THE SPECTRUM OF THE STRING AXIVERSE

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OVERVIEW

- Spectrum of the Axion Dark Sector

  Matthew J. Stott, David J.E. Marsh, Chakrit Pongkitivanichkul, Layne C. Price and Bobby S. Acharya

  *a*rXiv : *1706.03236*

- Black Hole Spin Constraints on the Mass Spectrum and Number of Axion-like Fields

  Matthew J. Stott and David J.E. Marsh

  *a*rXiv : *1805.02016*

AXIONS

Single
&
Multiple Fields

SINGLE

$$\mathcal{L} = -\frac{f_a^2}{2}\partial_\mu\theta\partial^\mu\theta - \mu^4 e^{-S}\left(1-\cos\theta\right)$$

$$\phi = f_a\theta \qquad m_a = \frac{\Lambda_a^2}{f_a} \qquad f_a \sim \frac{M_{pl}}{S}$$

MULTIPLE

$$\mathcal{L} = -\sum_{i,j=1}^{N_{\rm ax}} \mathcal{K}_{ij}\partial_\mu\theta_i\partial^\mu\theta_j - \sum_{\alpha=1}^{n_{\rm inst}}\sum_{j=1}^{N_{\rm ax}} \Lambda_\alpha U_\alpha(\mathcal{Q}_{j,\alpha}\theta_j + \delta_\alpha)$$

TREATMENT OF MIXED KINETIC TERMS AND GENERAL POTENTIAL

CANONICAL BASIS : $\mathcal{L} = -\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}\mathrm{diag}(\mu_{\rm ax}^2)\phi_i\phi_i$

EFFECTIVE MODEL I

Alignment & Sampling

KINETIC ALIGNMENT

[Bachlechner et al. (2014)]

$$\mathcal{L} = -\mathcal{K}_{ij}\partial_\mu\theta_i\partial^\mu\theta_j - \mathcal{M}_{ij}\theta_i\theta_j$$

LATTICE BASIS

$$\mathcal{K}_{ij} = U^T_{ik}\mathrm{diag}(\mathcal{K}_{kl})U_{lj} = \frac{1}{2}U^T\mathrm{diag}(f_a)\mathrm{diag}(f_a)U$$

$$\vec{f}_a = \sqrt{2\mathrm{eig}(\mathcal{K}_{ij})}$$

$$\tilde{\phi}_i = M_{pl}\mathrm{diag}(f_a)U_{ij}\theta_j$$

N-FLATION ALIGNMENT

[Easter & McAllister (2006)]

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\tilde{\phi}_i\partial^\mu\tilde{\phi}_j - \frac{1}{2}\tilde{\phi}_i\tilde{\mathcal{M}}_{ij}\tilde{\phi}_j$$

KINETIC BASIS

$$\tilde{\mathcal{M}} = 2\mathrm{diag}(1/f_a)U\mathcal{M}U^T\mathrm{diag}(1/f_a)$$

$$\tilde{\mathcal{M}} = V^T\mathrm{diag}(m_a^2)V \quad \phi = V\tilde{\phi} = M_{pl}V\mathrm{diag}(f_a)U\theta$$

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_j - \frac{1}{2}\phi_i\mathcal{M}_{ij}\phi_j$$

$$\vec{m}_a = \sqrt{eig(\mathcal{M}_{ij})}$$

RANDOM MATRIX THEORY

- *Initial Basis*

  Lattice/Kinetic?

- *Statistical Sampling*

  $\mathcal{N}(0,1)$

- *Matrix Shape*

  $\beta_{\mathcal{M}} \in (0,1]$

$$\mathcal{M}_{ij} \qquad \mathcal{K}_{ij}$$

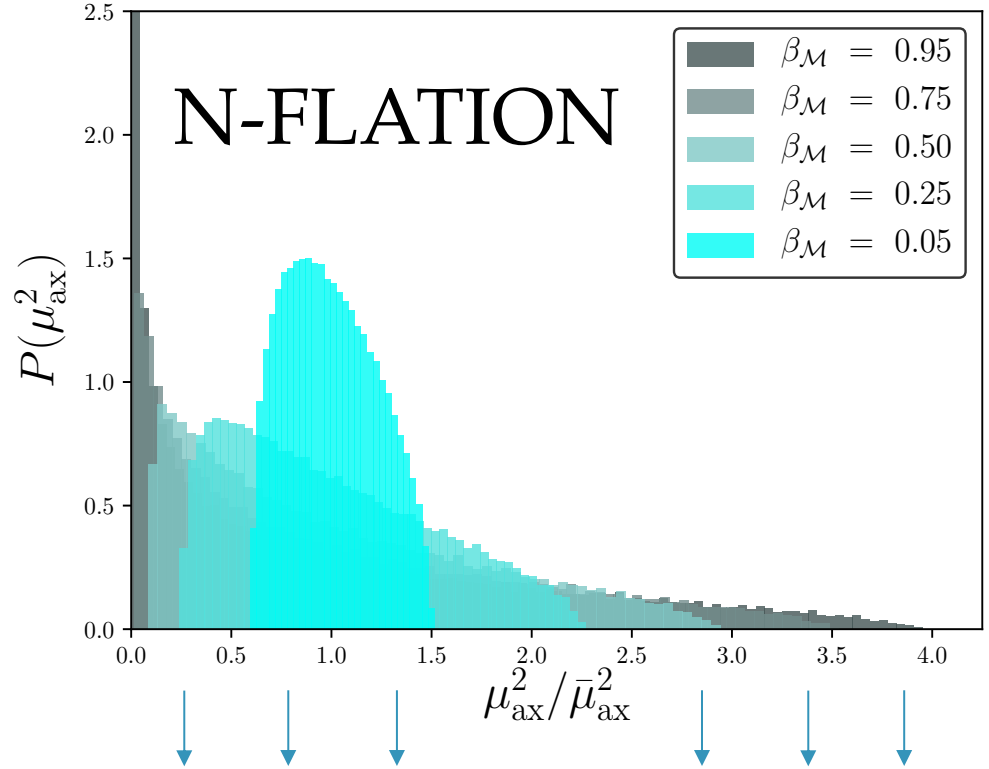
$$X_{ij} = \frac{1}{N} Y^T_{ik} Y_{kj}$$

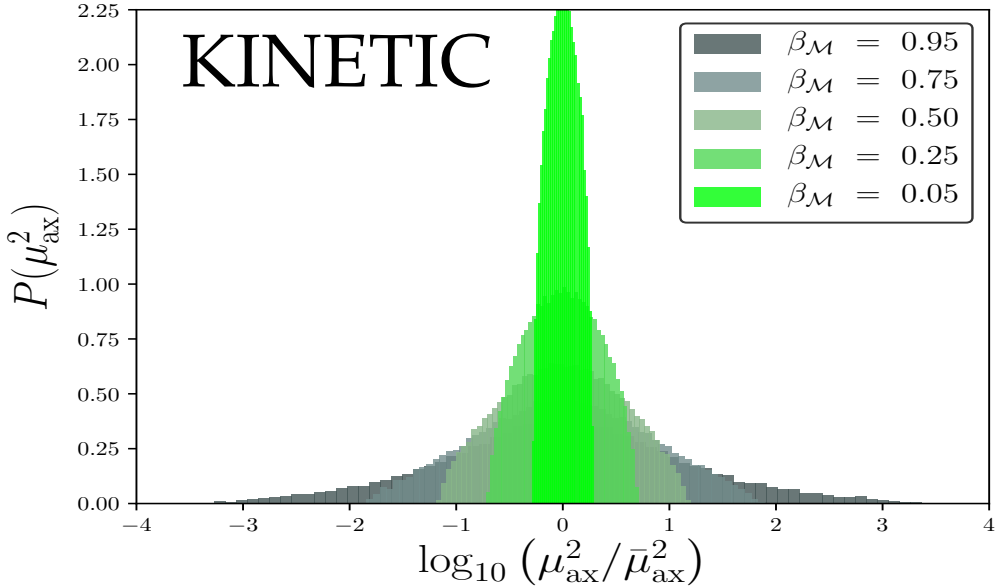
$$\in \mathbb{R}^{N \times P}$$

$$\beta_{\mathcal{M}} = \frac{N_{\text{ax}}}{P}$$

$$\beta_{\mathcal{M}} = \frac{h_{1,1}}{h_{1,1} + h_{1,2} + 1}$$

[Easter & McAllister (2006)]

