Exploring the String Axi- & Photi-verses with Cosmo/Astrophysics and the LHC

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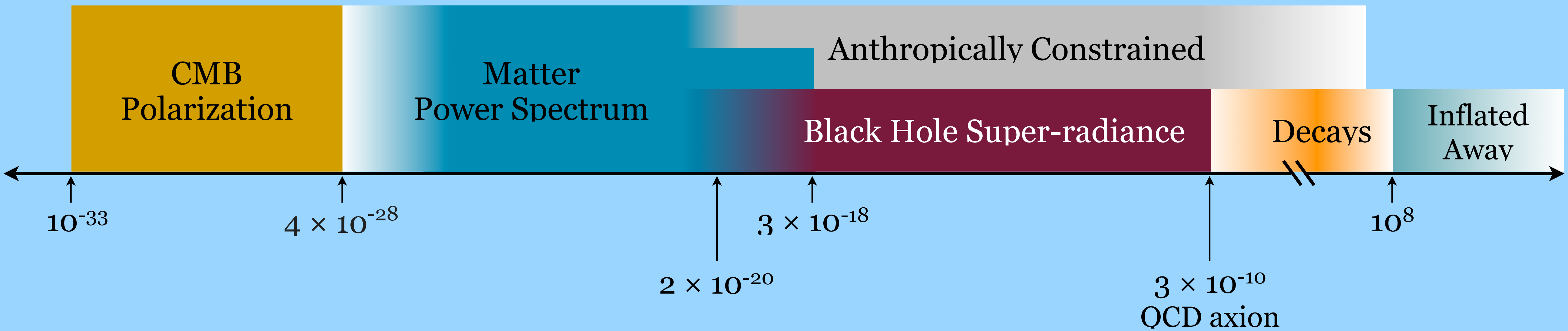
arXiv:0905.4720 and more to come...

The Axiverse

Taking strong CP and properties of axions in string theory seriously, there exists a **plenitude of axions** with log-flat distribution of masses

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



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

Neutron e.d.m.

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

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

A clear call for new dynamics

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

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

$f_a \lesssim 10^9 \mathrm{GeV}$ 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

Qu: is a fake symmetry broken by QCD plus $< 10^{-10} \times$ QCD common in a fundamental theory?

In string theory: YES!

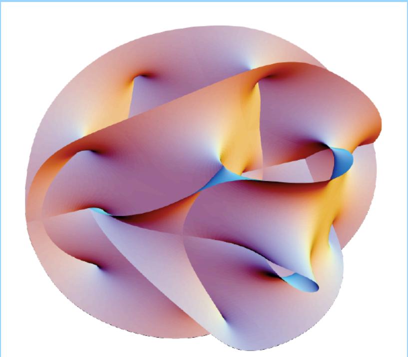
antisymmetric forms

B_2

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

$C_{1,3}$ (IIB)

