COSMOLOGICAL CONSTRAINTS ON THE KS AXIVERSE

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WITH DEMIRTAS, LONG, MARSH, McALLISTER, STOTT
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TAKE HOME MESSAGE: BLACK HOLES MAY CONSTRAIN STRING GEOMETRIES
OVERVIEW

CONTENTS

- Kreuzer-Skarke Axiverse
- Black Hole SuperRadiance (BHSR)
- Constraints
like hidden sectors with low confinement scales. This both opens up interesting phenomenology associated to the presence of this “dark world” and raises the question of how it managed to escape being observed so far. We will touch on some of the issues involved in the concluding Section 3.

For now we focus upon the observational signatures of the light axions that we have argued are generic to string theory once the strong CP problem is solved.

2 Cohomologies from Cosmology

CMB Polarization

Matter Power Spectrum

Anthropically Constrained

Black Hole Super-radiance

Decays

Inflated Away

Axion Mass in eV

$10^{-33}$

$4 \times 10^{-28}$

$3 \times 10^{-18}$

$2 \times 10^{-20}$

$3 \times 10^{-10}$

QCD axion

$10^8$
KREUZER-SKARKE AXIVERSE
pseudoscalar fields arise as zero KK modes of antisymmetric tensor fields

e.g. in Type IIB, $C_0, C_2, C_4$ all present

their numbers can be determined topologically

i.e. number of 4-cycles $\sim$ number of KK zero modes from $C_4 \sim h^{1,1}$

number of cycles in $M_6$ may be $O(10^5)$

masses of axions $\propto \exp(-\text{volumes of cycles})$
Stretched Kähler cone
Type IIB compactified on a CY3, $X$

Geometric data

\[ \theta_i := \int_{D_i} C_4 \]

\[ \tau_i := \frac{1}{2} \int_{D_i} J \wedge J \implies T_i := \tau_i + i \theta_i \]

\[ \mathcal{V} = \frac{1}{6} \int_X J \wedge J \wedge J \implies \mathcal{K} = -2 \log \mathcal{V} \implies K_{ij} = \partial_i \partial_j \mathcal{K} \]
$\mathcal{L} = \frac{M_P^2}{2} K_{ij} \partial^\mu \theta^i \partial_\mu \theta^j - \sum_{a=1}^{P} \Lambda_a \cos Q_a^i \theta_i$

Sample $\tau_i, \nu$

Prime effective divisors

$\sim e^{-2\pi \tau_i}$
**PENROSE PROCESS**

- spinning BHs (Kerr) drag matter in *ergoregion* to corotate with BH

- $\partial_t$ Killing vector becomes spacelike

- instability efficiency determined by:
  - $M_{\text{BH}}$
  - $m_a$

- superradiance only when:
  $$0 < \omega_a \lesssim \omega_+$$
BLACKHOLE SUPERRADIANCE

BHSR EXCLUSIONS

\[ P_{\text{ex}}^{\text{GRO J1655-40}} = 0.000000 \quad P_{\text{ex}}^{\text{LMC X-1}} = 0.000000 \quad P_{\text{ex}}^{\text{LMC X-3}} = 0.000000 \quad P_{\text{ex}}^{\text{M33 X-7}} = 0.000000 \quad P_{\text{ex}}^{\text{Total}} = 0.000000 \]
X-ray binary sources and active galactic nuclei (AGN) have seen a steady increase over the past decades with a number of developments in string/M theory. The most promising realisation for axions associated to GUT and supersymmetric models has been through observations of black hole (BH) spin measurements in BHs covering the approximate region defined by IMBH candidates. Well defined mass and spin function that corresponds to the absence of any well-defined value across the total BH mass range. The exclusion function formulated from the statistical model in Appendix B using the BHs compiled in Table I and is given as a function of the axion mass spanning both the stellar and supermassive regimes. Appendix B using the BHs compiled in Table I and is given as a function of the axion mass spanning both the stellar and supermassive regimes.