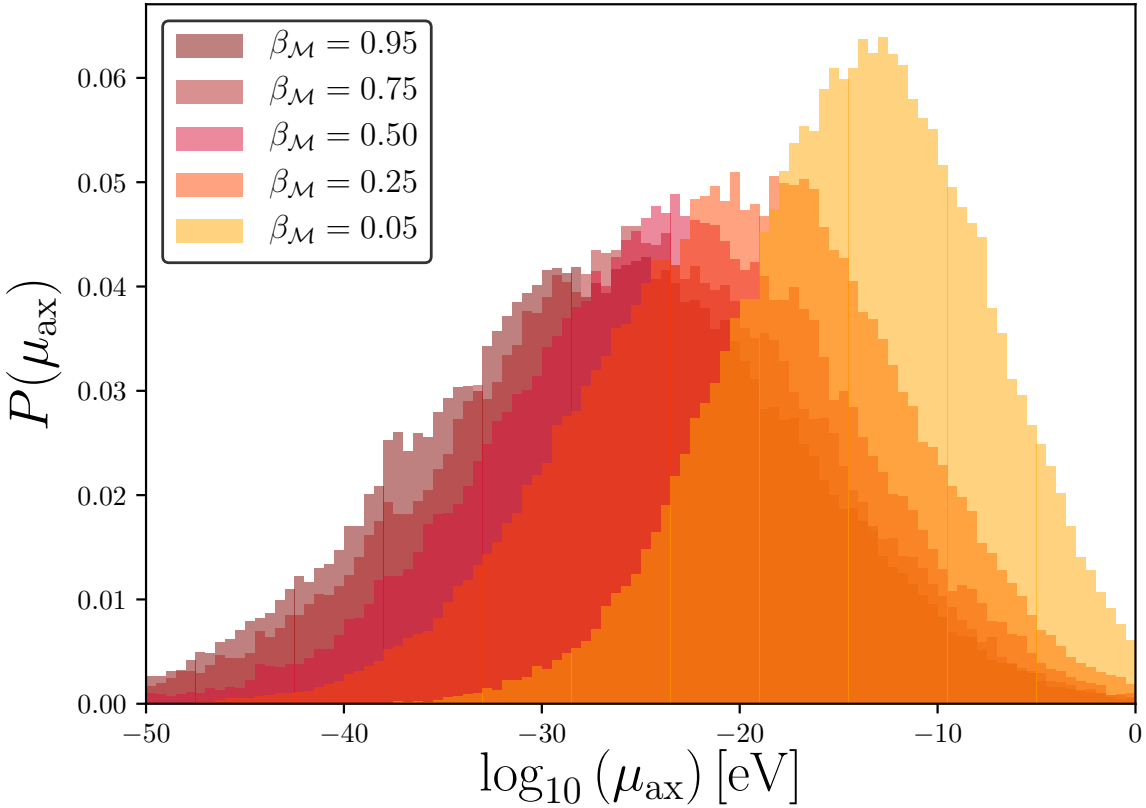




[B. S. Acharya et al. (2007)], [B. S. Acharya et al. (2008)], [B. S. Acharya & K. Bobkov (2010)]

$$\mathcal{M}_{ij} = \sum_{r=1}^{N} 4F\widetilde{\Lambda}_r^3 C_r e^{-S_r} \tilde{N}_r^i \tilde{N}_r^j$$

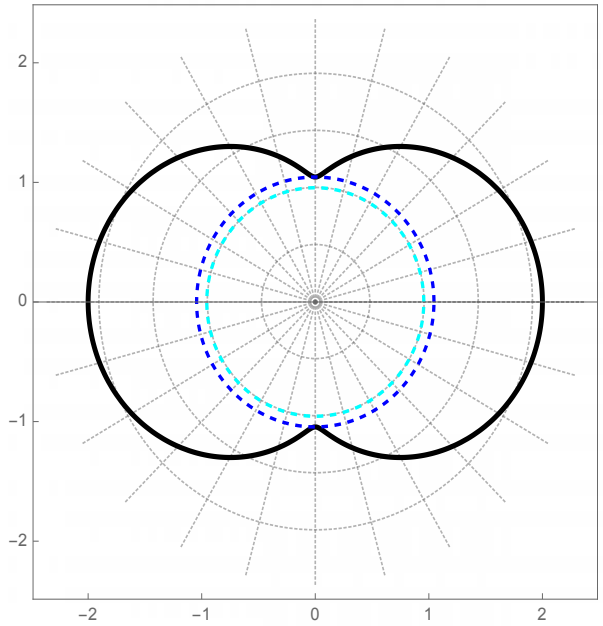
$$\alpha_{\rm GUT} = \frac{1}{V_X} \approx \frac{1}{25}$$