compactification →



many (100-10000) 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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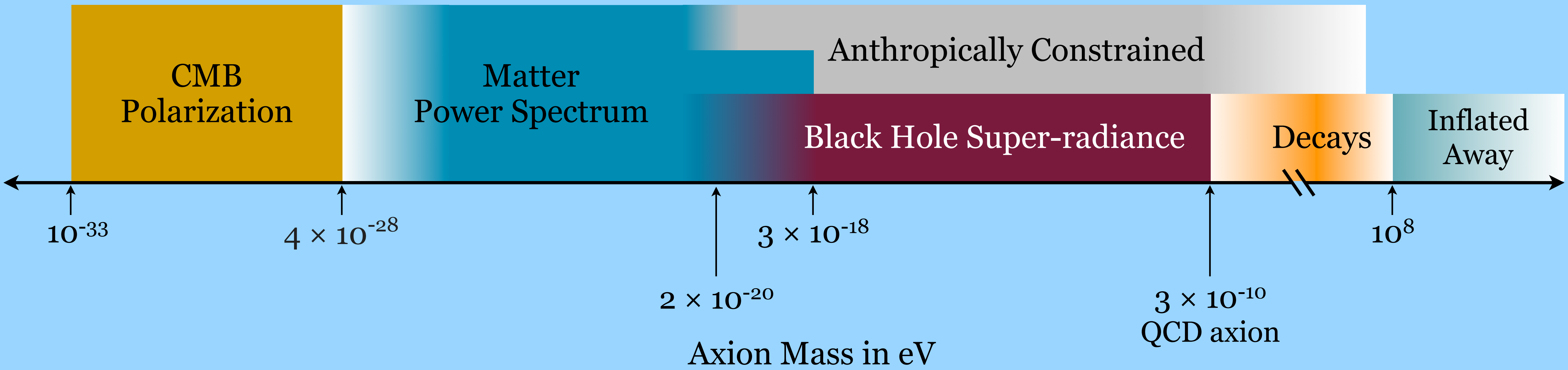
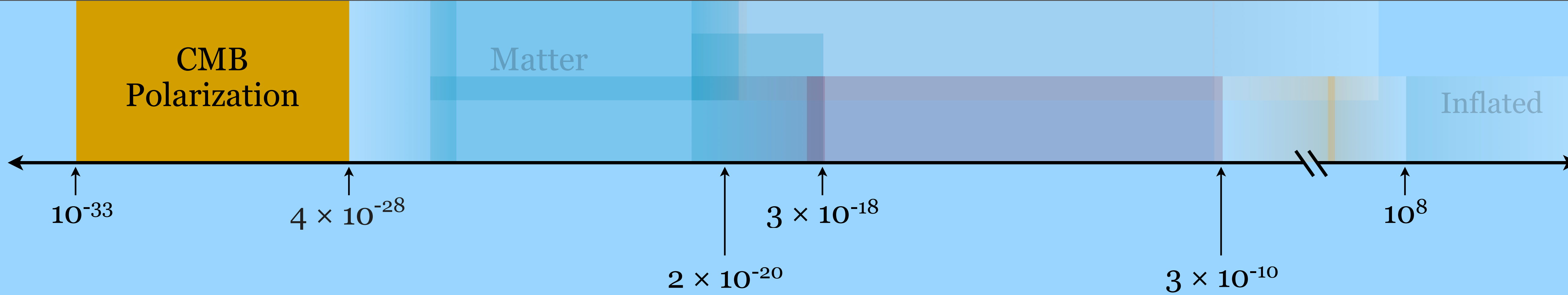
in explicit examples one finds: $f_a \sim \frac{M_{Pl}}{S}$

"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)





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

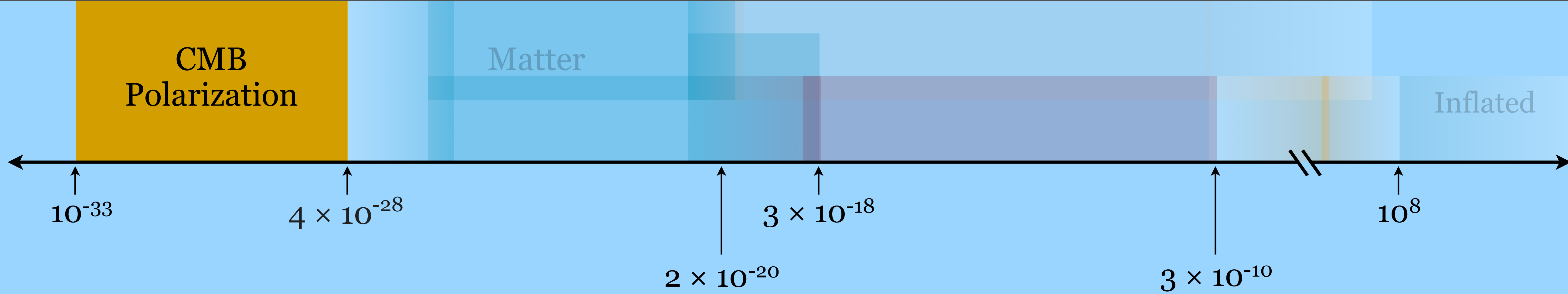
for slowly varying axion field

$$\vec{D} \equiv \left(\vec{E} + \frac{1}{2} \frac{C\alpha}{\pi f_a} a \vec{B} \right) \qquad \vec{H} \equiv \left(\vec{B} - \frac{1}{2} \frac{C\alpha}{\pi f_a} a \vec{E} \right)$$

