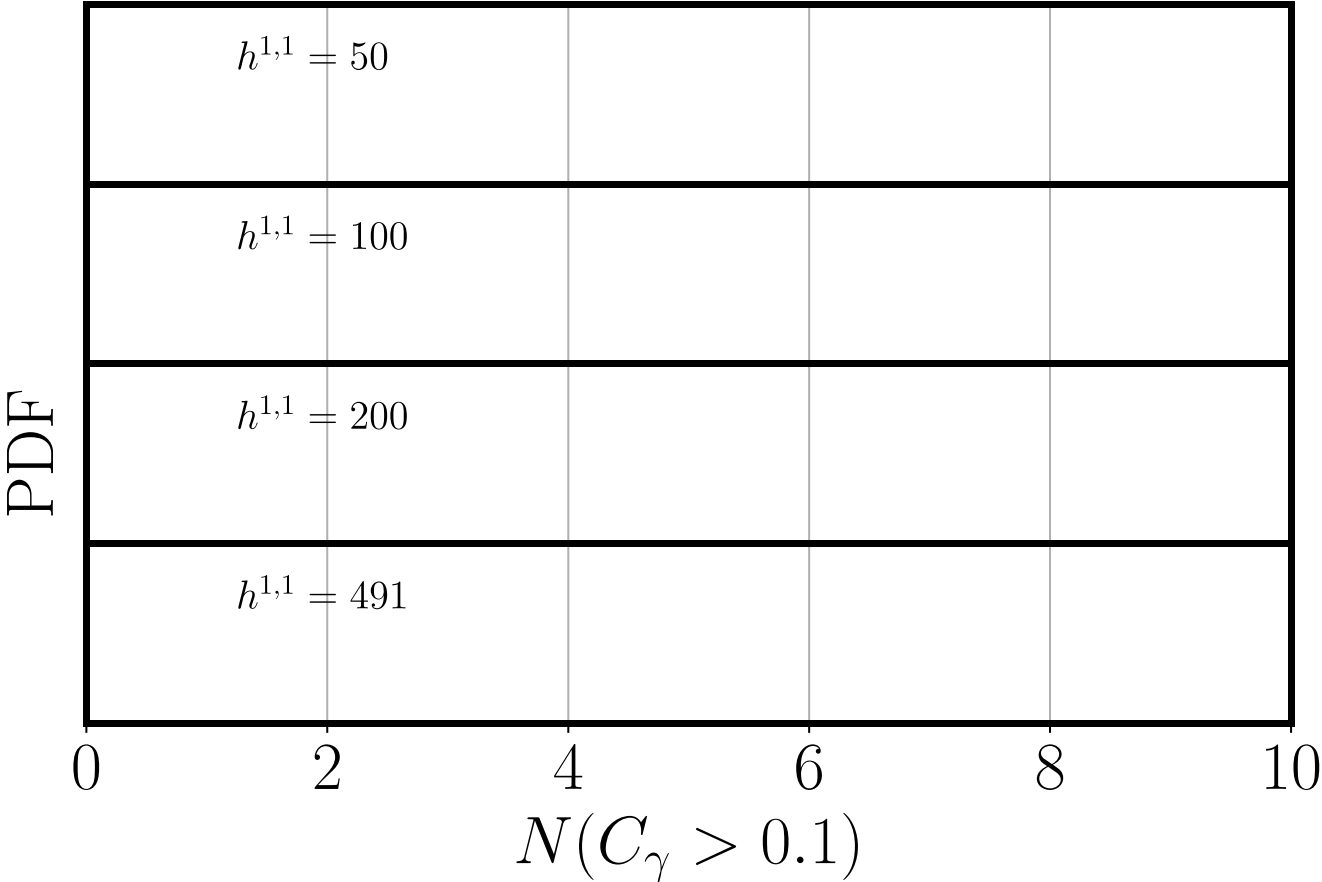
“Light threshold”: mass scale generated by ED3 branes on divisor $\rightarrow$ hierarchically suppressed coupling of axions lighter than this.