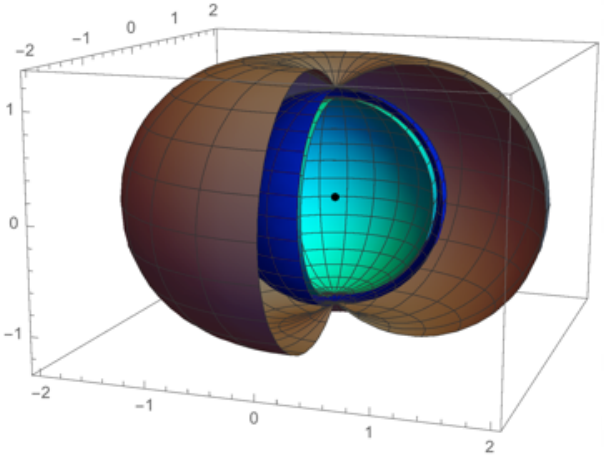


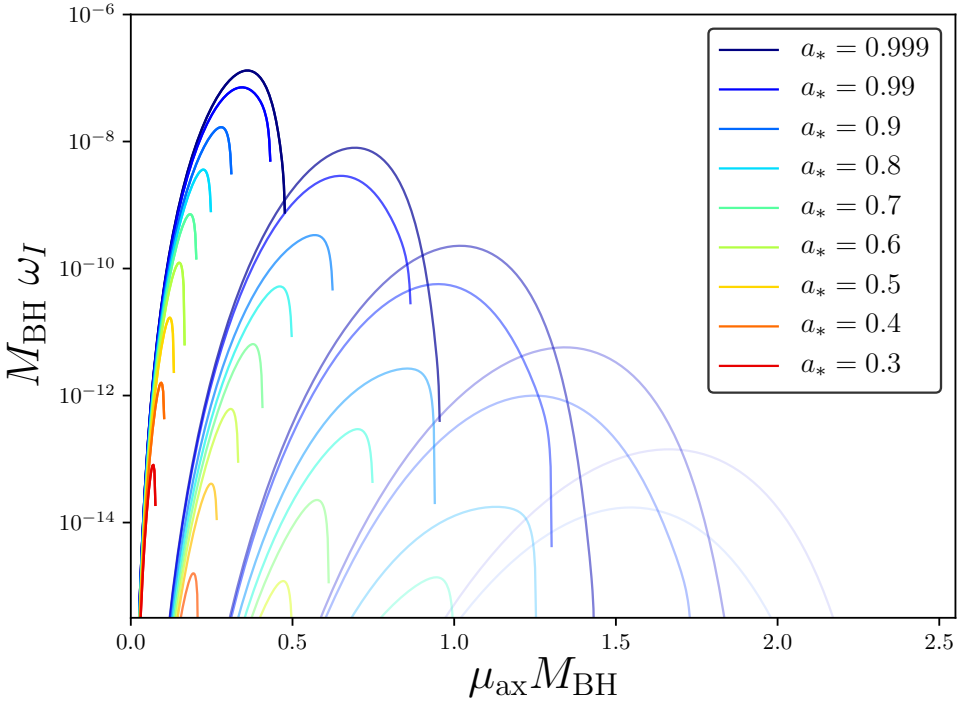
arXiv : *1805.02016*

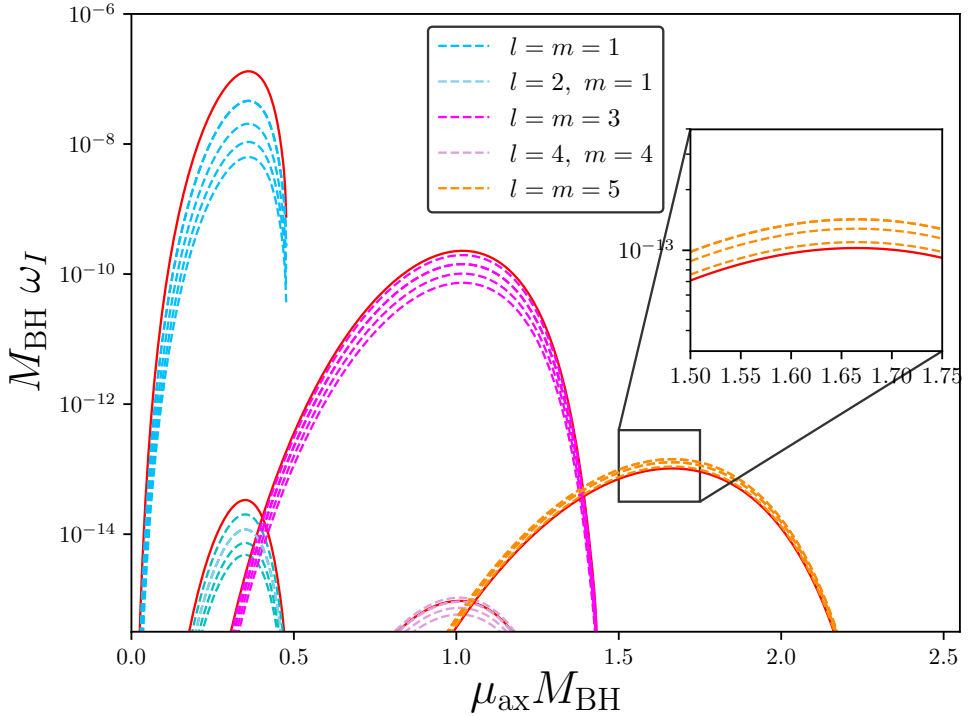
SUPERRADIANCE

Limits on the number of axion-like fields









$$\omega_{nlm} < m\Omega_H \;\rightarrow\; \text{Unstable}$$

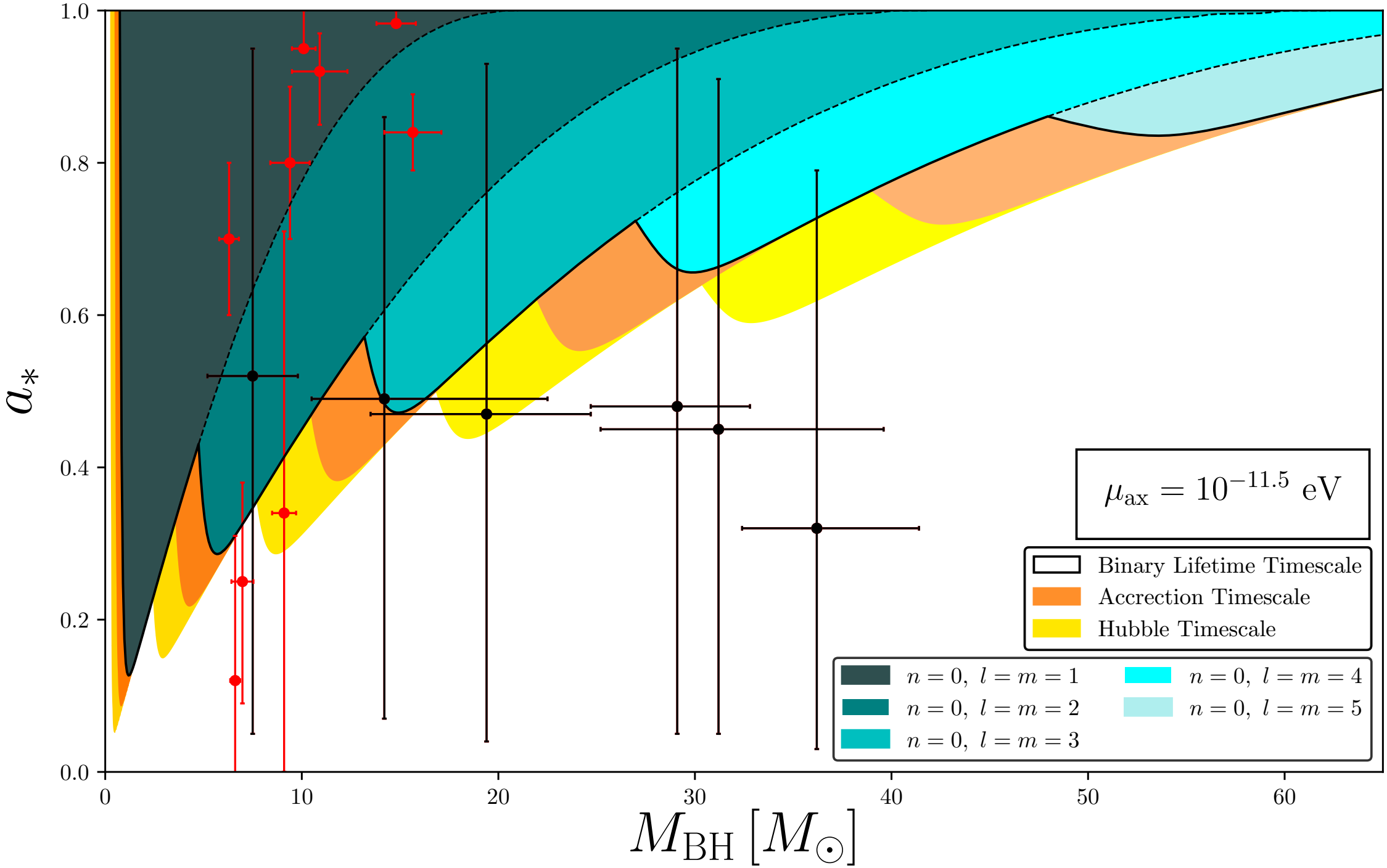
$$\omega_{nlm} = \omega_R + i\omega_I$$

$$\omega_I \equiv \Gamma_{nlm}$$

$$\alpha = r_g \mu_{\rm ax} \equiv \mu_{\rm ax} M_{\rm BH}$$

$$\Gamma_{nlm} \propto \alpha^{4l+4} \mu_{\rm ax}$$

$$\tau_{\rm Salpeter} = \frac{\sigma_{\rm T}}{4\pi m_{\rm P}} \sim 4.5 \times 10^7 \text{ yrs}$$


$\mu_{\rm ax} = 10^{-11.5}$ eV
Binary Lifetime Timescale
Accretion Timescale
Hubble Timescale
$n = 0,\ l = m = 1$
$n = 0,\ l = m = 2$
$n = 0,\ l = m = 3$
$n = 0,\ l = m = 4$
$n = 0,\ l = m = 5$
a_*
$M_{\rm BH}\ [M_\odot]$
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
60

$$P_{\rm allowed}(\mathcal{M}|\{d_i\}) = \prod_i P_{\rm allowed}(\mathcal{M}|d_i)$$