FIG. 6: Isocontour exclusion bounds with calculated total exclusion probabilities in the BH mass-spin Regge plane. The exclusion probability function (black line) is calculated using the statistical model in Table I. The blue/orange points correspond to mass/spin estimates of SMBHs from X-ray observations made in several BBH mergers by LIGO [68–70]. For primary and secondary black holes, the black hole spin data has recently been collected via the X-ray methods. The primary black hole's spin is measured via the analysis of the X-ray spectrum of the accretion disk or inner disk reflection model. In systems where the inner accretion disk or inner disk reflection model is not applicable, then estimates on the spin of BHs can be made. In systems where both the mass and spin of the BHs when compared to observations made in several BBH mergers by LIGO [68–70] are available, secondary black holes could fill the currently inaccessible portion of the BH mass-spin Regge plane.
CONSTRAINTS ON THE KS AXIVERSE
\[ \mathcal{L} = -\frac{1}{2} \partial_\mu \phi_i \partial^\mu \phi_j - \frac{1}{2} \phi_i \mathcal{M}_{ij} \phi_j - \frac{1}{4!} \mathcal{V}_{ijkl} \phi_i \phi_j \phi_k \phi_l \]
PERIODICITIES

CONSTRANTS
MULTIAXION POTENTIALS — PATH TO CONSTRAINTS

\[
\mathcal{L} = -\frac{1}{2} \partial_\mu \phi_i \partial^\mu \phi_j - \frac{1}{2} \phi_i M_{ij} \phi_j - \frac{1}{4!} \lambda_{ijkl} \phi_i \phi_j \phi_k \phi_l
\]

- **KS axiverse data:**
  - disparate scales in potentials – volume hierarchies
  - flat directions – extremely light axions
  - decreasing decay constants with more ALPs
  - potentials have many cosine terms – \( P \gg N \)

- some CPU hours later...
MASS SPECTRA — MASSLESS ALPS

CONSTRANTS

Float-16 Precision
Hubble Scale
CONSTRANTS

KS AXIVERSE POTENTIALS — BHSR EXCLUSIONS

Supermassive BHs

Stellar mass BHs

Exclusions:
- 68% CL
- 95% CL
- 99.7% CL

\( f_a = M_{Pl} \)
CONSTRAINTS

KS AXIVERSE POTENTIALS — BHSR EXCLUSIONS

Supermassive BHs

Stellar mass BHs

Combined

Fraction of $CY_{3s}$

$h^{1.1}$

Exclusions:
- 68% CL
- 95% CL
- 99.7% CL
CONCLUSIONS

CONSTRaining the KS Axiverse with BHSR

- Generate multiaxion potentials from string data
- Compute masses and quartics
- Use BHSR bounds to exclude classes of geometries
- Q: Can the string axiverse be constrained with BHSR?
  A: Yes!*  

*up to assumed structure of string data
NEXT STEPS

CONSTRAINING THE KS AXIVERSE

- Consider larger geometries – current optimised code could handle up to $h^{1,1} = 100$ (?)
- Venture into the Kähler cone?
- Other physical constraints – pure gravity / massless fields – need to be model independent
- Use ML to generate distributions of masses and decay constants – use lower $h^{1,1}$ data as training set
THANKS!
VENTURING INTO THE KAELHLE CONE
VENTURING INTO THE KAEGHLER CONE
$V_{min} = 0$