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

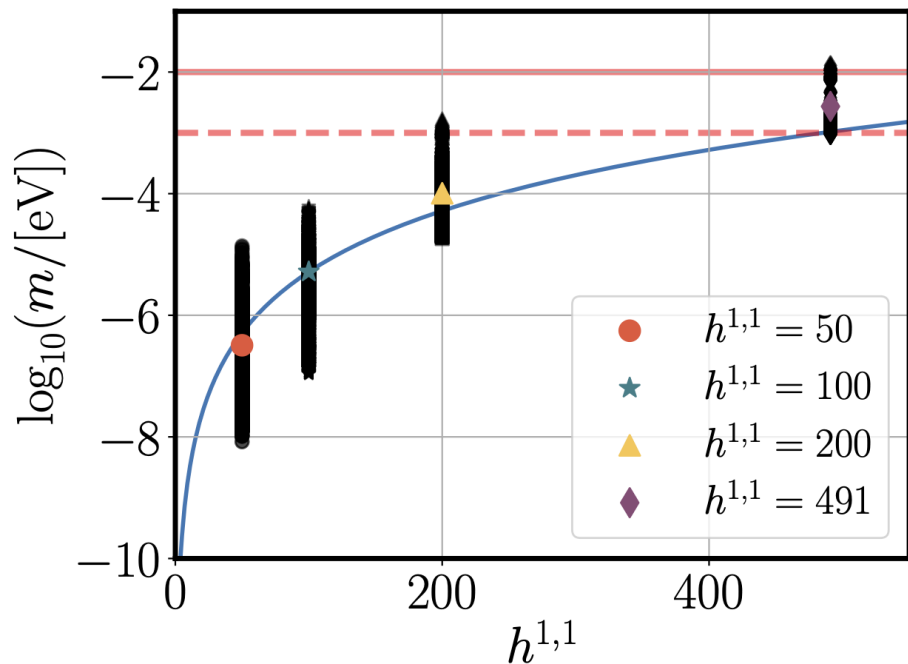
Stringy effects! Need CY to get K matrix. No “U(1) instantons” in field theory.

Number of axions with $O(1)$ coupling to photons is small.

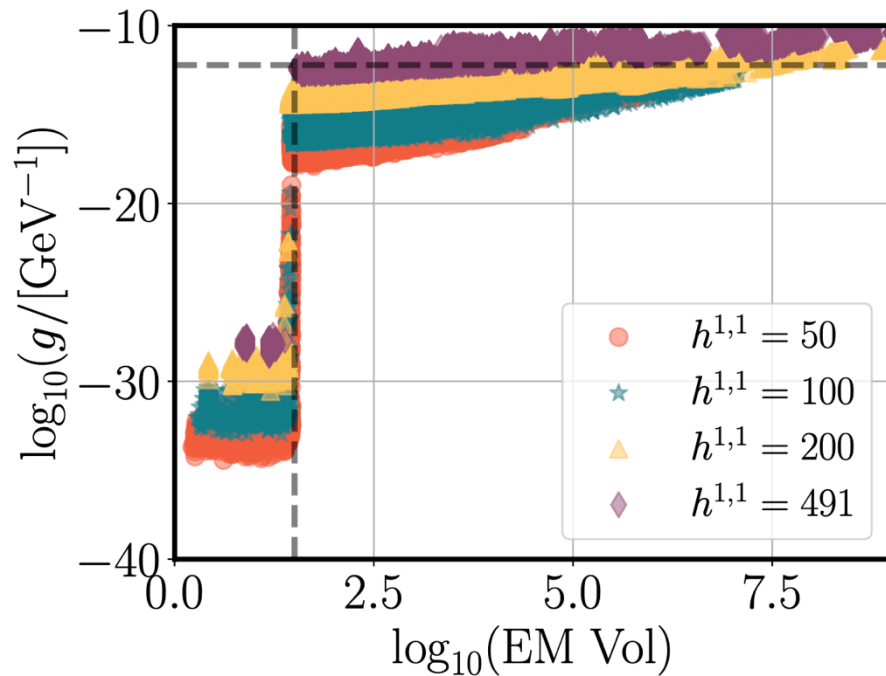
$$g = C_\gamma \frac{\alpha}{2\pi f_a}$$



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



Light threshold at $\text{Vol} \sim 30 \rightarrow$ X-ray spectra probe non-GUTs. May exclude some models with large $h^{1,1}$