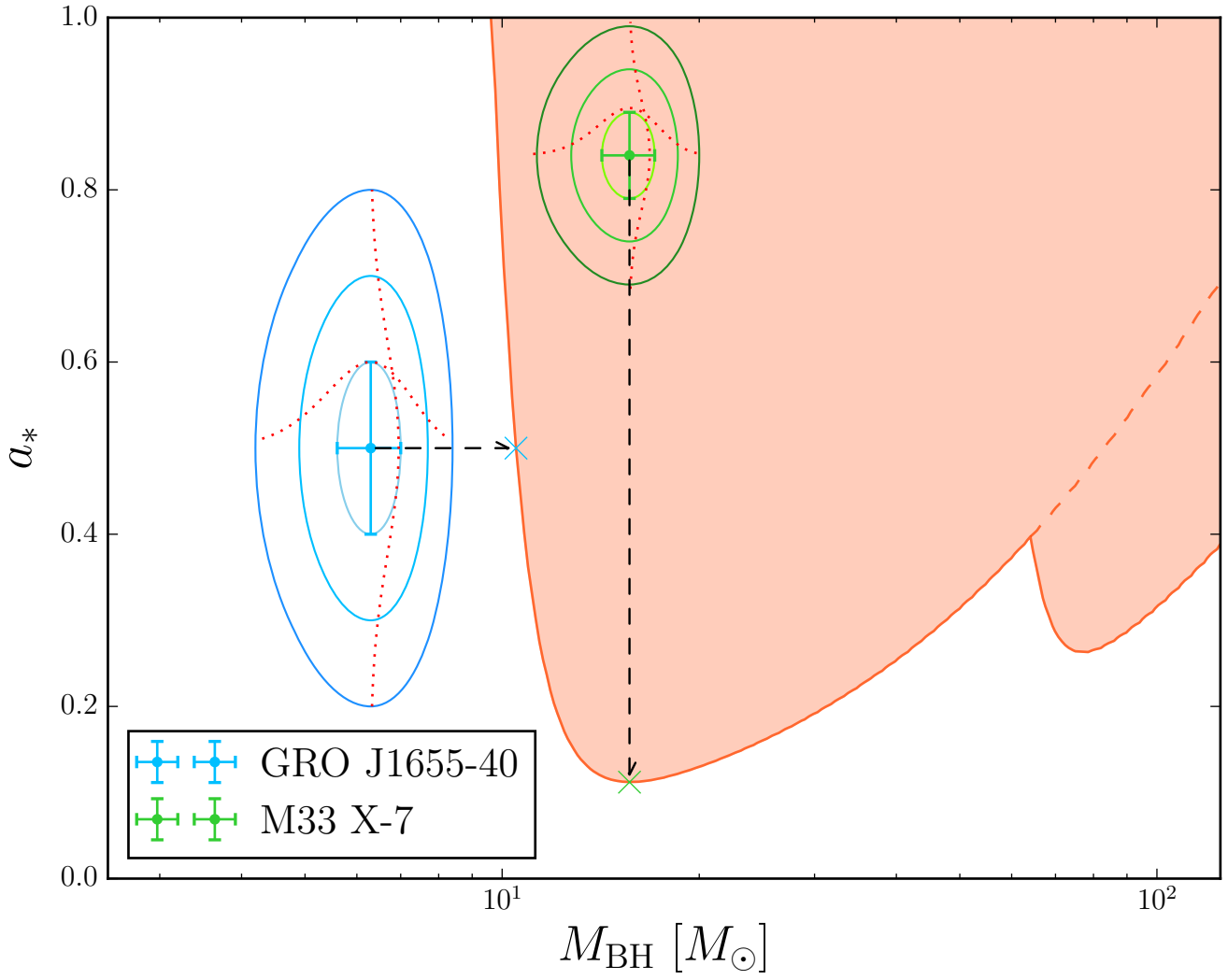
SINGLE

$$P_{\rm ex}(\mathcal{M}|\{d_i\}) = 1 - P_{\rm allowed}(\mathcal{M}|\{d_i\})$$

$$\Sigma_y^2 = \sigma_y^2 + f'(\bar{x})^2\sigma_x^2 \,.$$

$$\Sigma_x^2 = \sigma_x^2 + g'(\bar{y})^2\sigma_y^2 \,.$$

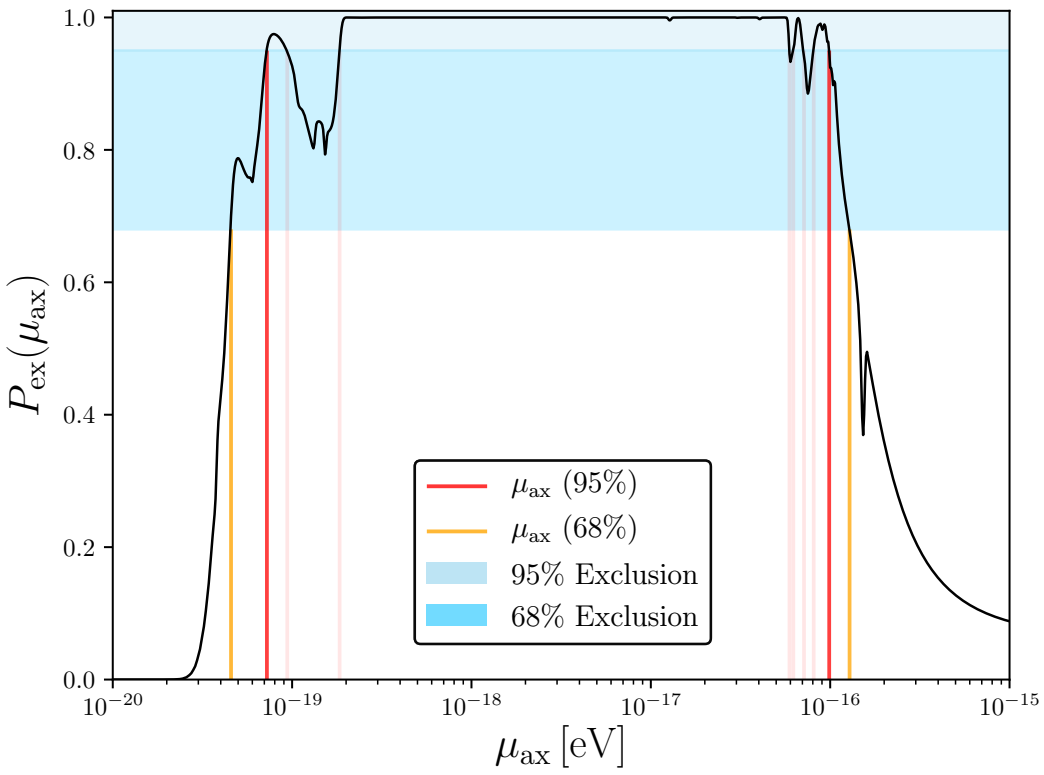
MULTIPLE



$$\mu_{\rm ax} = 10^{-12.75}\ {\rm eV}$$

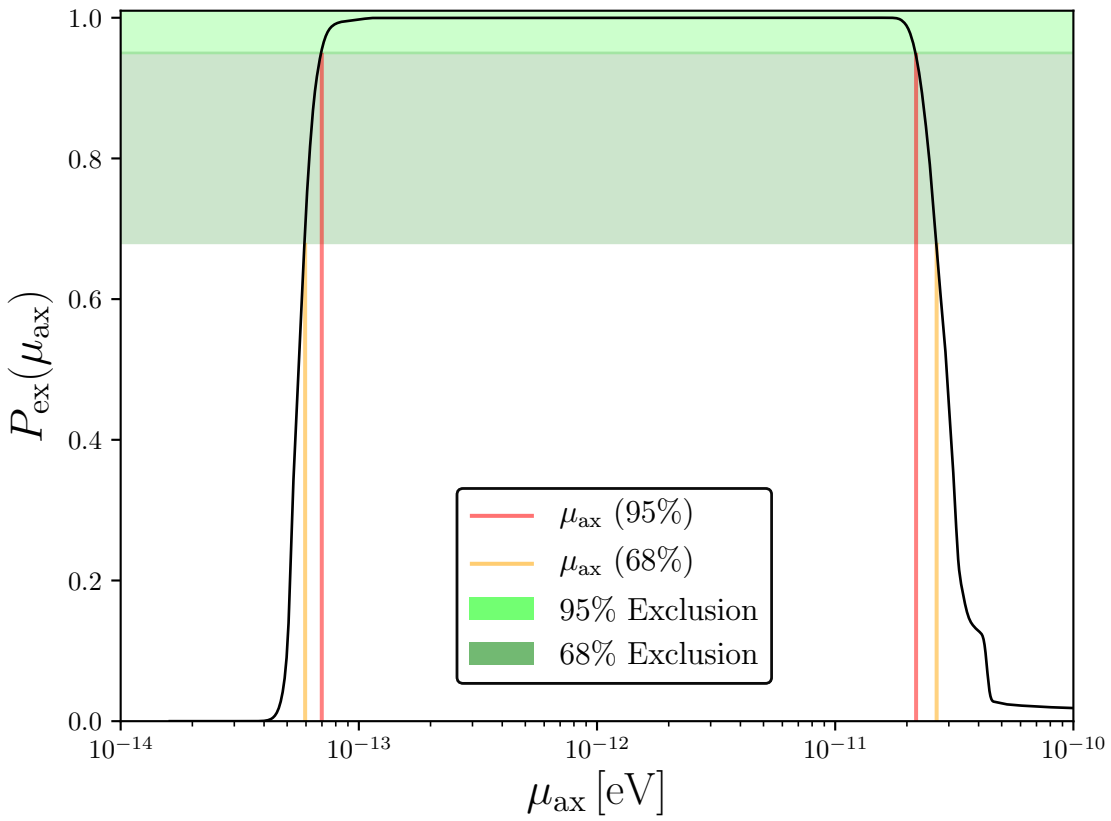
[A. Arvanitaki et al. *(2014)*] [V.Cardoso *et al.* *(2018)*]

$$7 \times 10^{-20}\ \mathrm{eV} \lesssim \mu_{\mathrm{ax}} \lesssim 1 \times 10^{-16}\ \mathrm{eV}$$