satisfy free wave eqns giving rotation of the CMB polarization

$$\Delta\beta = \frac{C\alpha}{2\pi f_a} \int d\tau \dot{a} = \frac{C\alpha}{2\pi f_a} \left(a(\tau_0) - a(\tau_{rec}) \right)$$

transforms E-mode into B-mode
BB, BT, EB cross correlations



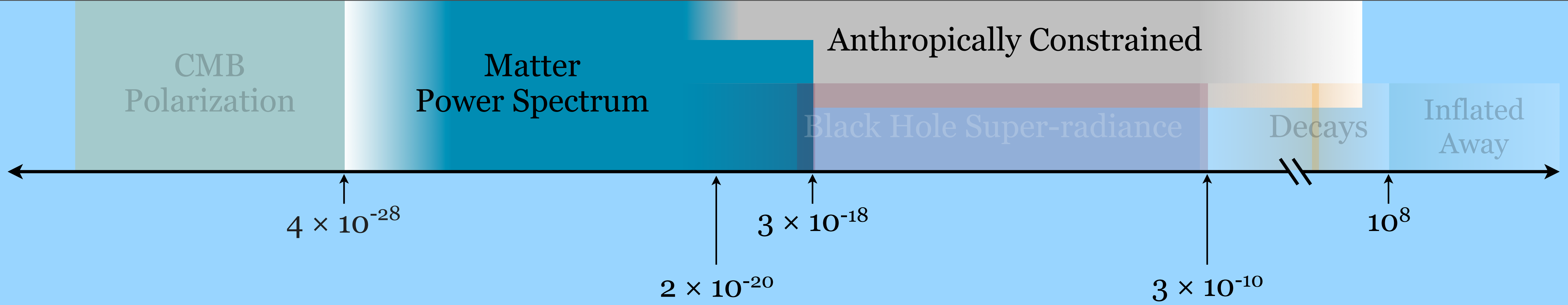
rotation angle max for $m_a < H(\tau_{rec})$ and $m_a > H_0$