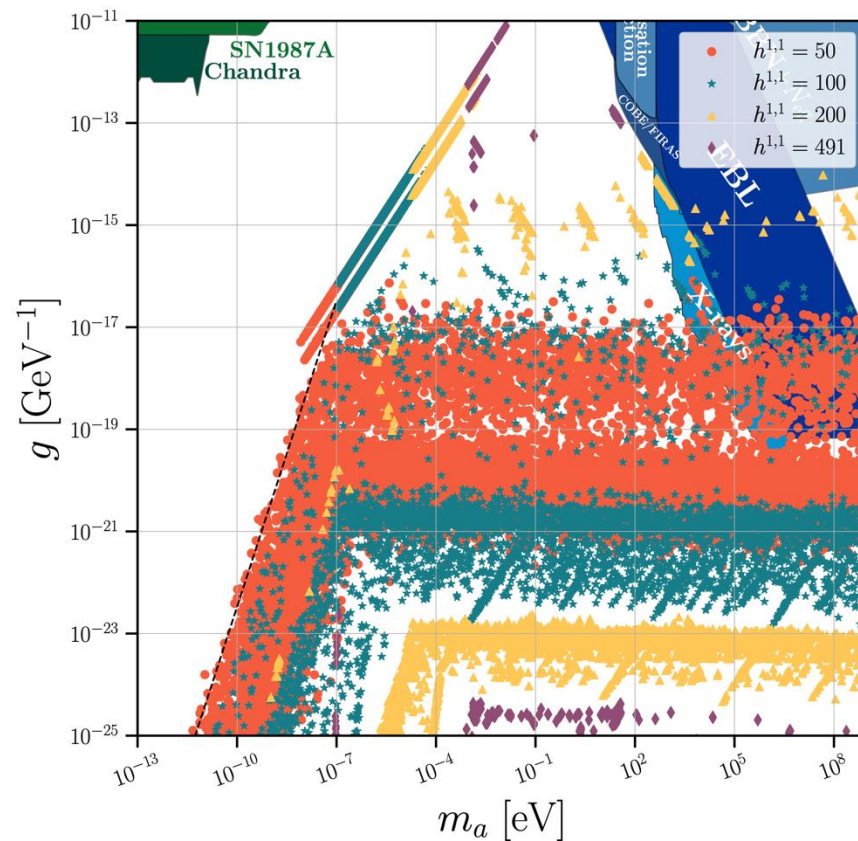
GUTs vs non-GUTs

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

→ The QCD induced mass is bigger than the ED3 one to solve strong CP.

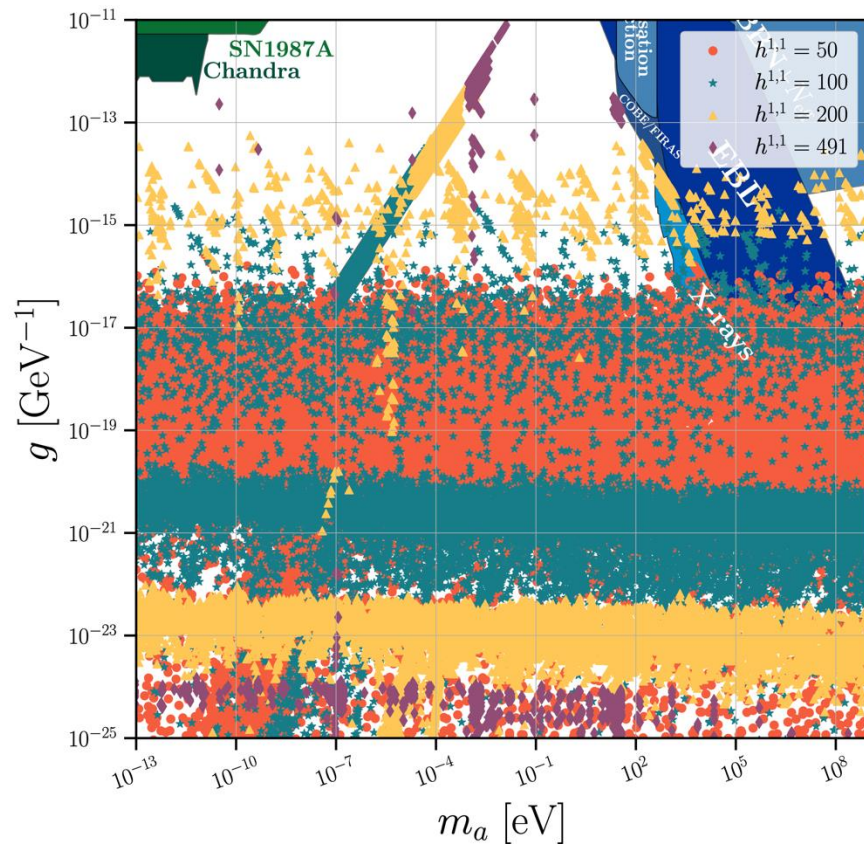
→ QCD axion provides the light threshold.