$V_{min} < 0$
<table>
<thead>
<tr>
<th>Object</th>
<th>Method</th>
<th>Mass (M(_{\odot}))</th>
<th>Spin (a(_{\ast}))</th>
<th>Mass CL</th>
<th>Spin CL</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stellar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW150914 (Primary)</td>
<td>EOBNR+IMRPhenom</td>
<td>36.2(+5.2)(-3.5)</td>
<td>0.32(+0.47)(-0.29)</td>
<td>90%</td>
<td>90%</td>
<td>68</td>
</tr>
<tr>
<td>GW150914 (Secondary)</td>
<td>EOBNR+IMRPhenom</td>
<td>29.1(+4.4)(-3.5)</td>
<td>0.48(+0.43)(-0.37)</td>
<td>90%</td>
<td>90%</td>
<td>68</td>
</tr>
<tr>
<td>GW151226 (Primary)</td>
<td>EOBNR+IMRPhenom</td>
<td>14.2(+8.3)(-3.7)</td>
<td>0.49(+0.42)(-0.26)</td>
<td>90%</td>
<td>90%</td>
<td>68</td>
</tr>
<tr>
<td>GW151226 (Secondary)</td>
<td>EOBNR+IMRPhenom</td>
<td>7.5(+2.3)(-2.3)</td>
<td>0.52(+0.43)(-0.47)</td>
<td>90%</td>
<td>90%</td>
<td>68</td>
</tr>
<tr>
<td>GW170104 (Primary)</td>
<td>Eff+Full precession</td>
<td>31.2(+8.4)(-6.0)</td>
<td>0.45(+0.46)(-0.40)</td>
<td>90%</td>
<td>90%</td>
<td>78</td>
</tr>
<tr>
<td>GW170104 (Secondary)</td>
<td>Eff+Full precession</td>
<td>19.4(+5.3)(-5.9)</td>
<td>0.47(+0.46)(-0.43)</td>
<td>90%</td>
<td>90%</td>
<td>78</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>Continuum (KERRBB2)</td>
<td>14.8(+1.0)(-1.0)</td>
<td>(\geq 0.983)</td>
<td>1(\sigma)</td>
<td>3(\sigma)</td>
<td>79/80</td>
</tr>
<tr>
<td>XTE J1550-564</td>
<td>Continuum (KERRBB2)</td>
<td>9.10(+0.61)(-0.61)</td>
<td>0.34(+0.37)(-0.34)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>81/82</td>
</tr>
<tr>
<td>A 0620-00</td>
<td>Continuum (KERRBB2)</td>
<td>6.61(+0.25)(-0.25)</td>
<td>0.12(+0.19)(-0.19)</td>
<td>1(\sigma)</td>
<td>1(\sigma)</td>
<td>83/84</td>
</tr>
<tr>
<td>4U 1543-475</td>
<td>Continuum (KERRBB)</td>
<td>9.4(+1.0)(-1.0)</td>
<td>0.8(+0.1)(-0.1)</td>
<td>1(\sigma)</td>
<td>1(\sigma)</td>
<td>85/86</td>
</tr>
<tr>
<td>GRO J1655-40</td>
<td>Continuum (KERRBB)</td>
<td>6.30(+0.50)(-0.50)</td>
<td>0.7(+0.10)(-0.10)</td>
<td>95%</td>
<td>1(\sigma)</td>
<td>87/88</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>Continuum (KERRBB2)</td>
<td>10.1(+0.6)(-0.6)</td>
<td>(\geq 0.95)</td>
<td>1(\sigma)</td>
<td>1(\sigma)</td>
<td>89/90</td>
</tr>
<tr>
<td>LMC X-1</td>
<td>Continuum (KERRBB2)</td>
<td>10.91(+1.41)(-1.41)</td>
<td>0.92(+0.05)(-0.07)</td>
<td>1(\sigma)</td>
<td>1(\sigma)</td>
<td>91/92</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>Continuum (KERRBB2)</td>
<td>6.98(+0.56)(-0.56)</td>
<td>0.25(+0.13)(-0.16)</td>
<td>1(\sigma)</td>
<td>1(\sigma)</td>
<td>93/94</td>
</tr>
<tr>
<td>M33 X-7</td>
<td>Continuum (KERRBB2)</td>
<td>15.65(+1.45)(-1.45)</td>
<td>0.84(+0.05)(-0.05)</td>
<td>1(\sigma)</td>
<td>1(\sigma)</td>
<td>95/96</td>
</tr>
<tr>
<td><strong>Supermassive</strong></td>
<td></td>
<td>(\times 10^6 [M(_{\odot})])</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mrk 335</td>
<td>Reflection (Suzaku)</td>
<td>14.20(+5.70)(-3.70)</td>
<td>0.83(+0.09)(-0.13)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/98</td>
</tr>
<tr>
<td>Fairall 9</td>
<td>Reflection (Suzaku)</td>
<td>255.0(+56.0)(-56.0)</td>
<td>0.52(+0.19)(-0.15)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/99</td>
</tr>
<tr>
<td>Mrk 79</td>
<td>Reflection (Suzaku)</td>
<td>52.40(+14.40)(-14.40)</td>
<td>0.70(+0.1)(-0.1)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/100</td>
</tr>
<tr>
<td>NGC 3783</td>
<td>Reflection (Suzaku)</td>
<td>29.80(+5.40)(-5.40)</td>
<td>(\geq 0.98)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/101</td>
</tr>
<tr>
<td>MCG-6-30-15</td>
<td>Reflection (Suzaku)</td>
<td>2.90(+1.80)(-1.60)</td>
<td>(\geq 0.98)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>102/103</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>Reflection (Suzaku)</td>
<td>12.20(+1.40)(-1.40)</td>
<td>0.69(+0.09)(-0.09)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/104</td>
</tr>
<tr>
<td>Ark 120</td>
<td>Reflection (Suzaku)</td>
<td>150.0(+19.0)(-19.0)</td>
<td>0.64(+0.19)(-0.19)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/98</td>
</tr>
<tr>
<td>Mrk 110</td>
<td>Reflection (Suzaku)</td>
<td>25.10(+6.10)(-6.10)</td>
<td>(\geq 0.89)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/98</td>
</tr>
<tr>
<td>NGC 4051</td>
<td>Reflection (Suzaku)</td>
<td>1.91(+0.78)(-0.78)</td>
<td>(\geq 0.99)</td>
<td>1(\sigma)</td>
<td>90%</td>
<td>97/105</td>
</tr>
</tbody>
</table>
**KREUZER-SKARKE AXIVERSE**

