String Axiverse

Sergei Dubovsky
(Stanford U.)

with Mina Arvanitaki, Savas Dimopoulos,
Nemanja Kaloper, and John March-Russel

$$S_\theta = \frac{\theta}{32\pi^2}\int d^4x\,\epsilon^{\mu\nu\lambda\rho}\,\mathrm{Tr}\,G_{\mu\nu}G_{\lambda\rho}$$

Neutron e.d.m.:

$$\bar\theta = \theta + \arg\det m_q \lesssim 10^{-10}$$

- Like for CC and EW hierarchy a precise cancelation of apparently unrelated quantities is required
- NO anthropic reason

A CLEAR CALL FOR A NEW DYNAMICS

The QCD axion

$$S_a = \int d^4x \left(\frac{1}{2}(\partial_\mu a)^2 + \frac{a}{32\pi^2 f_a} \epsilon^{\mu\nu\lambda\rho} \mathrm{Tr}\, G_{\mu\nu} G_{\lambda\rho} \right)$$

$$m_a \approx 6 \times 10^{-10} \mathrm{eV} \left(\frac{10^{16} \mathrm{GeV}}{f_a} \right)$$

$f_a \lesssim 10^9 \mathrm{GeV}$ and $f_a \sim 10^{11} \mathrm{GeV}$ are excluded

$f_a \gg 10^{12} \mathrm{GeV}$ is an especially interesting region:

would be the evidence that Ω_{DM} is fixed anthropically whether a fake symmetry broken by QCD plus $< 10^{-10} \times$ QCD is common in a fundamental theory?

In string theory: YES!

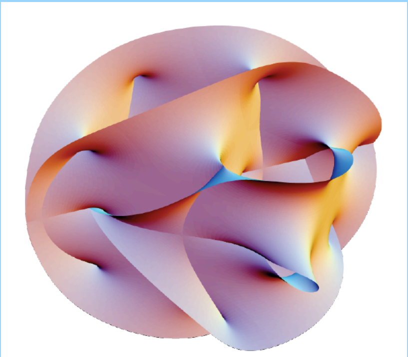
antisymmetric forms

B_2

$C_{0,2,4}$ (IIA)

$C_{1,3}$ (IIB)

compactification →



many (100-100000) KK zero modes from topology (cohomologies)

Chern-Simons coupling (Green-Schwarz anomaly cancelation) → axionic couplings

String theory does NOT predict the QCD axion

- light axions can be removed from the spectrum by orientifold planes, fluxes, branes
- non-perturbative effects may generate contributions to the potential $> 10^{-10} \times$ QCD

QCD axion is a constraint on string model building

In particular, SUSY preserving moduli stabilization is disfavored

↓

cosmological moduli problem is back, we assume:

$$H_{inf} \sim 0.1 \text{ GeV} \qquad T_{rh} \sim 10^7 \text{ GeV}$$

Taking seriously QCD axion and string theory one expects

MANY LIGHT AXIONS

relevant phenomenological parameters: $m \quad f_a$

$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - m^2 f_a^2 U(a/f_a)$$

$$m^2 f_a^2 = \mu_{UV}^4 e^{-S}$$

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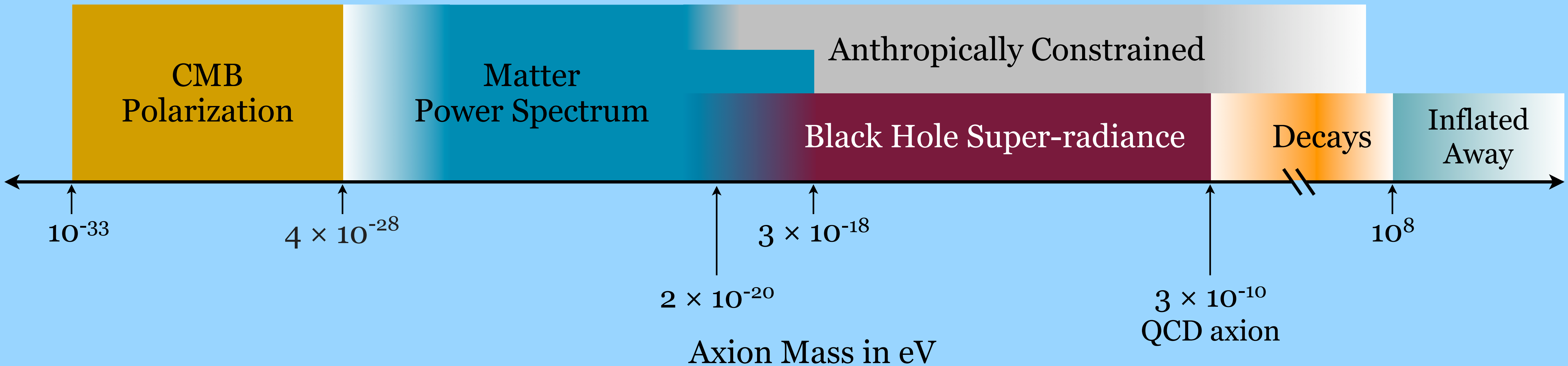
in explicit examples one finds: $f_a \sim \frac{M_{Pl}}{S}$

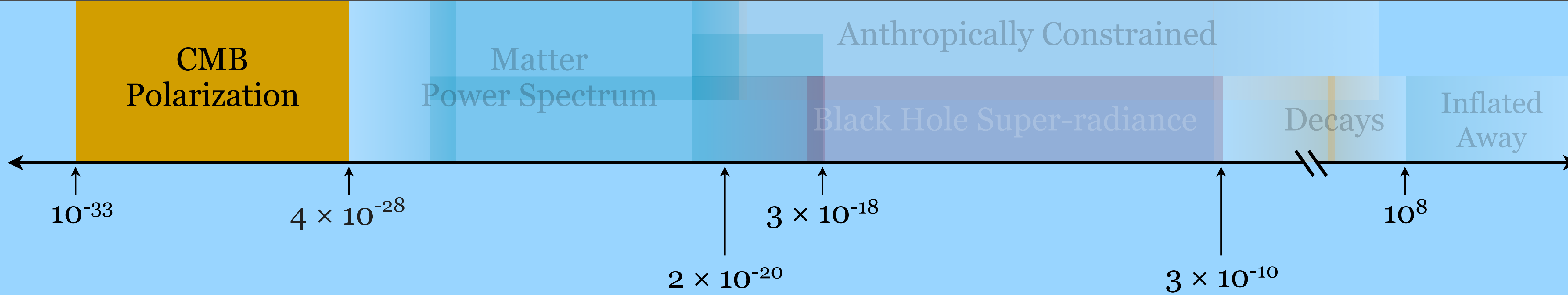
"weak gravity conjecture": $f_a < \frac{M_{Pl}}{S}$

strong CP: $S \gtrsim 200$

$f_a \sim M_{GUT}$ m: homogeneously distributed over log(energy)