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

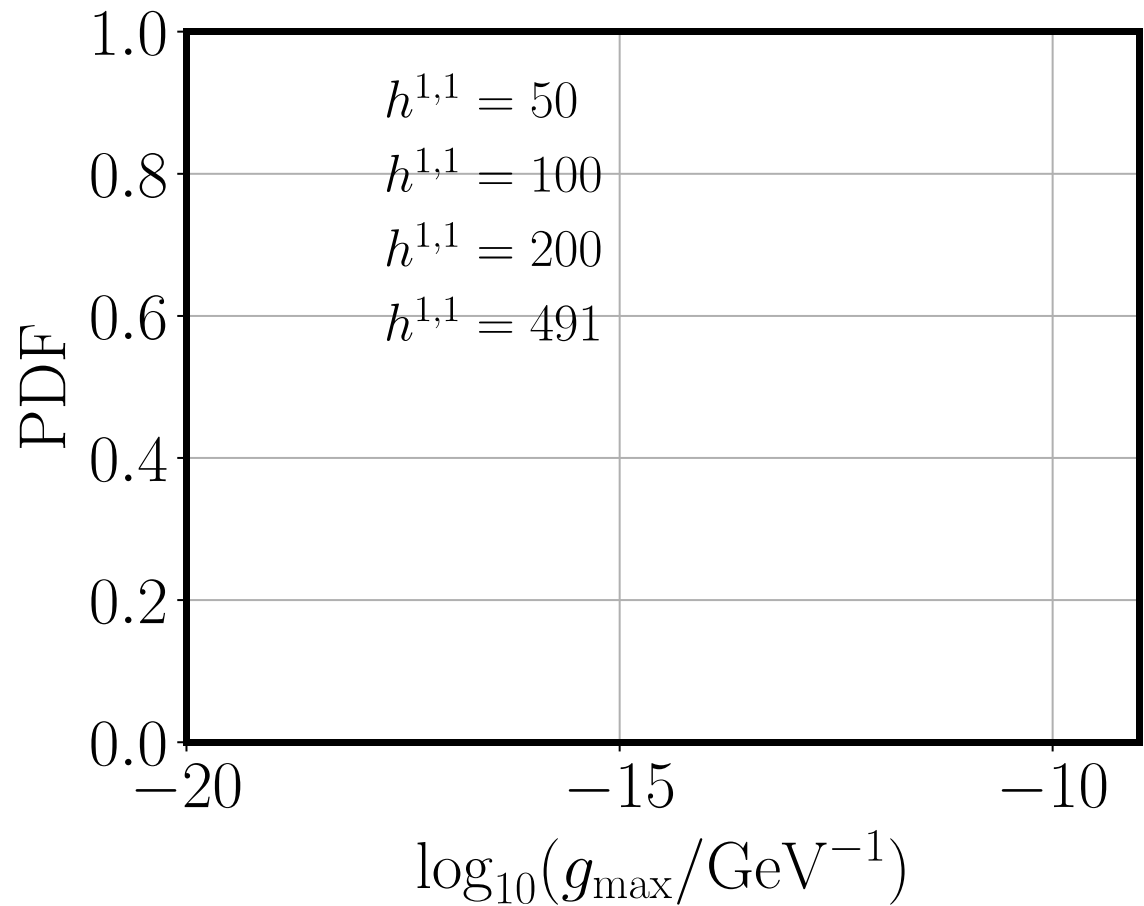


GUTs vs non-GUTs

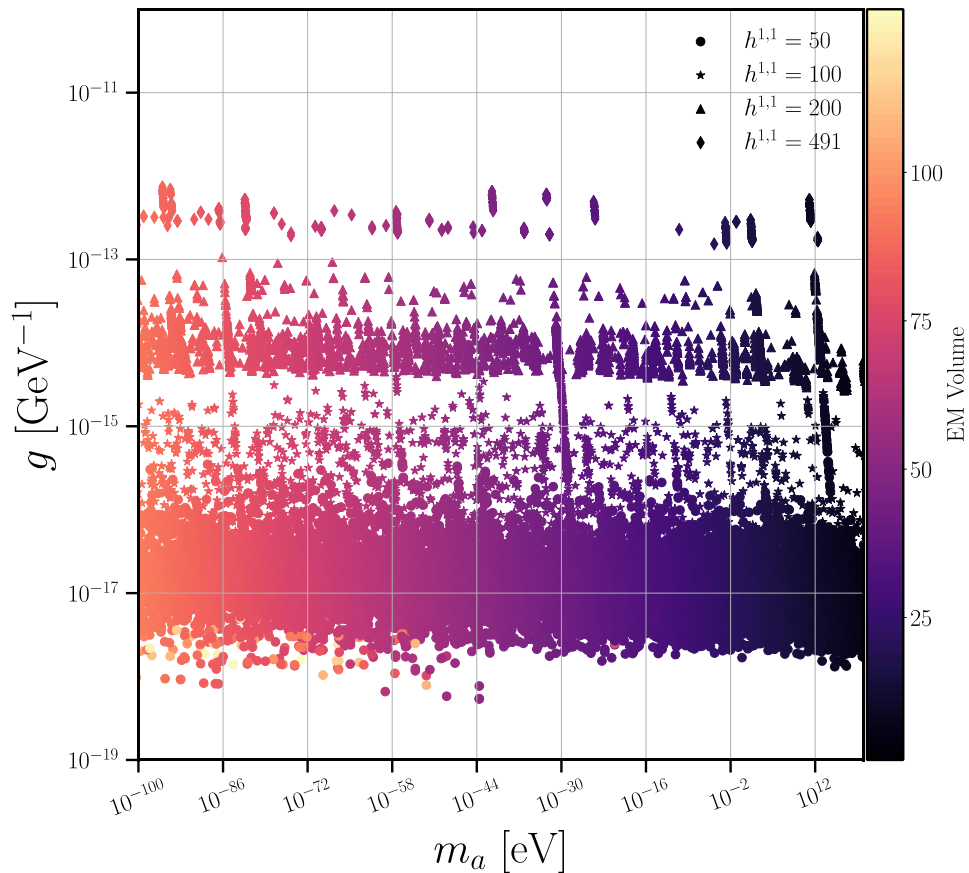
Non-GUTs: (almost) anything goes.