axion field primordial value set during inflation

$$\langle a(\tau_{rec}) \rangle \sim \pi f_a / \sqrt{3}$$

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

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

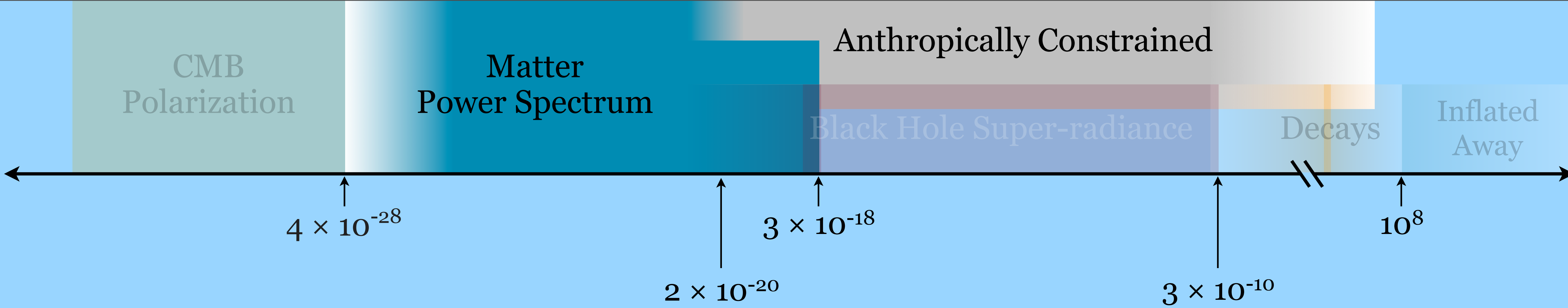


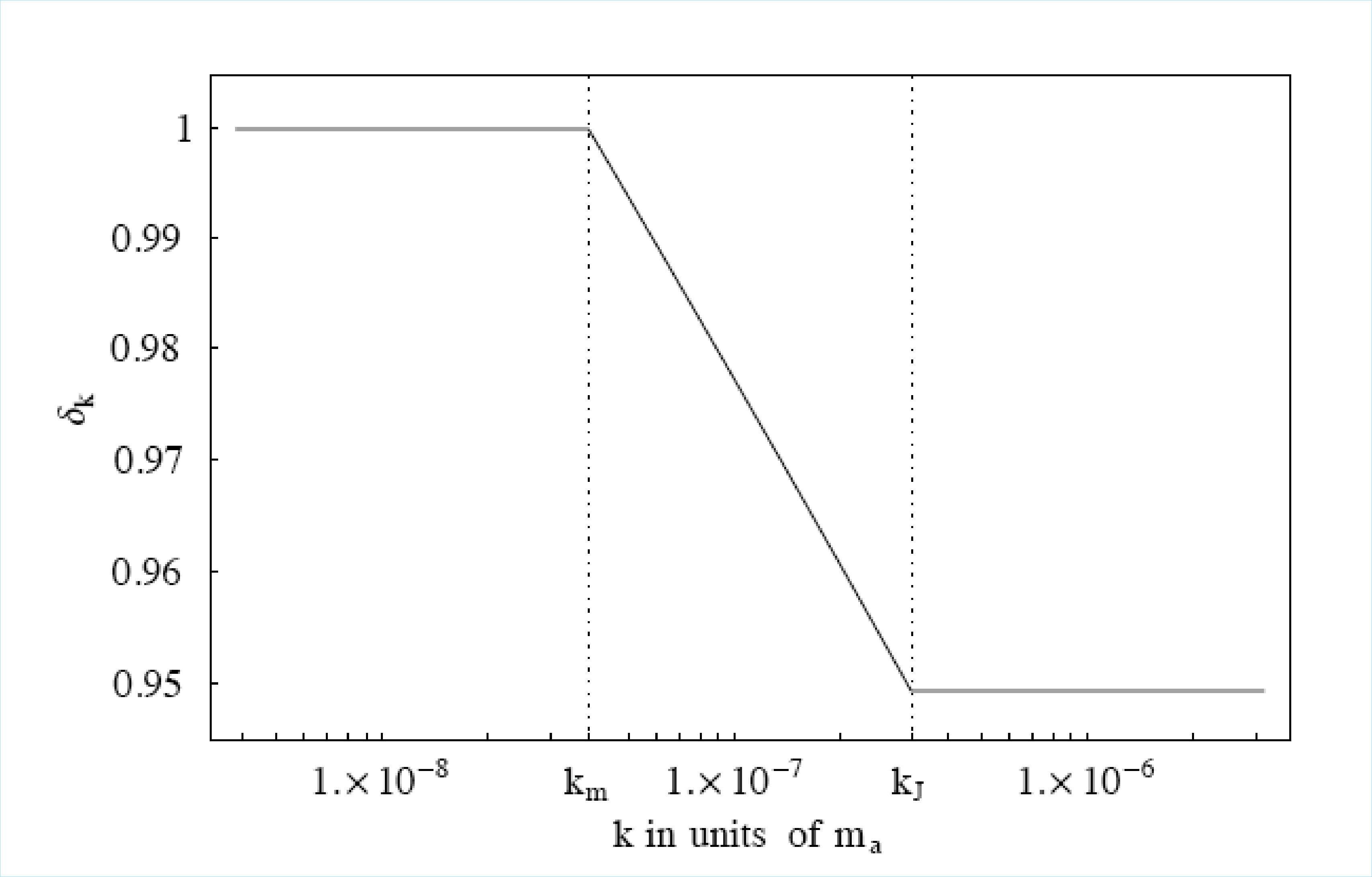
Purely gravitational signature: presence of steps in matter power spectrum if axions part of DM