Cohomologies from Cosmology

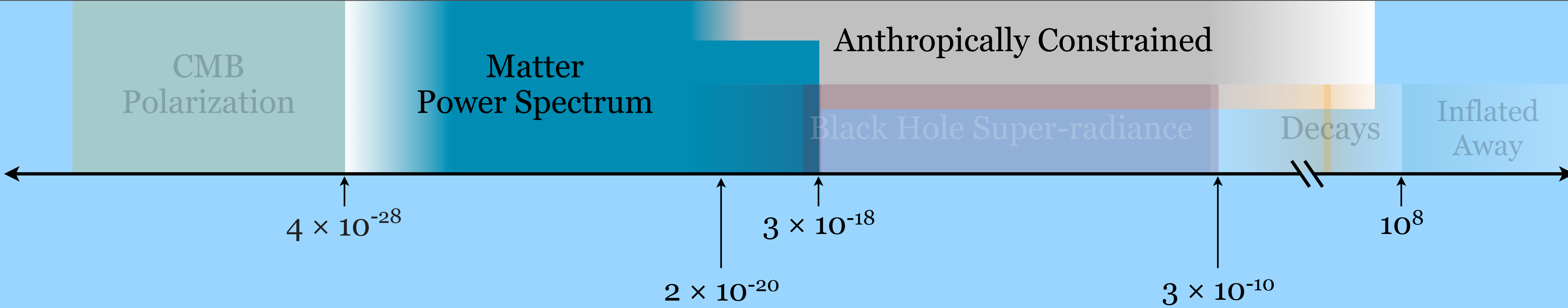


model-dependence: $$\mathcal{L}_\gamma = \frac{C\alpha}{4\pi f_a} a \epsilon^{\mu\nu\lambda\rho} F_{\mu\nu} F_{\lambda\rho}$$

rotation of the CMB polarization transforms
E-mode into B-mode
BB, BT, ET

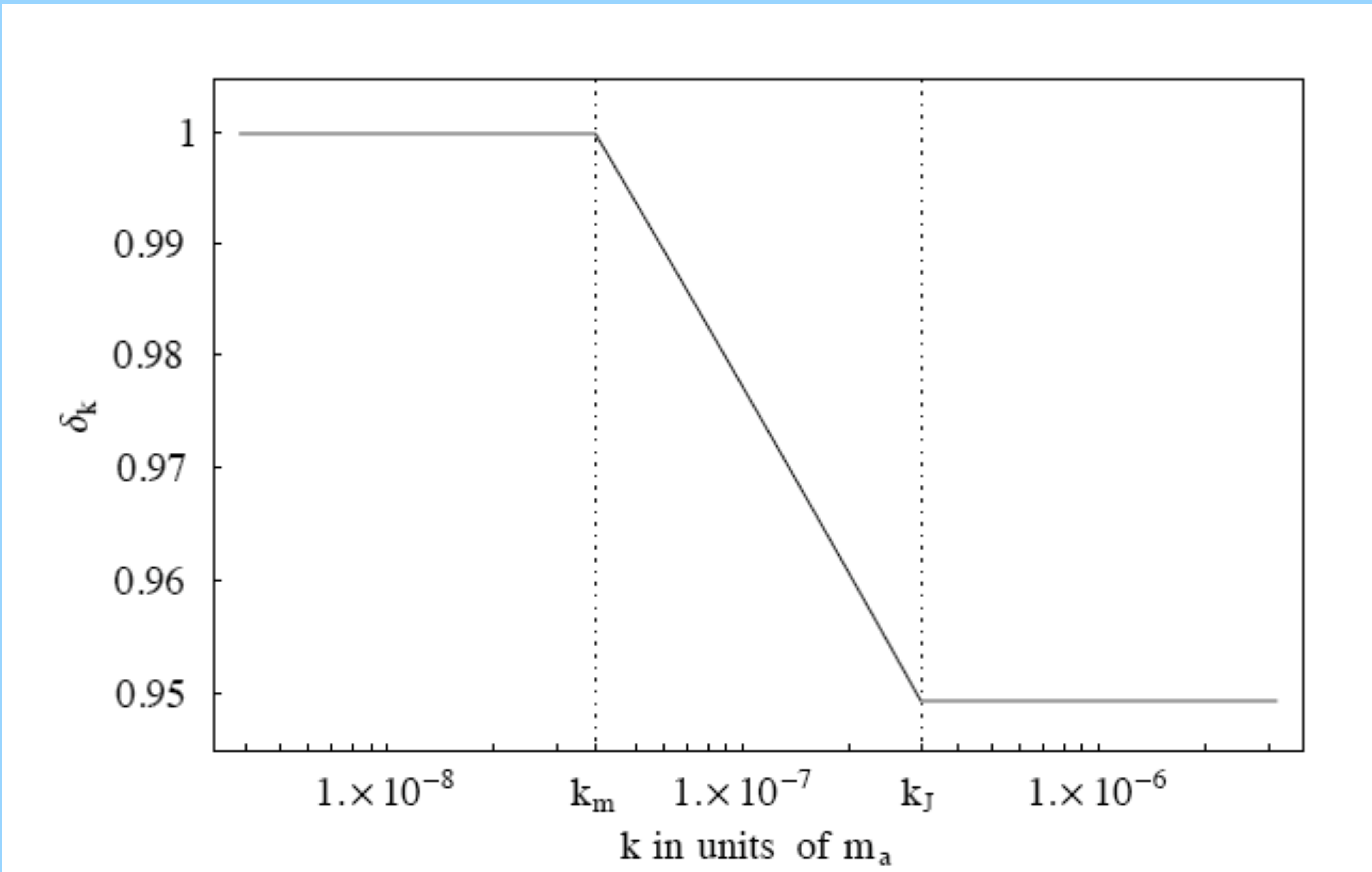
$$\Delta\beta = \frac{C\sqrt{N}\alpha}{2\pi f_a}(a(\tau_0) - a(\tau_{rec})) = \frac{C\sqrt{N}\alpha}{2\sqrt{3}} \sim few \times 10^{-3}\sqrt{N}$$