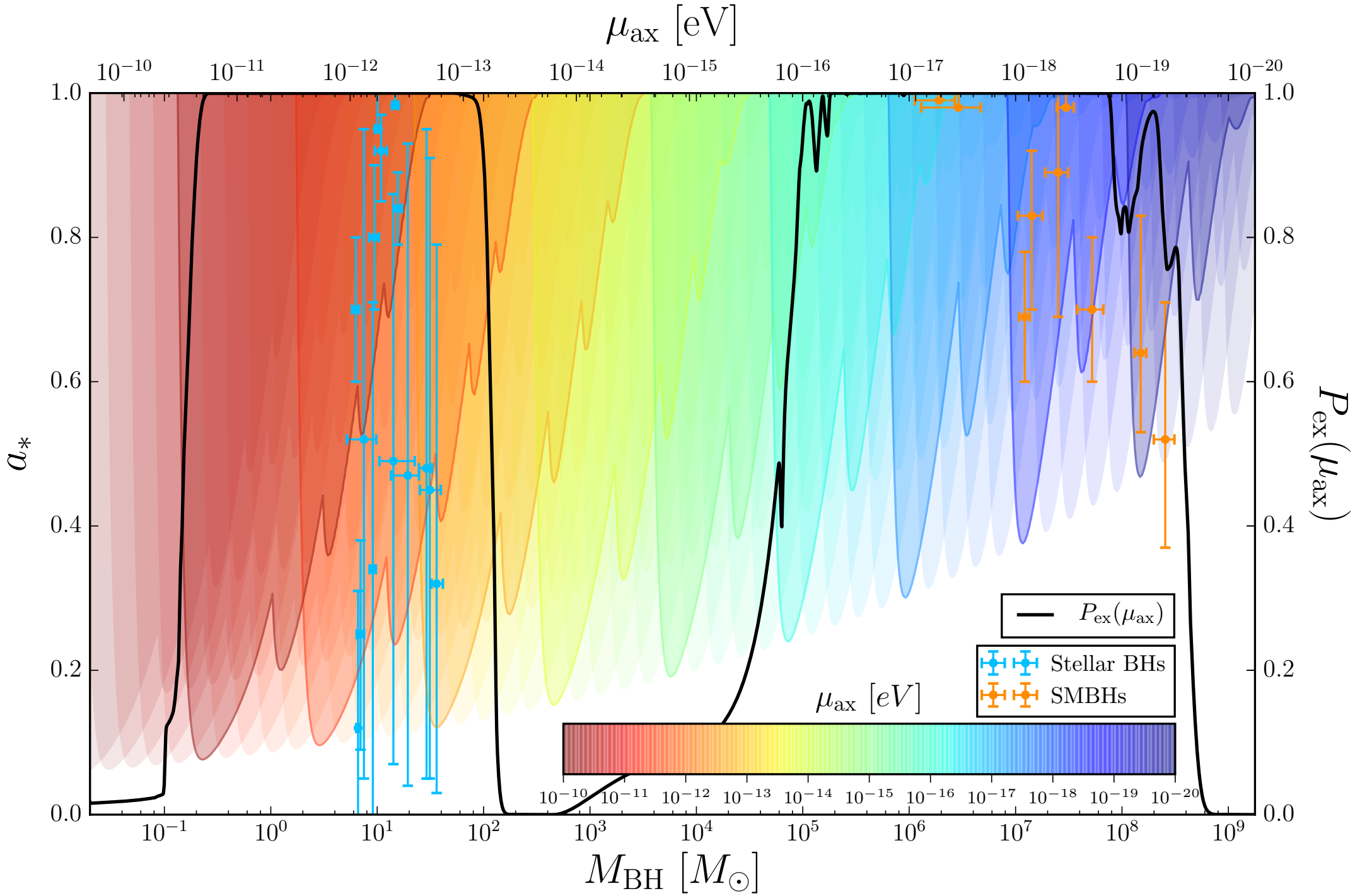


SUPERMASSIVE BLACK HOLES

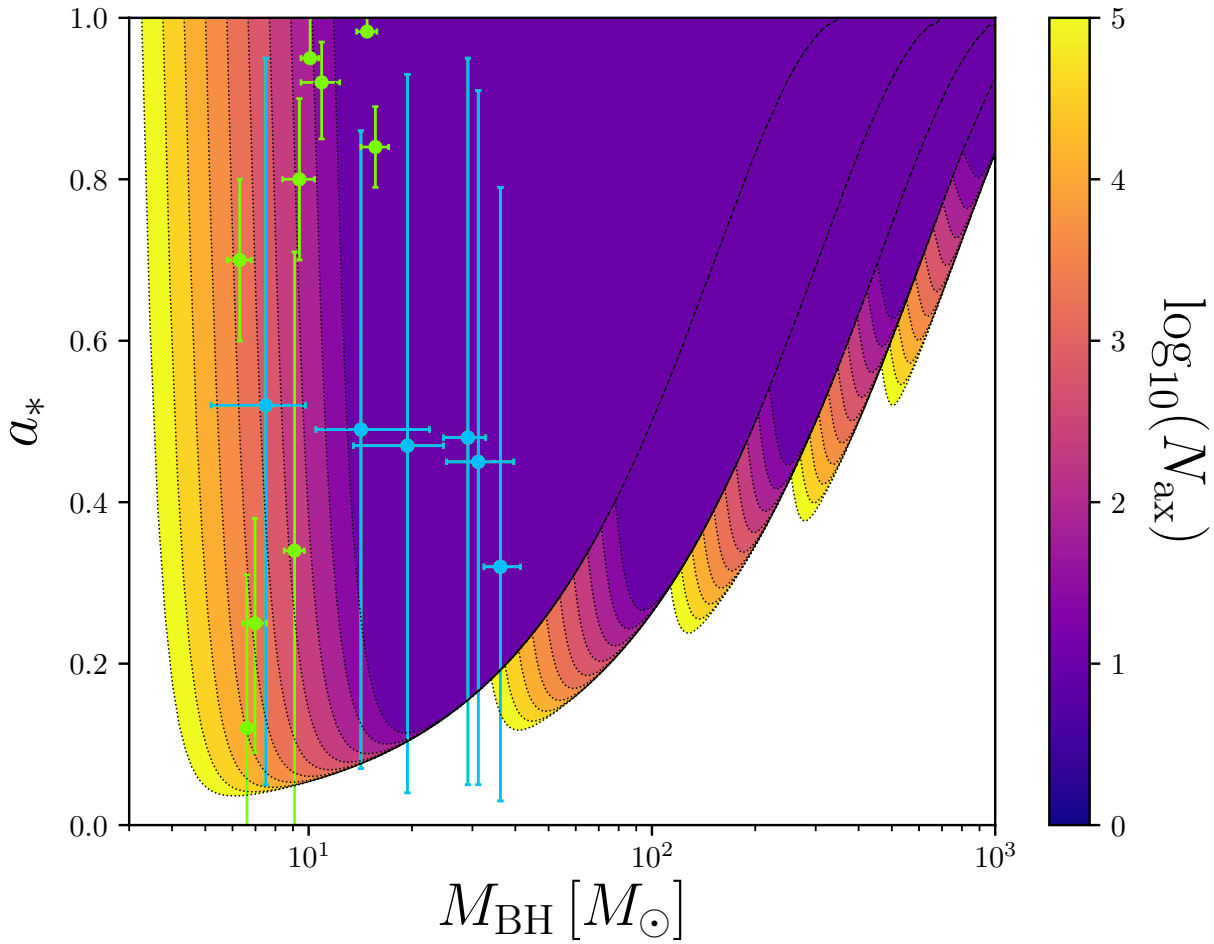
STELLAR BLACK HOLES



$$7 \times 10^{-14}\ \mathrm{eV} \lesssim \mu_{\mathrm{ax}} \lesssim 2 \times 10^{-11}\ \mathrm{eV}$$


$\mu_{\rm ax}$ [eV]
10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18} 10^{-19} 10^{-20}
a_*
0.0 0.2 0.4 0.6 0.8 1.0
$P_{\rm ex}(\mu_{\rm ax})$
$M_{\rm BH}$ $[M_\odot]$
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}
$P_{\rm ex}(\mu_{\rm ax})$
Stellar BHs
SMBHs
$\mu_{\rm ax}$ $[eV]$
10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18} 10^{-19} 10^{-20}