Axion DM behaves just like ColdDM (despite being a BEC) except at "small" scales where

Uncertainty Principle prevents density perturbation growth at

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





$$k_m \sim (mH_0)^{1/2}(\Omega_m/z_{eq})^{1/4}$$

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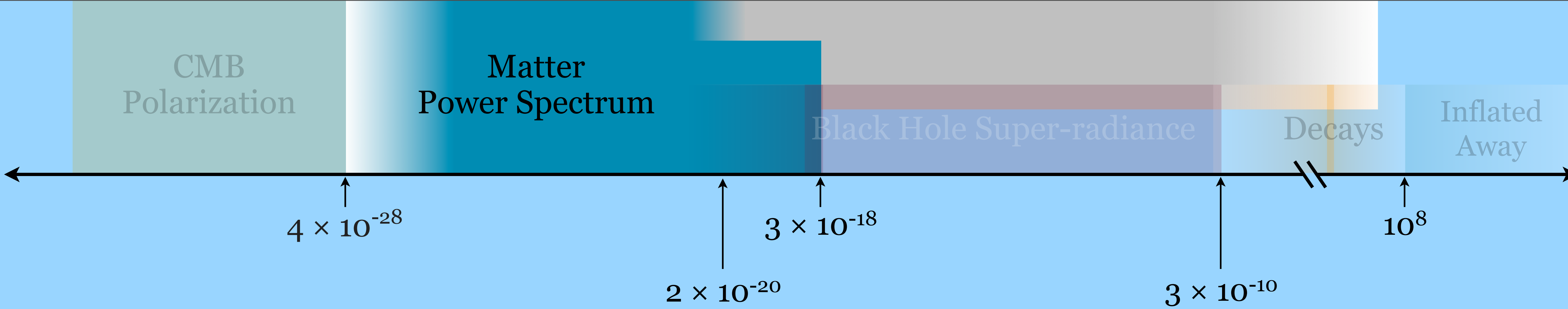
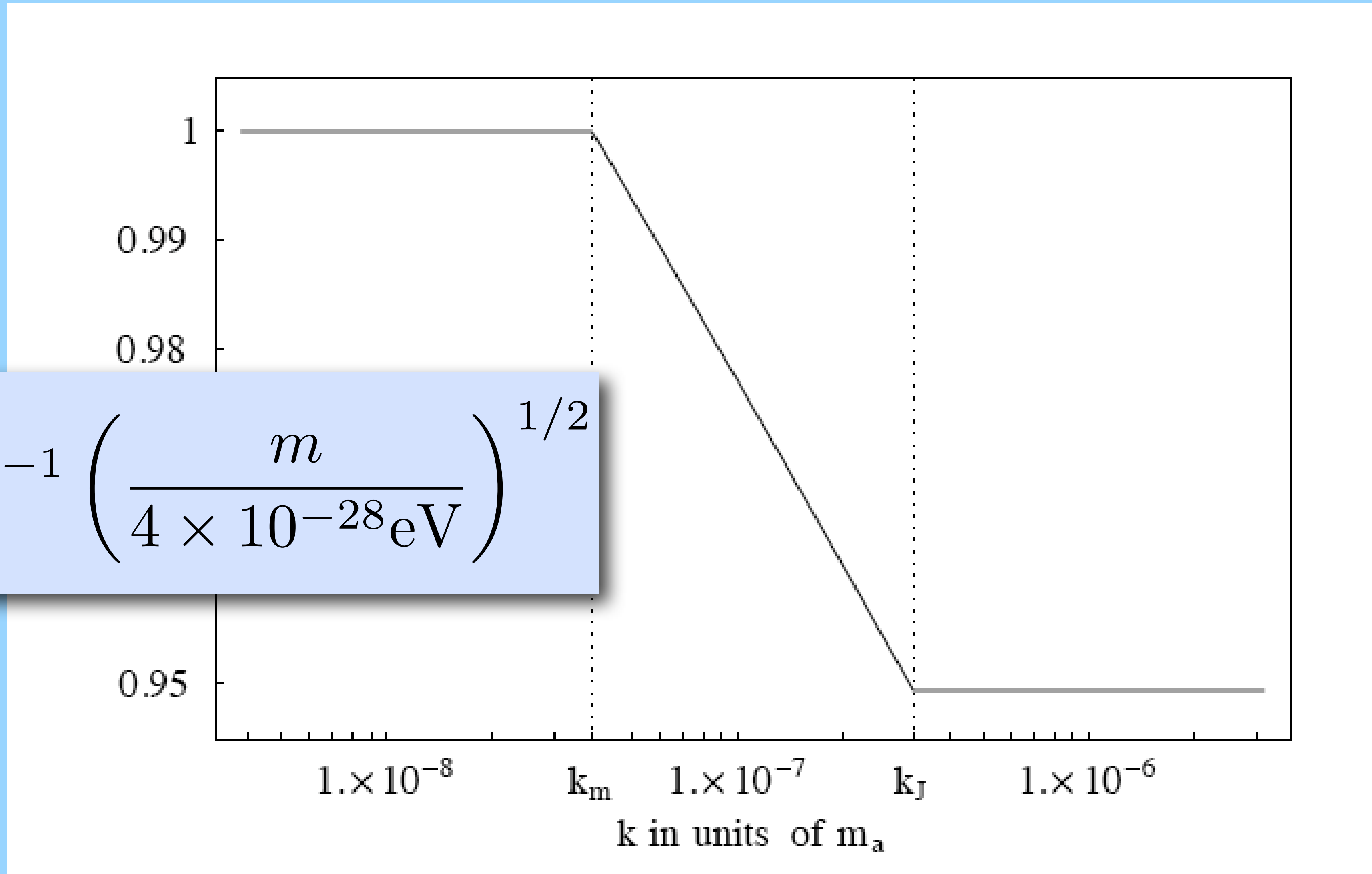
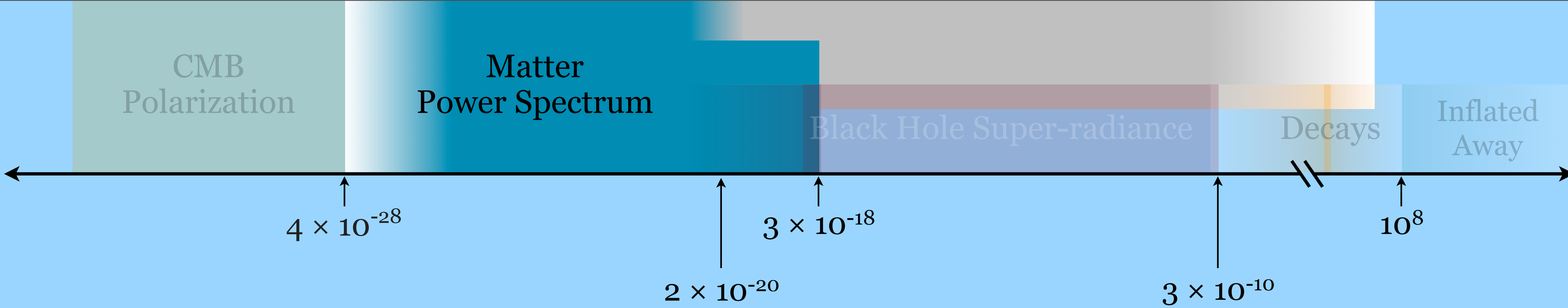