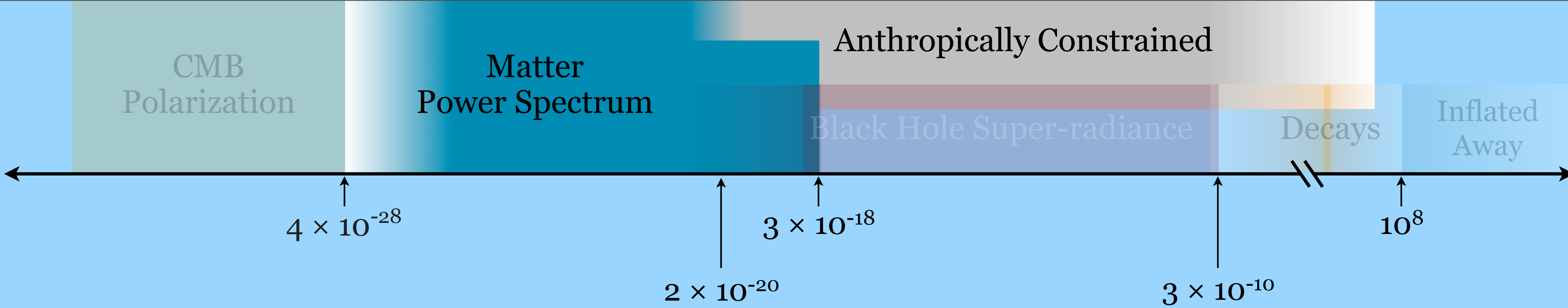
- constant over the sky
- independent of f_a , H_{infl}
- current bound: 0.035 Planck: 10^{-3} CMBPol: 10^{-4}



Uncertainty principle prevents density perturbation growth at

$$\frac{k_J}{a} > \sqrt{Hm}$$





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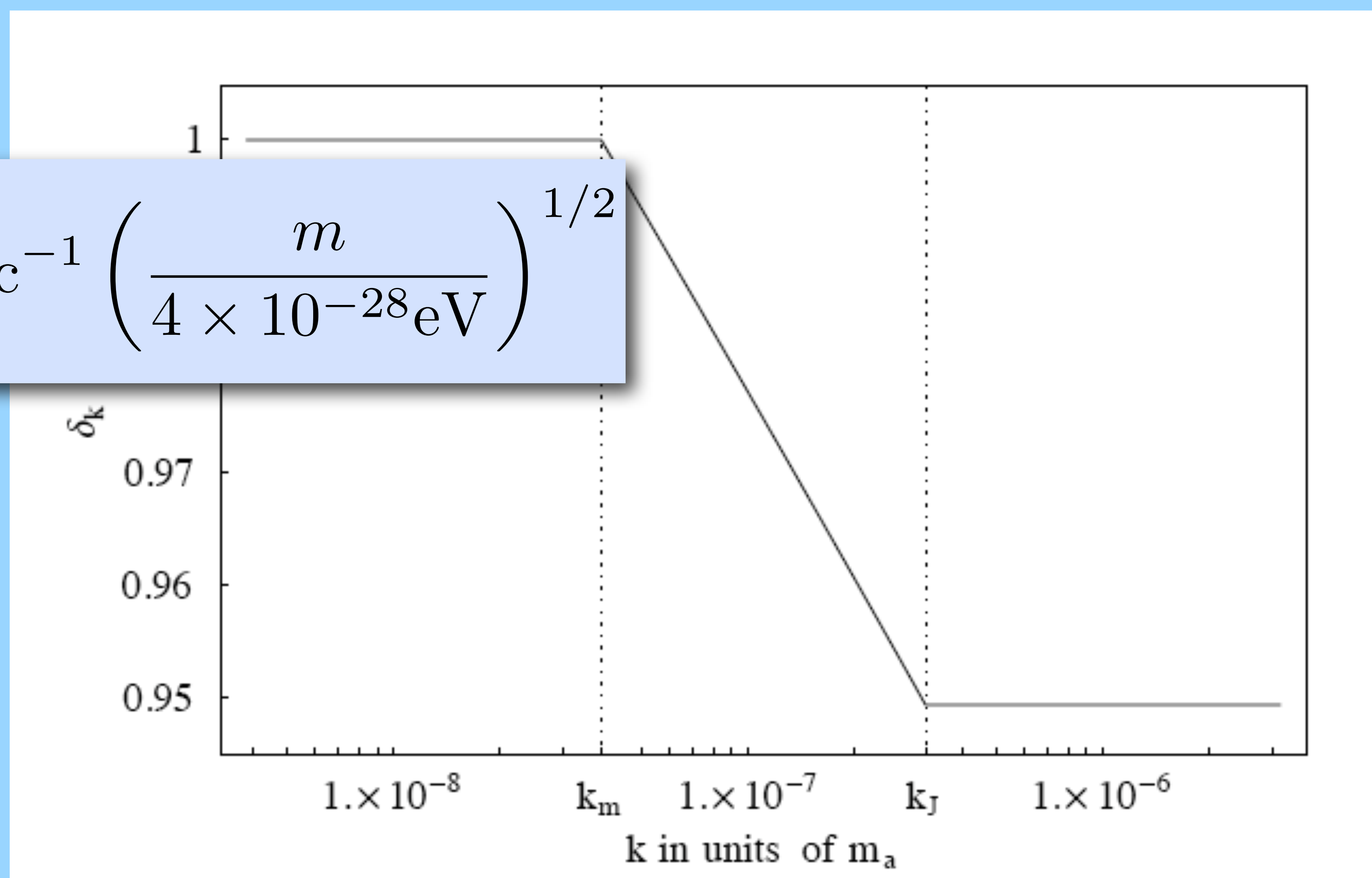
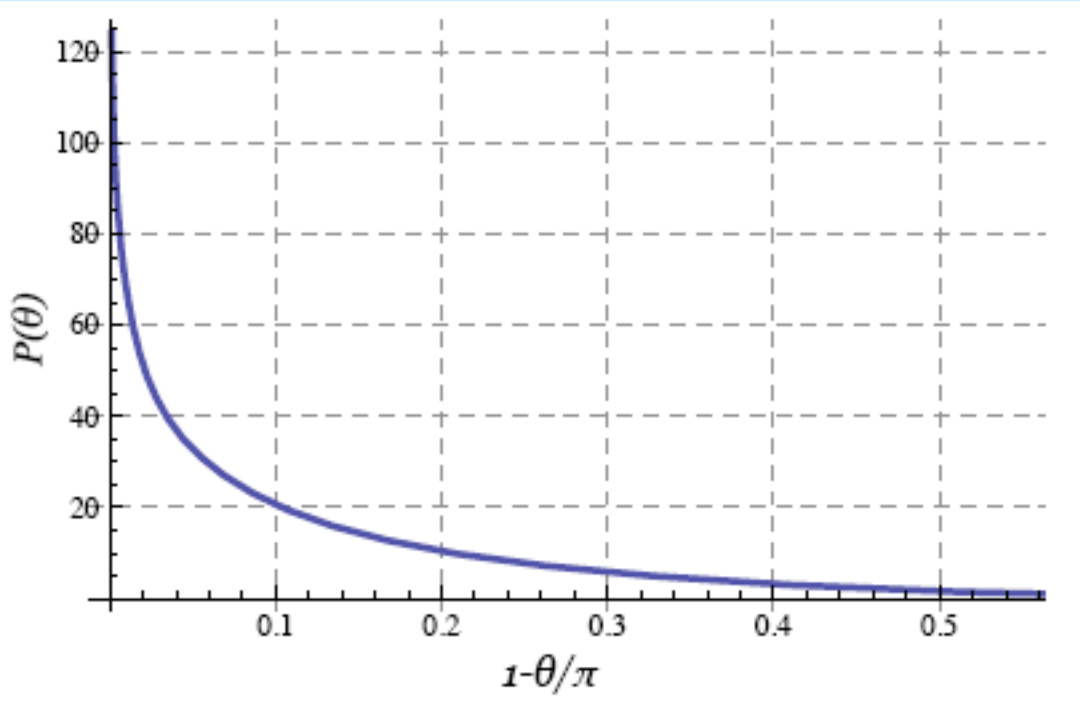