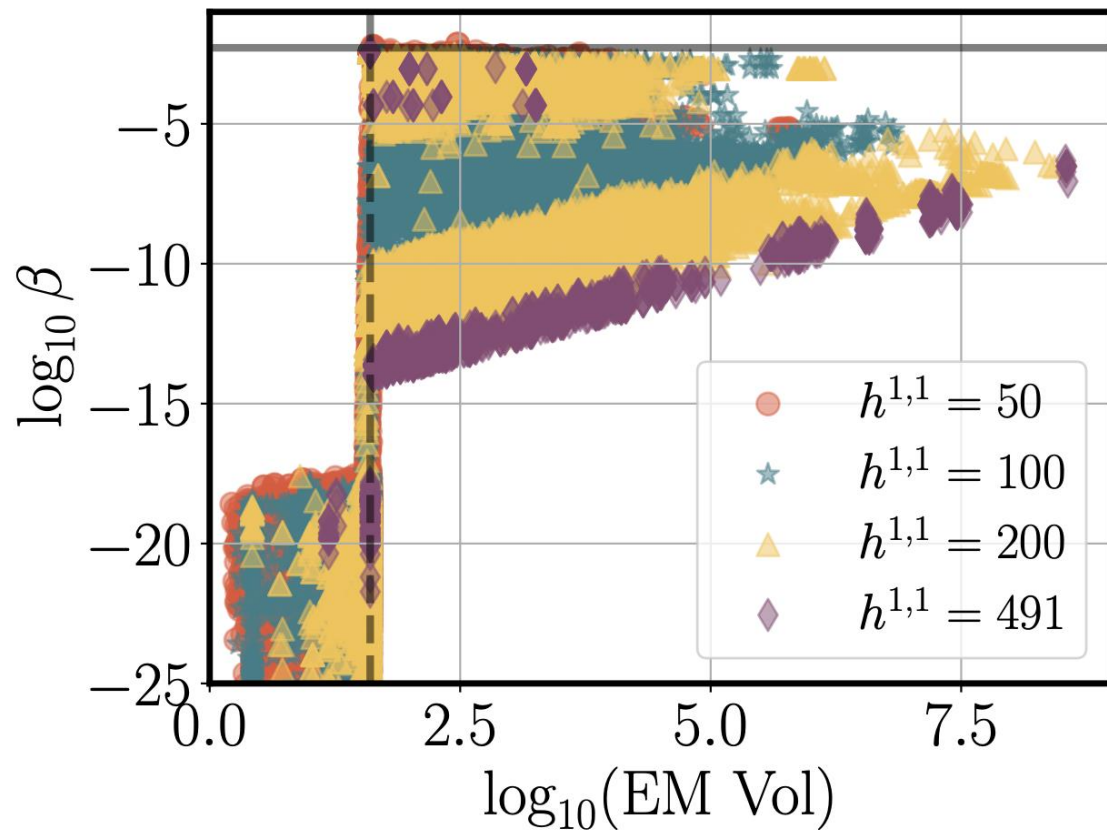
The maximum value of g increases with h_{11} due to increasing cycle volumes.



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



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



keV – GeV axions Primakoff freeze-in then decay. Disfavours reheating $T > 10^{10}$ GeV $\rightarrow$ upper limit on SUSY scale from dim-5 decays of moduli?

$$h^{1,1} = 50$$