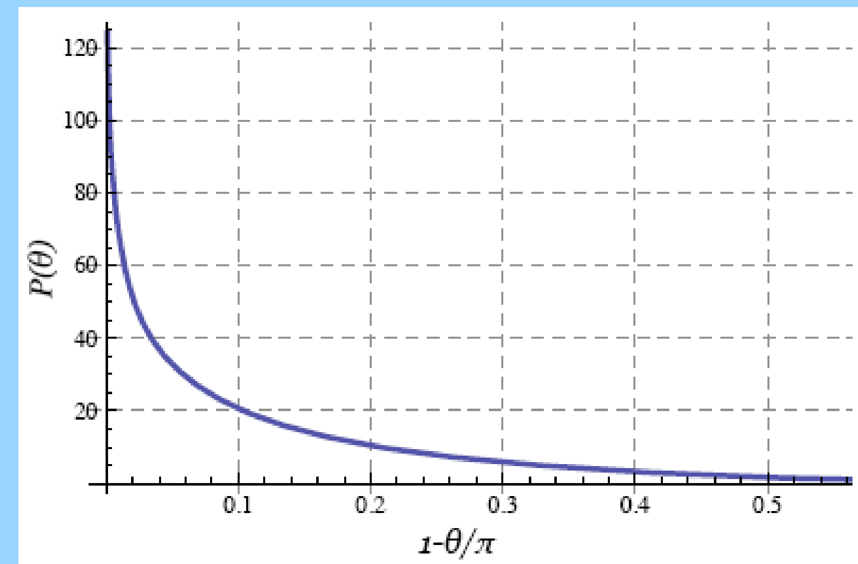


$$k_m = 0.01\text{Mpc}^{-1}\left(\frac{m}{4\times 10^{-28}\text{eV}}\right)^{1/2}$$

step size: $S = \frac{\Omega_a}{\Omega_m}\log z_{eq}/z_{obs} \approx 8\frac{\Omega_a}{\Omega_m}$ for typical observation z



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



Future large-scale structure obs:

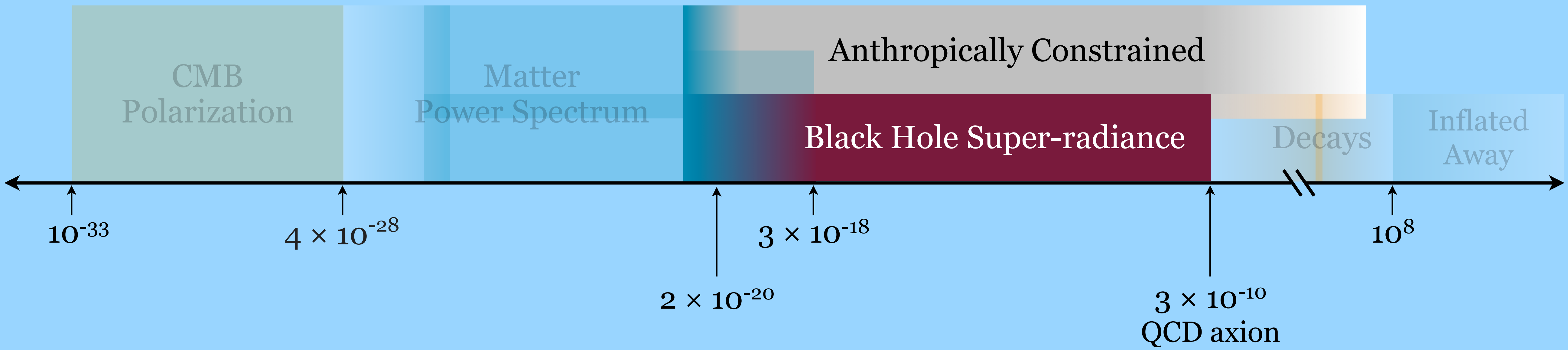
BOSS (SDSS III): S few % at $k \sim 0.1\mathrm{Mpc}^{-1}$ $\quad m_a \sim \text{few} \times 10^{-26}\mathrm{eV}$

21 cm tomography: $k \sim 10^{-2} \div 10^{3}\mathrm{Mpc}^{-1}$ $\quad m_a < 3 \times 10^{-18}\mathrm{eV}$