$$k_m = 0.01\mathrm{Mpc}^{-1}\left(\frac{m}{4\times10^{-28}\mathrm{eV}}\right)^{1/2}$$

The size of the step:

$$S = \frac{\Omega_a}{\Omega_m} \log z_{eq}/z_{obs} \approx 8\frac{\Omega_a}{\Omega_m}$$

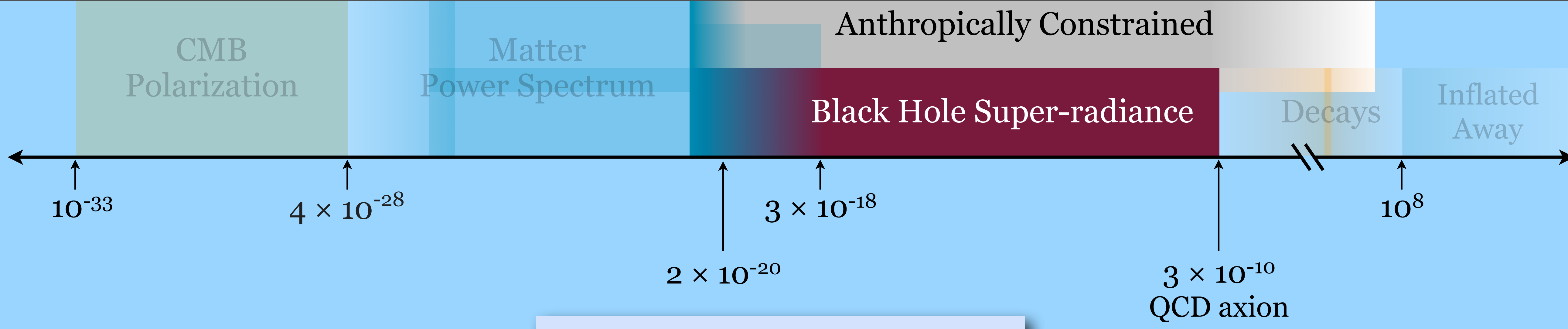
$$\frac{\Omega_a}{\Omega_m} = \frac{f_a^2}{3M_{Pl}^2}\frac{z_m}{z_{eq}}P(\theta_i)$$



BOSS: 1% at $\frac{z_m}{z_{eq}} \sim 10$

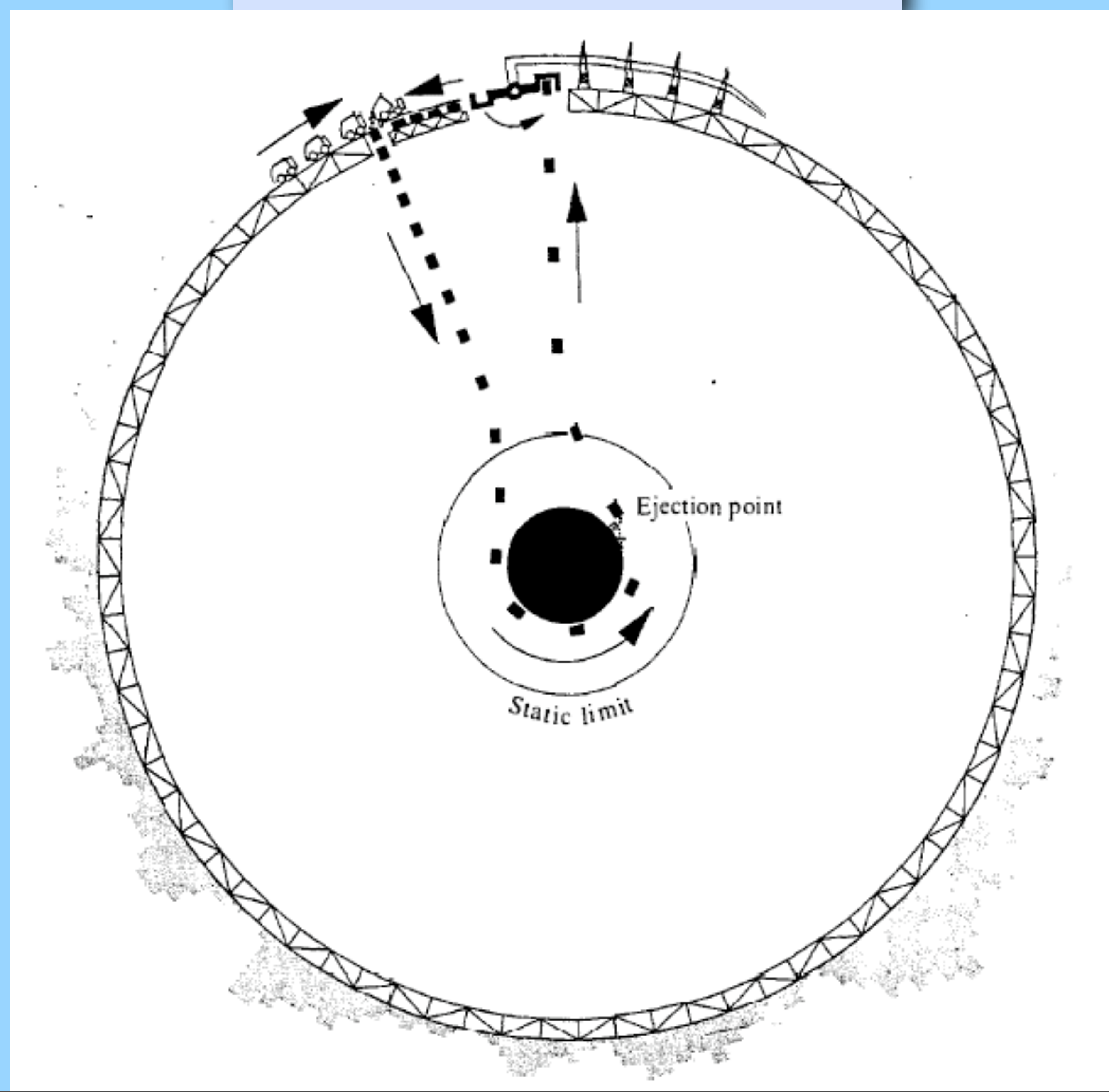
21 cm tomography: up to $\frac{z_m}{z_{eq}} \sim 10^5$