$$\mu_{\rm ax} = 10^{-12.75}\ {\rm eV}$$



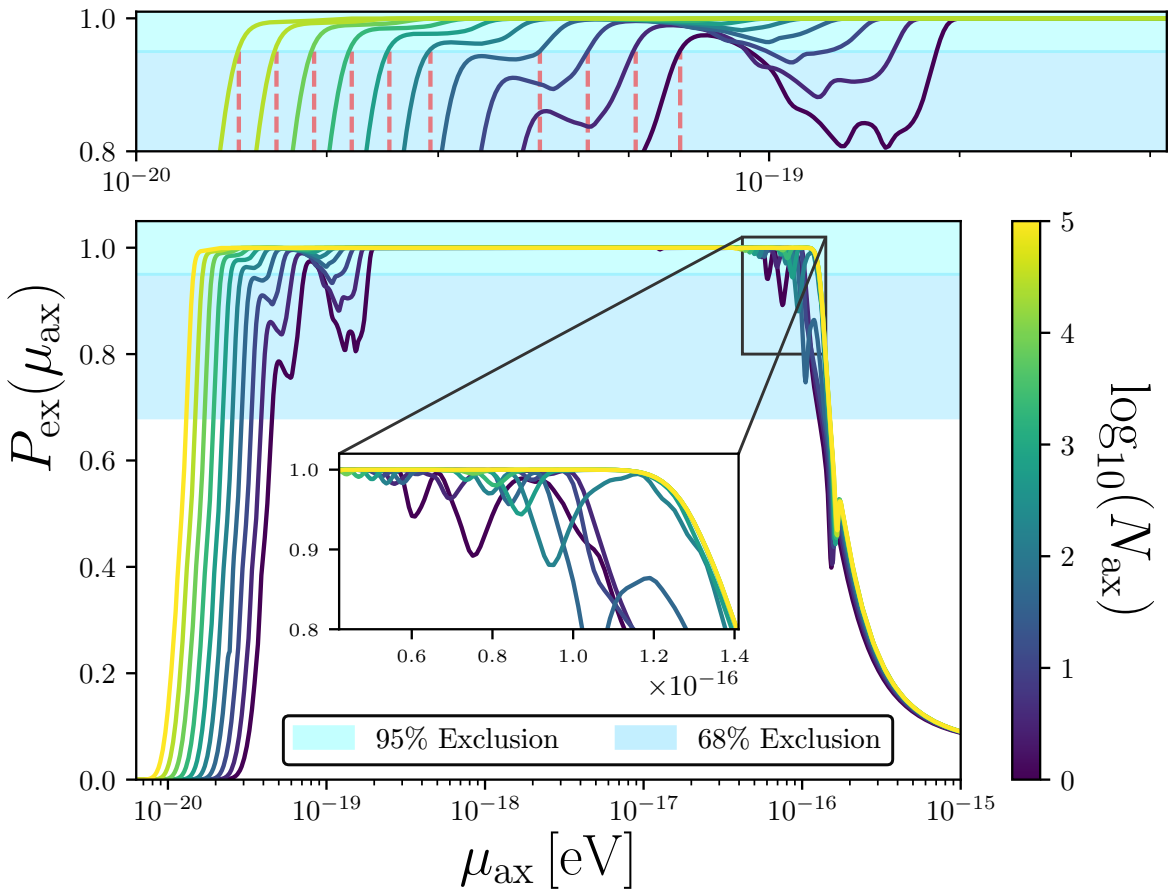
$$f_a \geq 10^{14-16}\ {\rm GeV}$$

GENERAL

$$\Gamma_{\rm tot} = \sum_i^{N_{\rm ax}} \Gamma_i$$

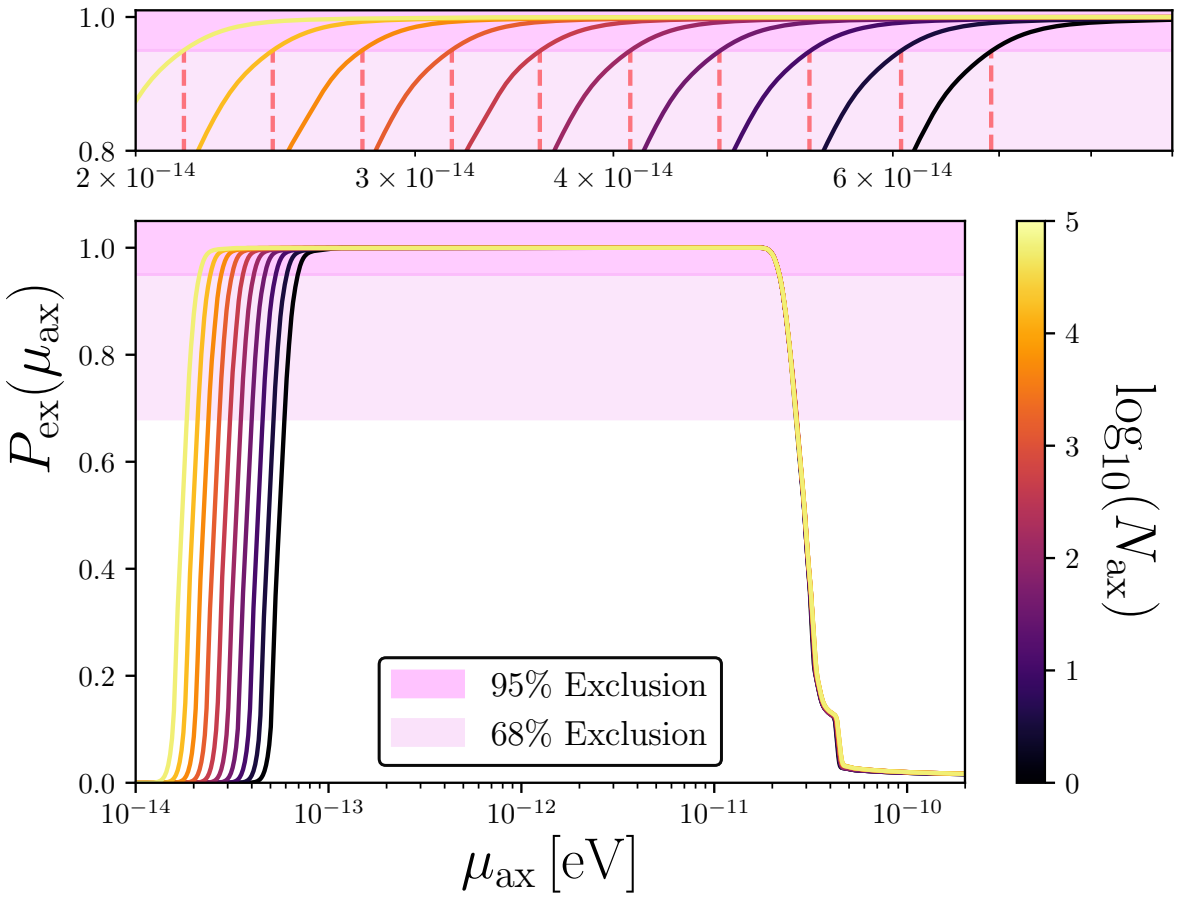
$$\Gamma_{\rm tot} = N_{\rm ax}\Gamma$$

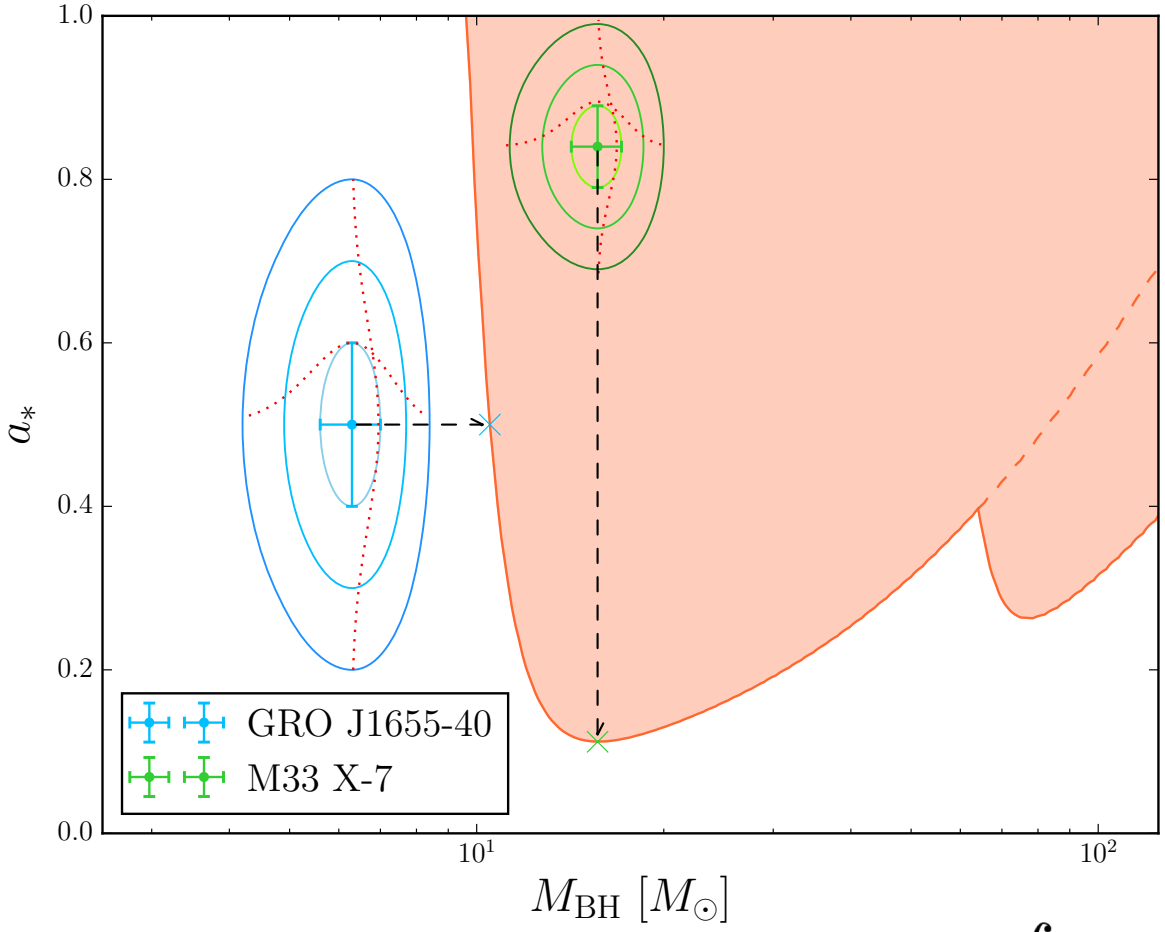
DEGENERATE



SUPERMASSIVE BLACK HOLES

STELLAR BLACK HOLES





$$P_{\rm ex}(\mathcal{M}|\{d_i\}) = 1 - P_{\rm allowed}(\mathcal{M}|\{d_i\})$$

SINGLE

$$P_{\rm allowed}(\mathcal{M}|\{d_i\}) = \prod_i P_{\rm allowed}(\mathcal{M}|d_i)$$

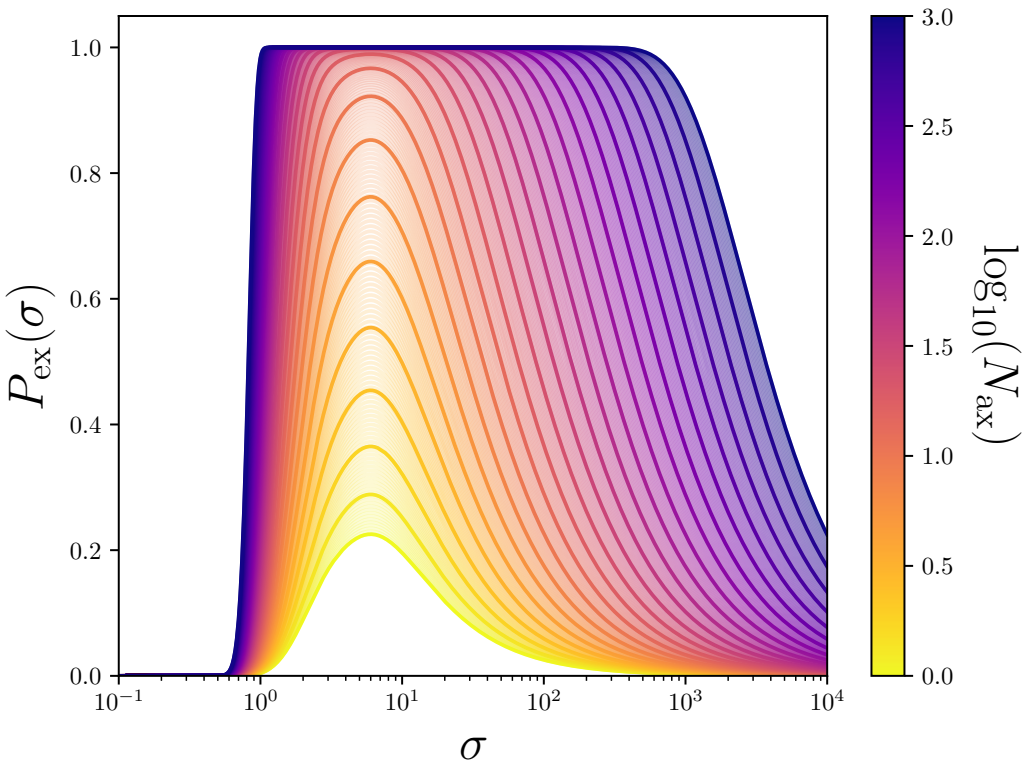
$$\Sigma_y^2 = \sigma_y^2 + f'(\bar{x})^2\sigma_x^2 \,.$$