**CHANGING BASIS**

\[
\mathcal{L} = -\frac{M_P^2}{2} K_{ij} \partial_\mu \theta^i \partial^\mu \theta^j - \sum_{a=1}^{P} \Lambda_a \cos Q^i_a \theta_i
\]

Canonical basis:
\[
\tilde{\phi} = M_{P_1} \text{diag} \left( \vec{f}_a \right) \mathbf{U} \theta
\]

\[
\mathbf{U} = \text{eigenvector} (\mathbf{K}) \quad \vec{f}_a = \sqrt{\text{eigenvalue}(\mathbf{K})}
\]

Mass eigenbasis:
\[
\phi = M_{P_1} \mathbf{V} \text{diag} \left( \vec{f}_a \right) \mathbf{U} \theta
\]

\[
\mathbf{V} = \text{eigenvector} (\tilde{\mathbf{M}})
\]

\[
\mathcal{L} = -\frac{1}{2} \partial_\mu \phi_i \partial^\mu \phi_j - \frac{1}{2} \phi_i \mathbf{M}_{ij} \phi_j - \frac{1}{4!} \lambda_{ijkl} \phi_i \phi_j \phi_k \phi_l
\]
\[
W = W_0 + \sum_{\alpha} A_{\alpha} \exp \left( -2\pi q^i_{\alpha} T_i \right)
\]

\(W_0 \equiv 1\)

\(A_{\alpha} (\text{CS moduli}) \equiv 1\)

Divisor volume
\[ V = -\frac{8\pi}{\nu^2} \left[ \sum_{\alpha} q_{\alpha}^i \tau_i e^{-2\pi q_{\alpha}^i \tau_i} \cos (2\pi q_{\alpha}^i \theta_i) \right. \]

\[ + \sum_{\alpha > \alpha'} \left( \pi (K^{-1})_{ij} q_{\alpha}^i q_{\alpha'}^j + (q_{\alpha}^i + q_{\alpha'}^i) \tau_i \right) \]

\[ \times e^{-2\pi \tau_i (q_{\alpha}^i + q_{\alpha'}^i)} \cos \left( 2\pi \theta_i (q_{\alpha}^i - q_{\alpha'}^i) \right) \]