$S \sim 1$ at $m \approx 1.4 \times 10^{-20}\text{eV}\frac{1}{P(\theta)^2}\left(\frac{3M_{Pl}^2/f_a^2}{10^4}\right)^2$

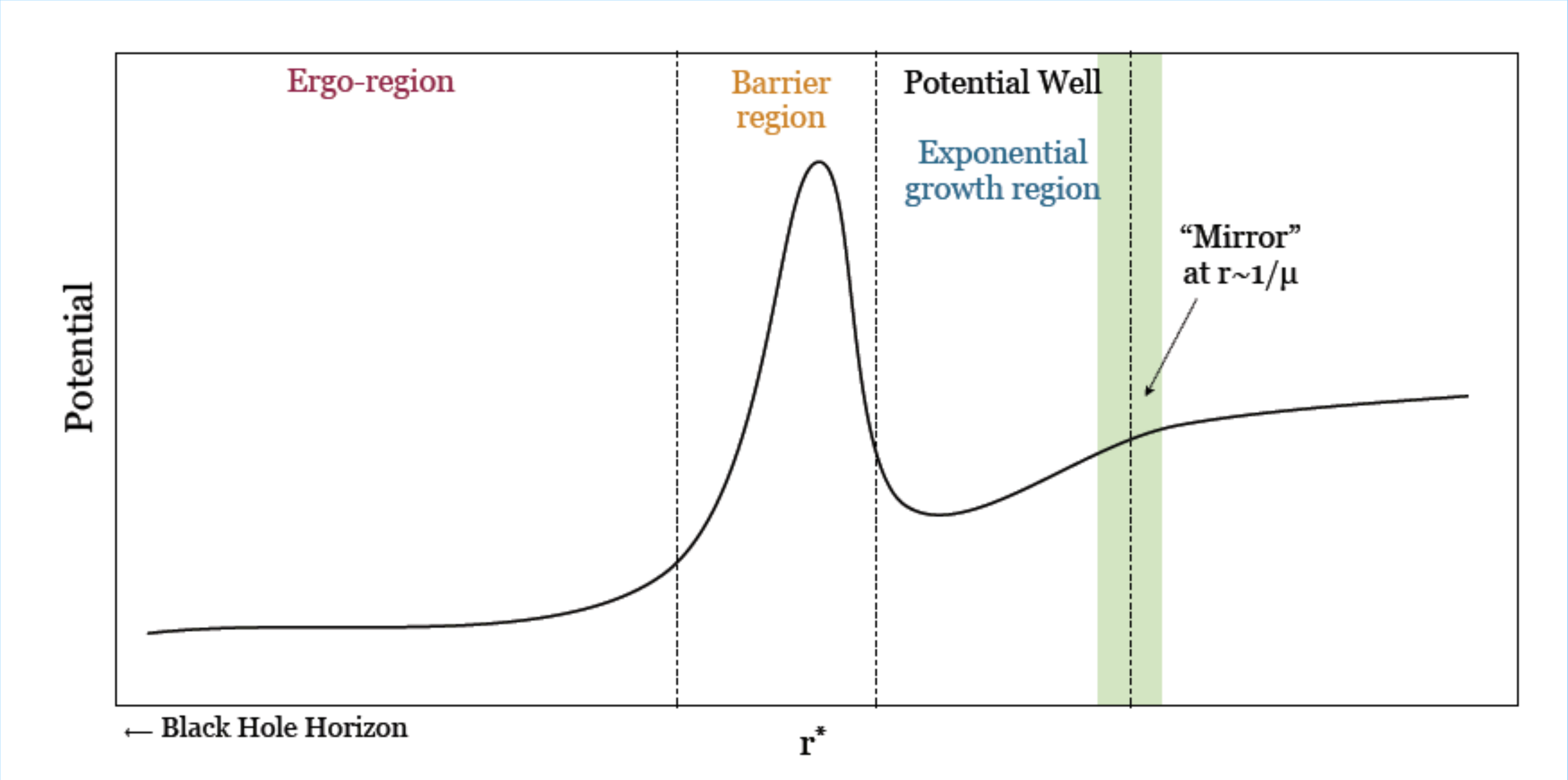


Penrose process

$$\delta M < 0$$



$$\delta J < 0$$

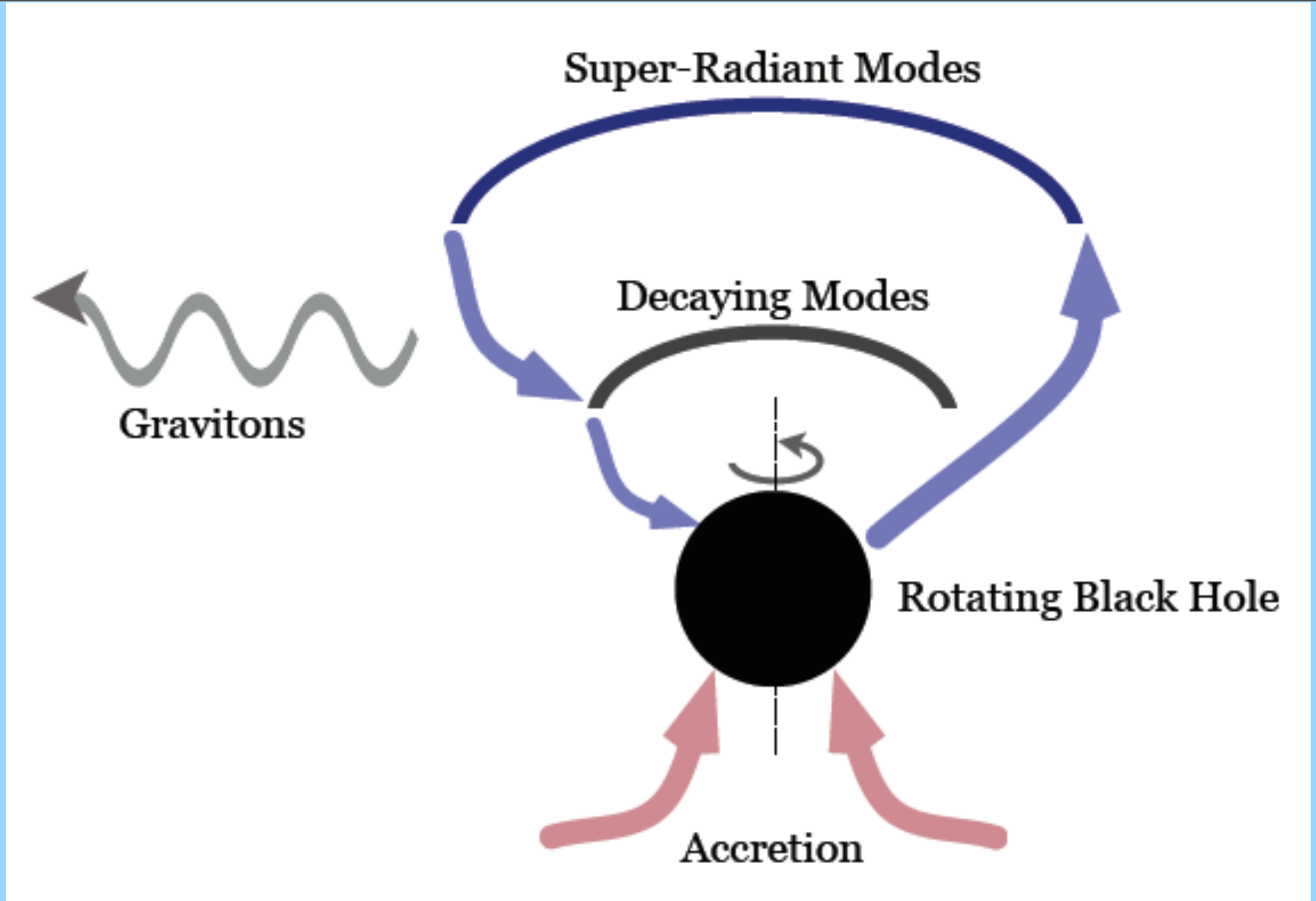


$$\tau_{heavy} = 10^7 e^{1.84 R_g m} R_g\,, \qquad \text{for } R_g m \gg 1 \text{ and } a = 1\,,$$

$$\tau_{light} = 24\left(\frac{a}{R_g}\right)^{-1}\left(R_g m\right)^{-9} R_g\,, \qquad \text{for } R_g m \ll 1\,,$$