$$\Sigma_x^2 = \sigma_x^2 + g'(\bar{y})^2\sigma_y^2 \,.$$

MULTIPLE

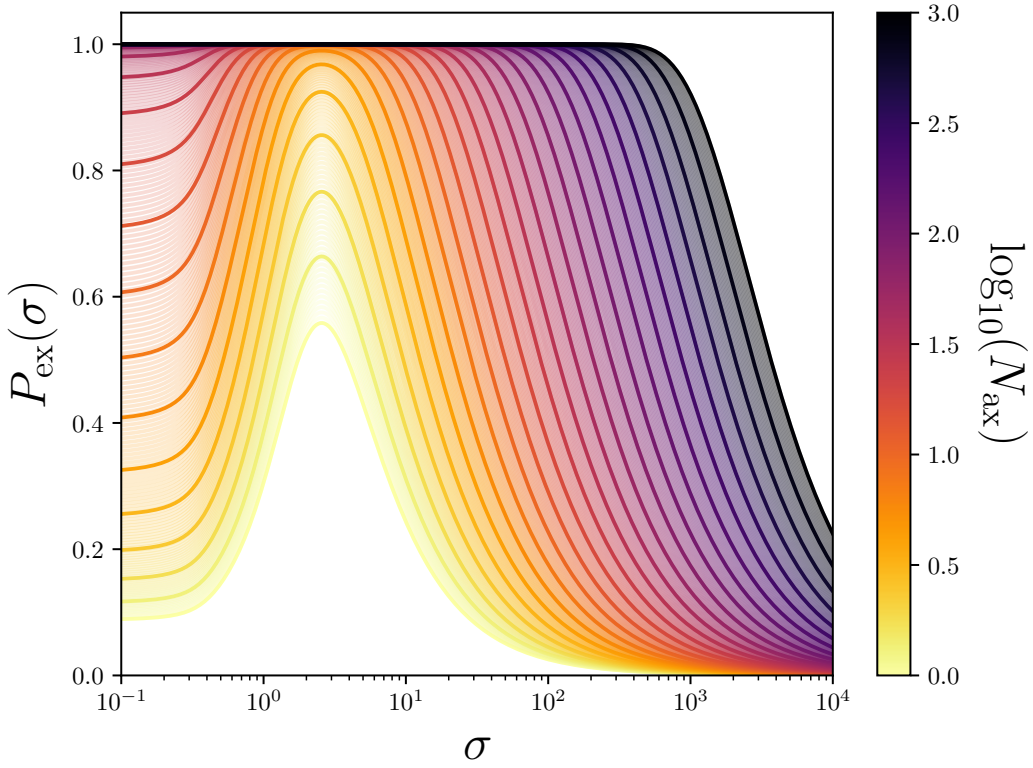
$$N_{\rm ax} \begin{cases} P_{\rm al}(\theta, N_{\rm ax} = 1|\mathcal{M}) = \int {\rm d}\mu_{\rm ax} p(\mu_{\rm ax}|\theta, \mathcal{M}) P_{\rm al}(\mu_{\rm ax}|N_{\rm ax} = 1) \\ P_{\rm al}(\theta, N_{\rm ax}|\mathcal{M}) = \left[\int {\rm d}\mu_{\rm ax}\; p(\mu_{\rm ax}|\theta, \mathcal{M}) P_{\rm al}(\mu_{\rm ax}|N_{\rm ax} = 1)\right]^{N_{\rm ax}} \\ P_{\rm ex}(\theta, N_{\rm ax}|\mathcal{M}) = 1 - P_{\rm al}(\theta, N_{\rm ax}|\mathcal{M}) \end{cases}$$

FUZZY DARK MATTER

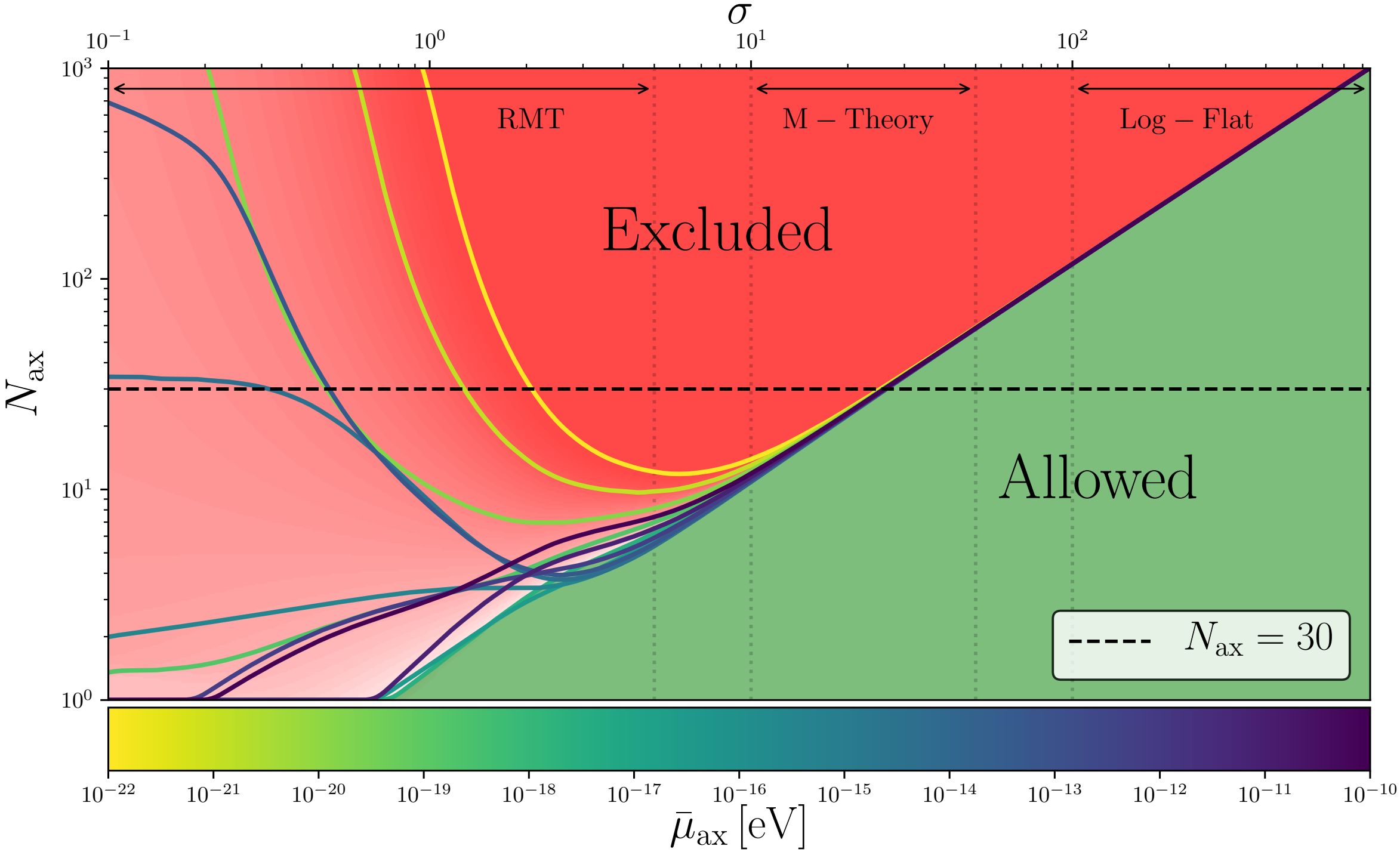


$$\mu_{\rm FDM} \approx 10^{-22}\ {\rm eV}$$

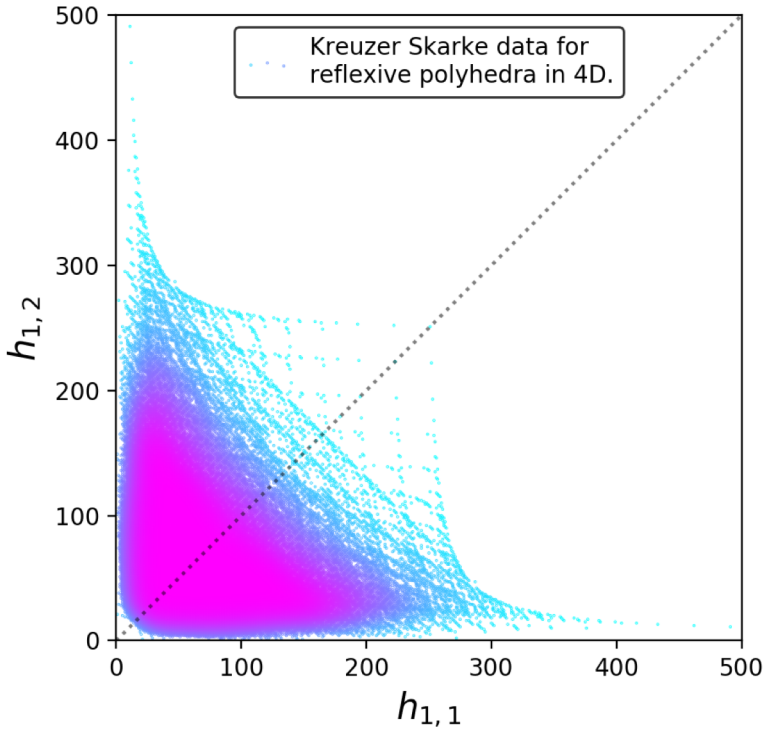
GRAND UNIFIED THEORIES

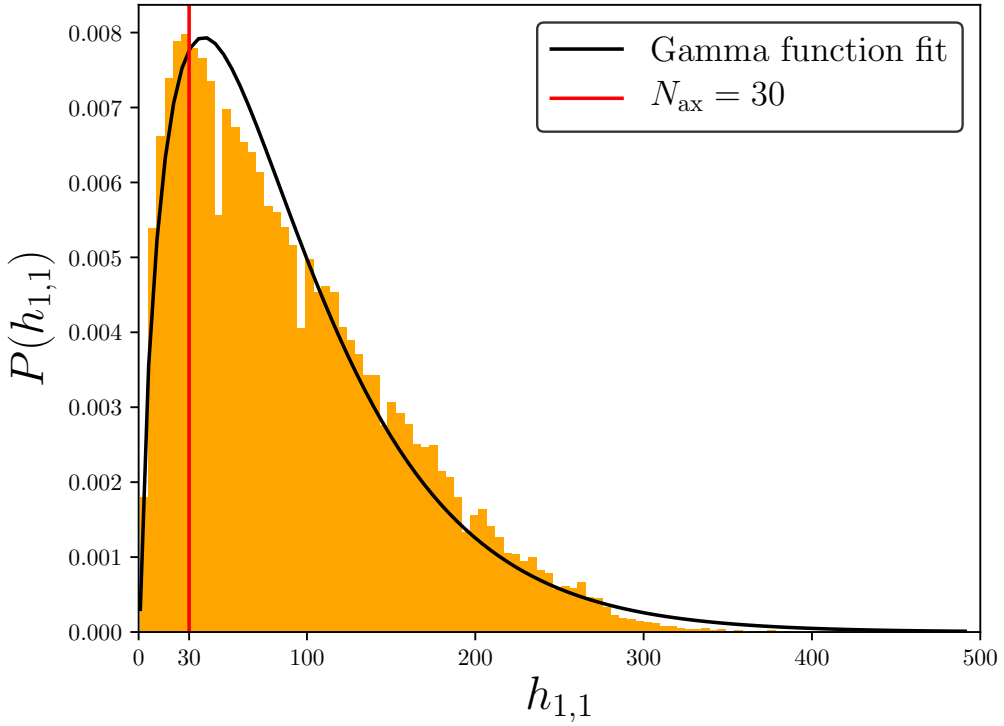


$$\mu_{\rm GUT} \approx 10^{-15}\ {\rm eV}$$


σ
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{2}
10^{1}
10^{0}
$N_{\rm ax}$
RMT
M − Theory
Log − Flat
Excluded
Allowed
$N_{\rm ax} = 30$
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
$\bar{\mu}_{\rm ax}$ [eV]

THANK YOU !