$$\tau_{optimal} = 0.6 \times 10^7 R_g\,, \qquad \text{for } R_g m \approx 0.4$$

Always a slow process

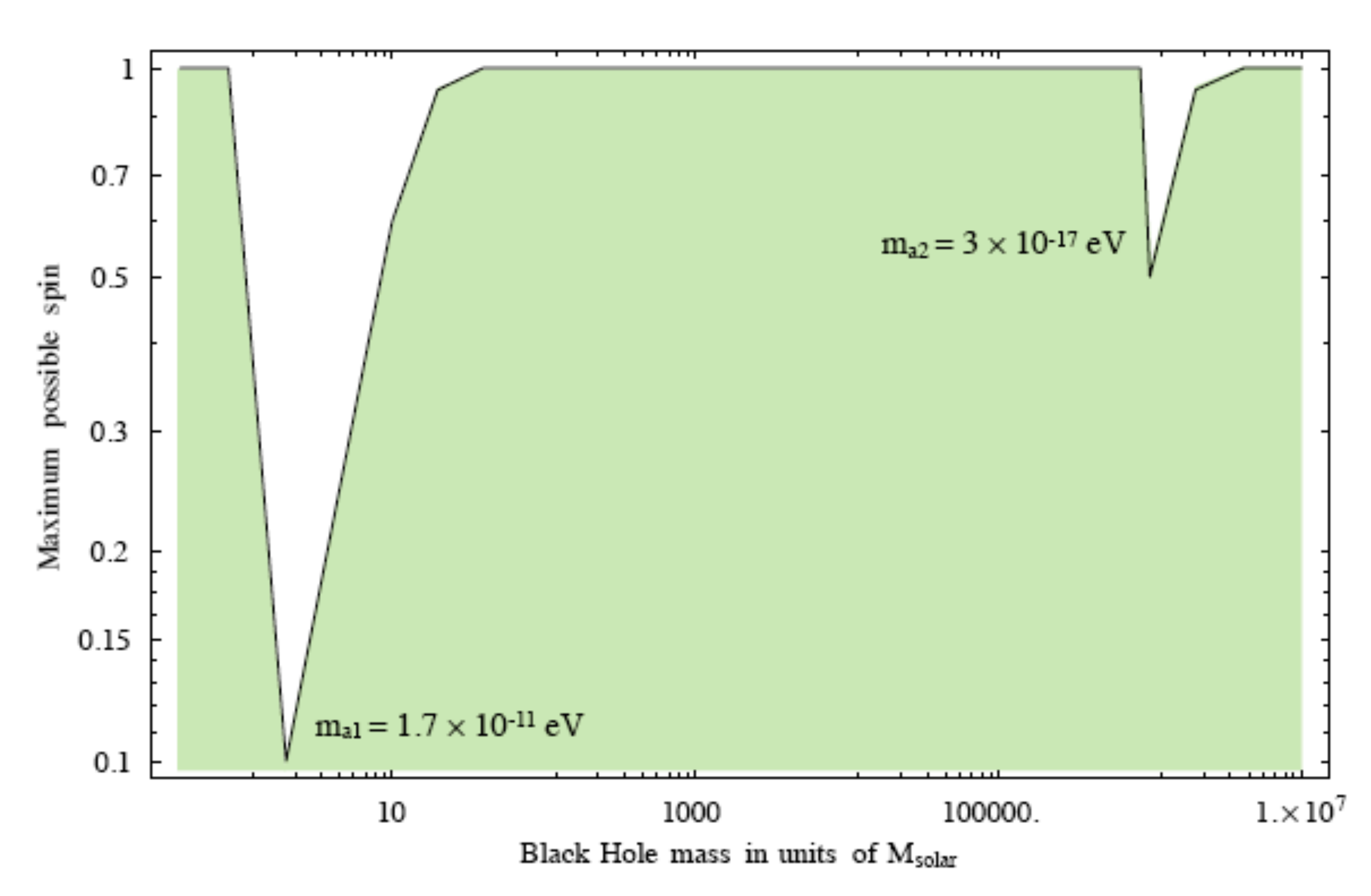


stationary regime: $M_{axions} \simeq 10^{-7} M_{BH}$ for $M_{BH} \gtrsim 10^7 M_\odot$

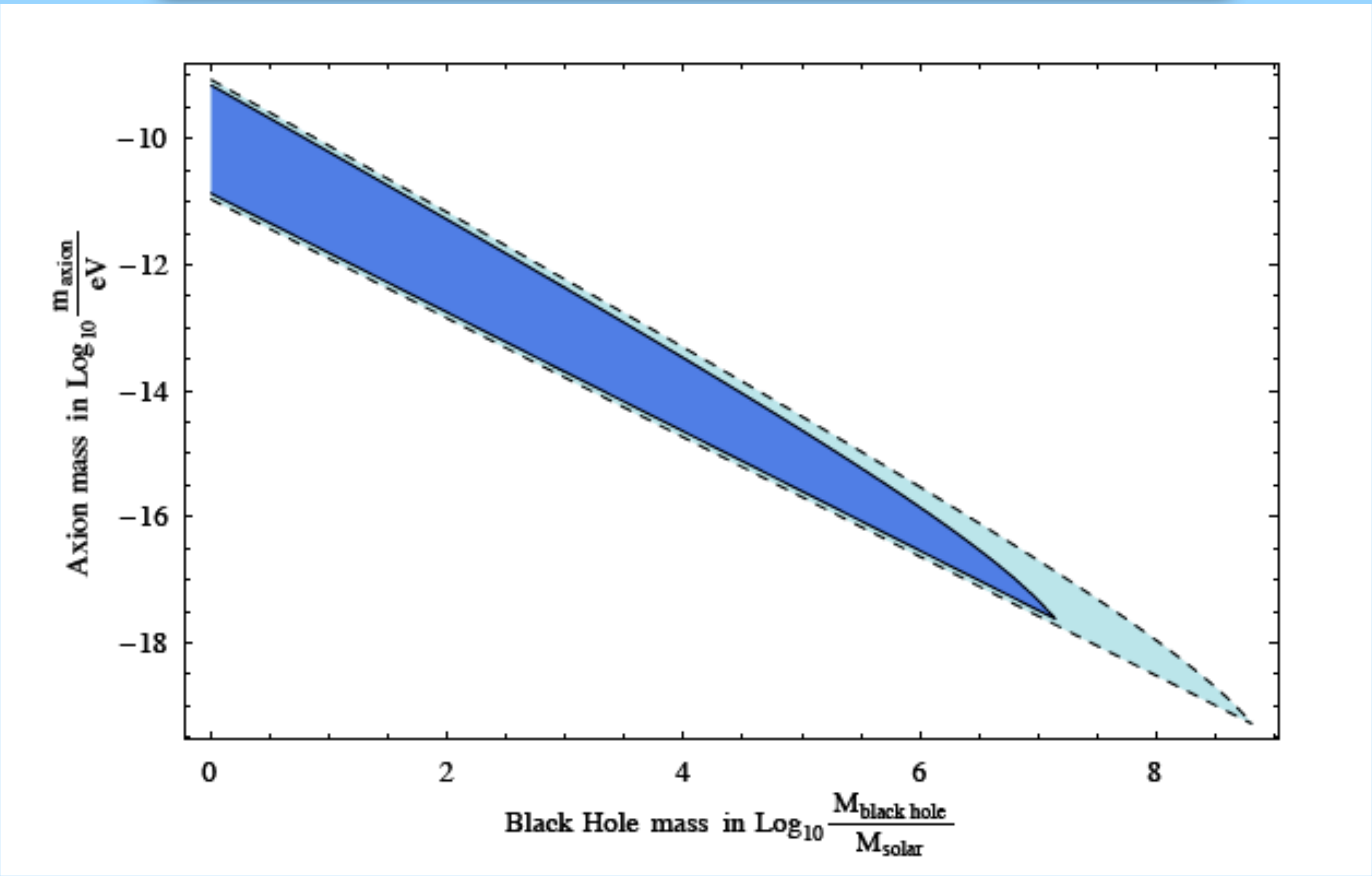
$$h \sim 3 \times 10^{-22} \left(\frac{10^{-2}\text{Hz}}{\nu}\right)^{1/2} \left(\frac{M}{10^7 M_\odot}\right)^{1/2} \left(\frac{100 \text{ Mpc}}{L}\right)$$

GW pulsar?!

Black hole Regge plot



Precision Black Hole Physics



Current data:

several stellar mass rotating BH's

one $\sim 3 \times 10^6 M_\odot$

Reach for the QCD axion

detector for the GUT scale QCD axion:

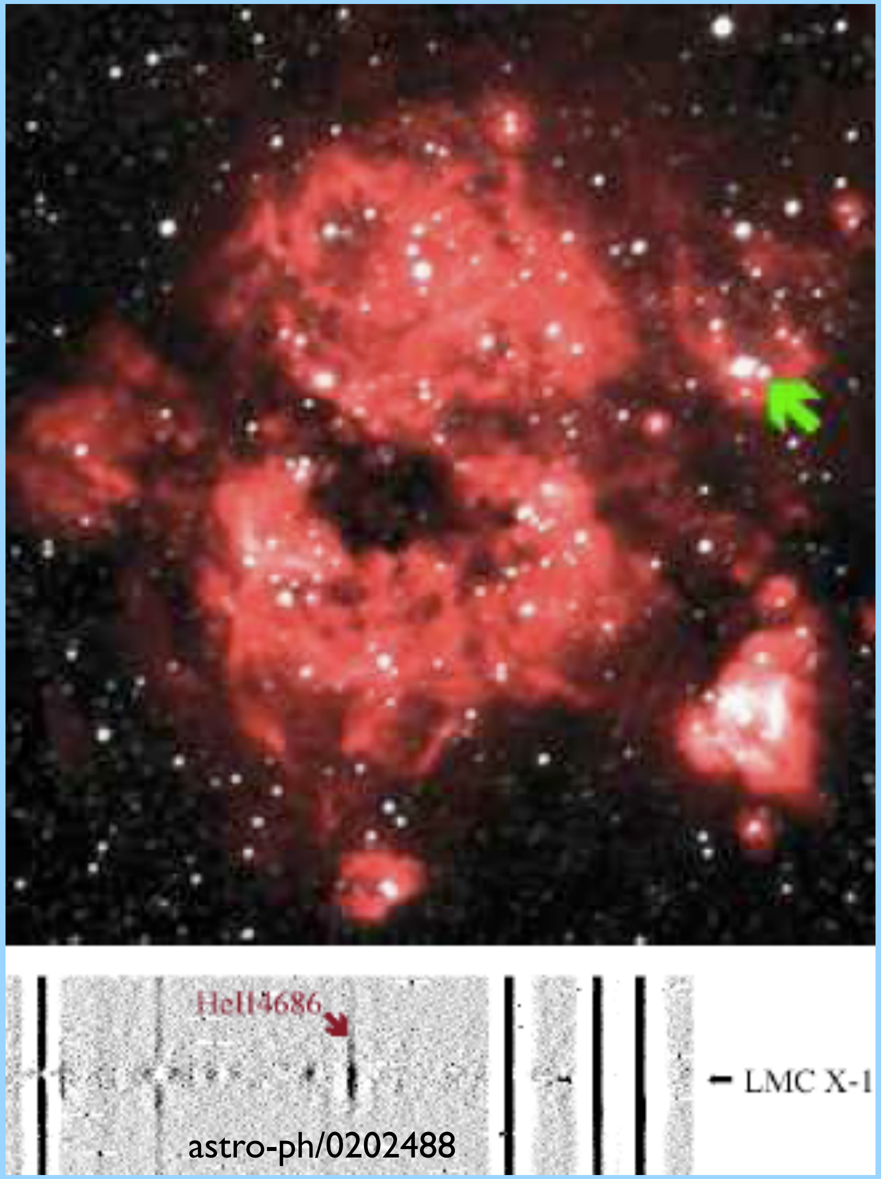
LMC X-1

$$10M_\odot\,,\;\; a/R_g = 0.91$$

$$f_a \lesssim 2\times 10^{17}\ \mathrm{GeV}$$

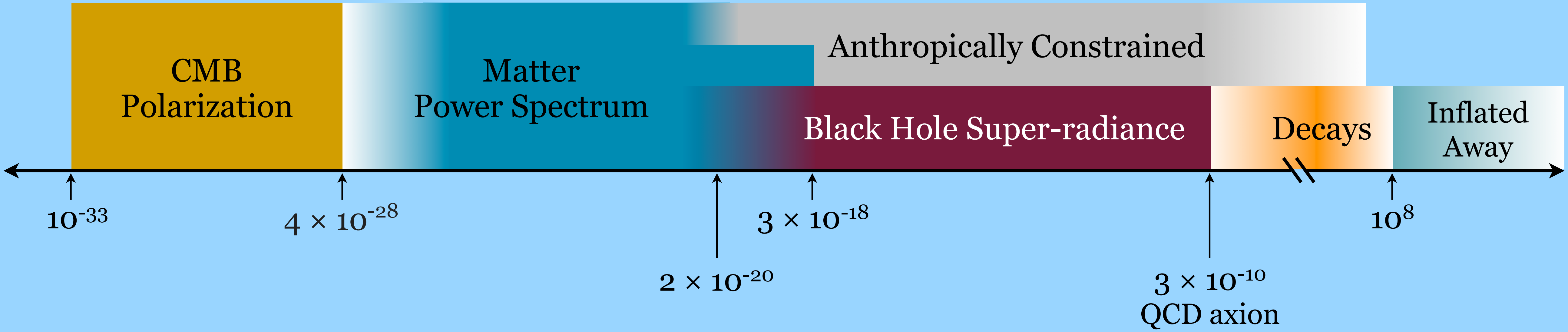
$2M_\odot\,,\;\; a/R_g = 1$ would probe

$$2\times 10^{16}\ \mathrm{GeV}$$



In the next decade cosmo and astro observations will be exploring 23 orders of magnitude in energy

Taking strong CP and properties of axions in string theory seriously, suggests this is not a desert, and we have a chance to be observationally exploring the topology of the compactification manifold



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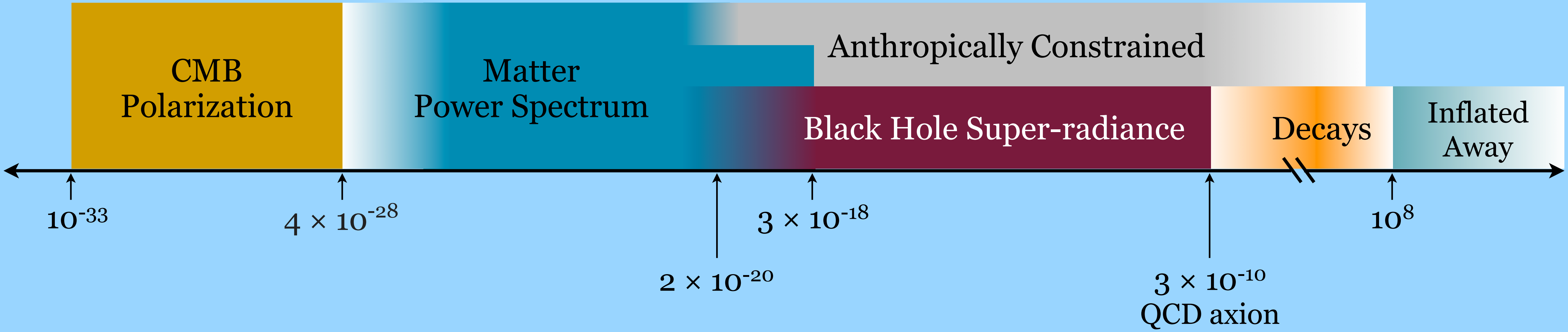
A couple of afterthoughts:

- Multiplicity of axions provides a chance to check observationally statistical studies of the string landscape/inflationary measures



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- Multiplicity of axions provides a chance to check observationally statistical studies of the string landscape/inflationary measures
- Could axions themselves be responsible for the scanning of the CC?