Kreuzer Skarke data for reflexive polyhedra in 4D.
$h_{1,2}$
$h_{1,1}$
0
100
200
300
400
500


Gamma function fit
$N_{\mathrm{ax}} = 30$
$P(h_{1,1})$
$h_{1,1}$
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0
30
100
200
300
400
500

[B. S. Acharya et al. (2007)], [B. S. Acharya et al. (2008)], [B. S. Acharya & K. Bobkov (2010)]

EFFECTIVE MODEL II

M-Theory Axiverse

$$W_{\text{Inst}} = \sum_{i=1}^{N} \tilde{\Lambda}_i^3 e^{ib_i F_i} \qquad V \approx \quad F\left(\sum_{i=1}^{N_{\text{ax}}} \frac{\partial}{\partial z_i} \sum_{j=1}^{N} \widetilde{\Lambda}_j^3 e^{ib_j F_j}\right) + \text{c.c.}$$

$$V \approx \quad \sum_{i=1}^{N_{\text{ax}}} \sum_{j=1}^{N} \frac{2F\widetilde{\Lambda}_j^3 b_j N_j^i}{M_S} e^{-b_j \sum_k^{N_{\text{ax}}} N_j^k s_k} \cos\left(\sum_{k=1}^{N_{\text{ax}}} b_j N_j^k t_k\right)$$

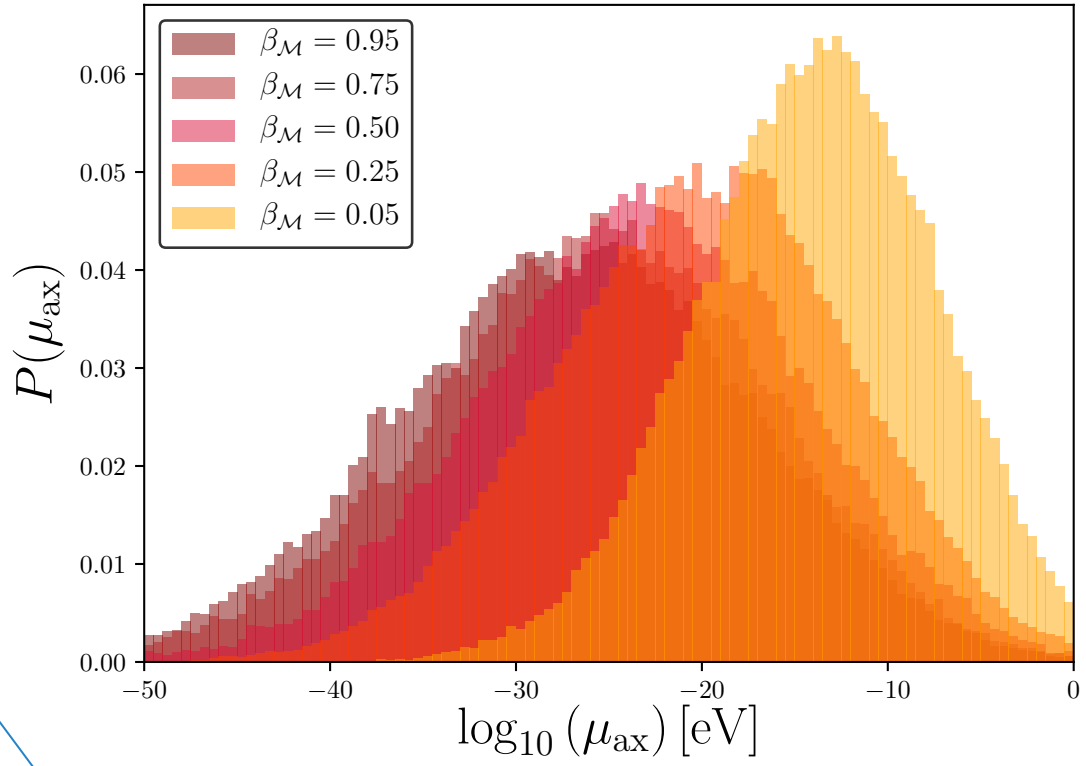
$$\mathcal{M}_{ij} = \quad \sum_{k=1}^{N_{\text{ax}}} \sum_{r=1}^{N} \frac{4F\widetilde{\Lambda}_r^3 b_r N_r^k}{M_S^3} e^{-b_r \sum_m^{N_{\text{ax}}} N_r^m s_m} b_r N_r^i b_r N_r^j$$

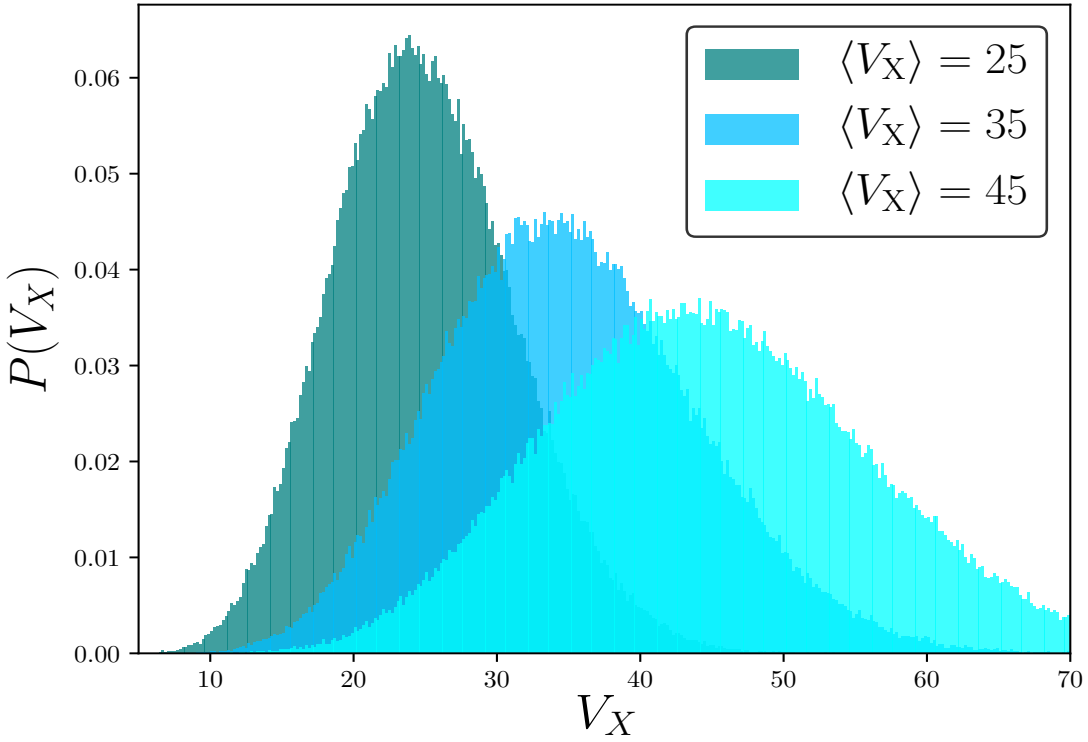
$$\mathcal{M}_{ij} = \sum_{r=1}^{N} 4F\widetilde{\Lambda}_r^3 C_r e^{-S_r} \tilde{N}_r^i \tilde{N}_r^j \qquad \mathcal{M}_{ij} = \frac{1}{N} A_{ir} A_{jr}$$

$$A_{ir} = \left(2\sqrt{F\widetilde{\Lambda}_r^3 C_r}\right) e^{-S_r/2} \widetilde{N}_r^i$$

$$F_i = \sum_k^{n_{\rm ax}} N_i^k z_k = \sum_k^{n_{\rm ax}} N_i^k (t_k + i s_k)$$

$$V_X^i = \mathrm{Im}(F_i) = \sum_{k=1}^{n_{\rm ax}} N_i^k s_k = \frac{1}{2\pi} \sum_{k=1}^{n_{\rm ax}} \widetilde{N}_i^k s_k$$





$$\alpha_{\rm GUT} = \frac{1}{V_X} \approx \frac{1}{25}$$

$$\langle V_X \rangle = \frac{N_{\rm ax} \tilde{N}_{\rm max} \langle s \rangle}{4\pi}$$