Note: starting to probe anthropic region

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

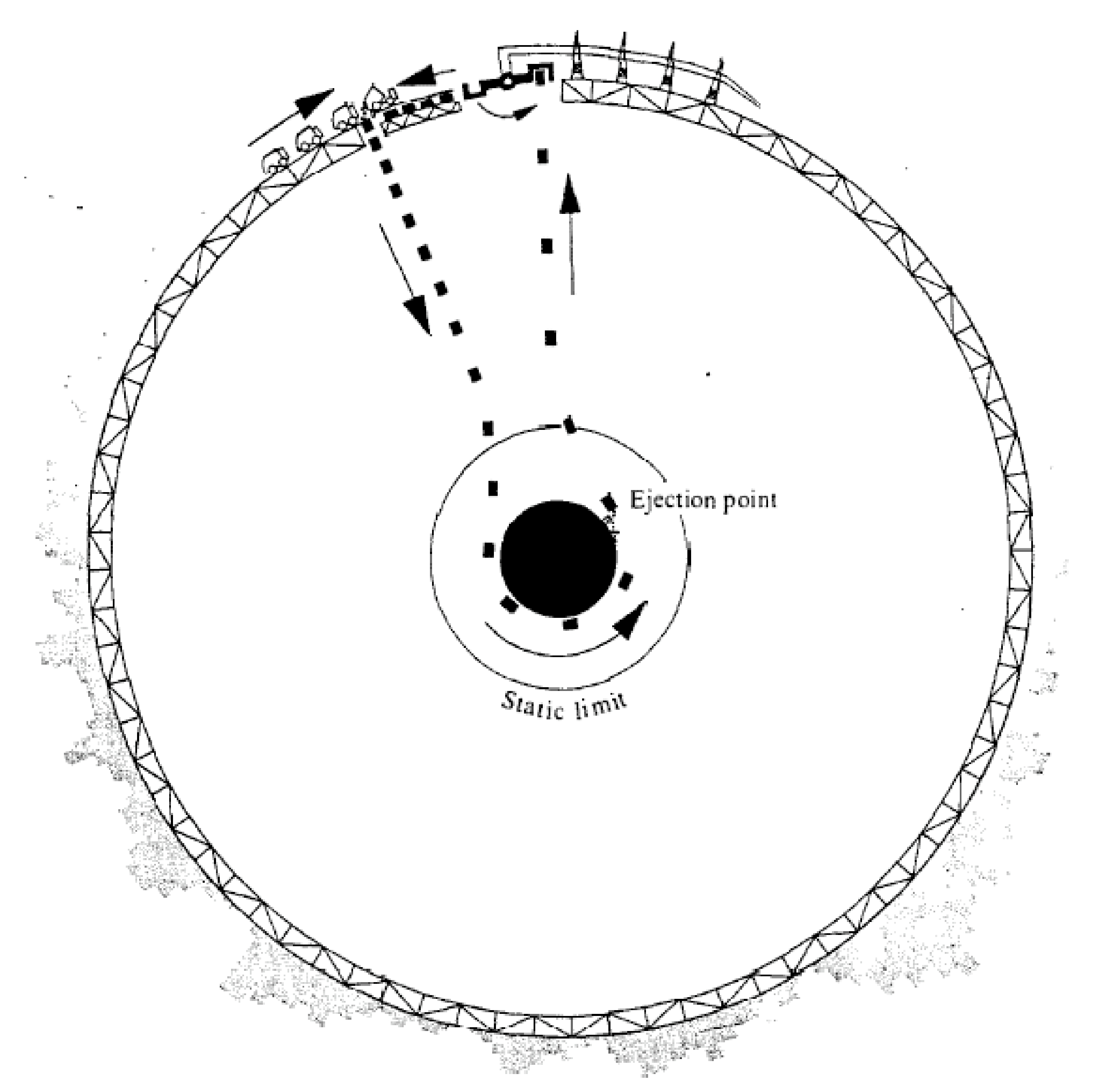
Kerr Black Hole Super-Radiance



Light axions allow Kerr black holes to efficiently spin-down via a quantum stimulated-emission process

Classical Penrose process for extracting M, J

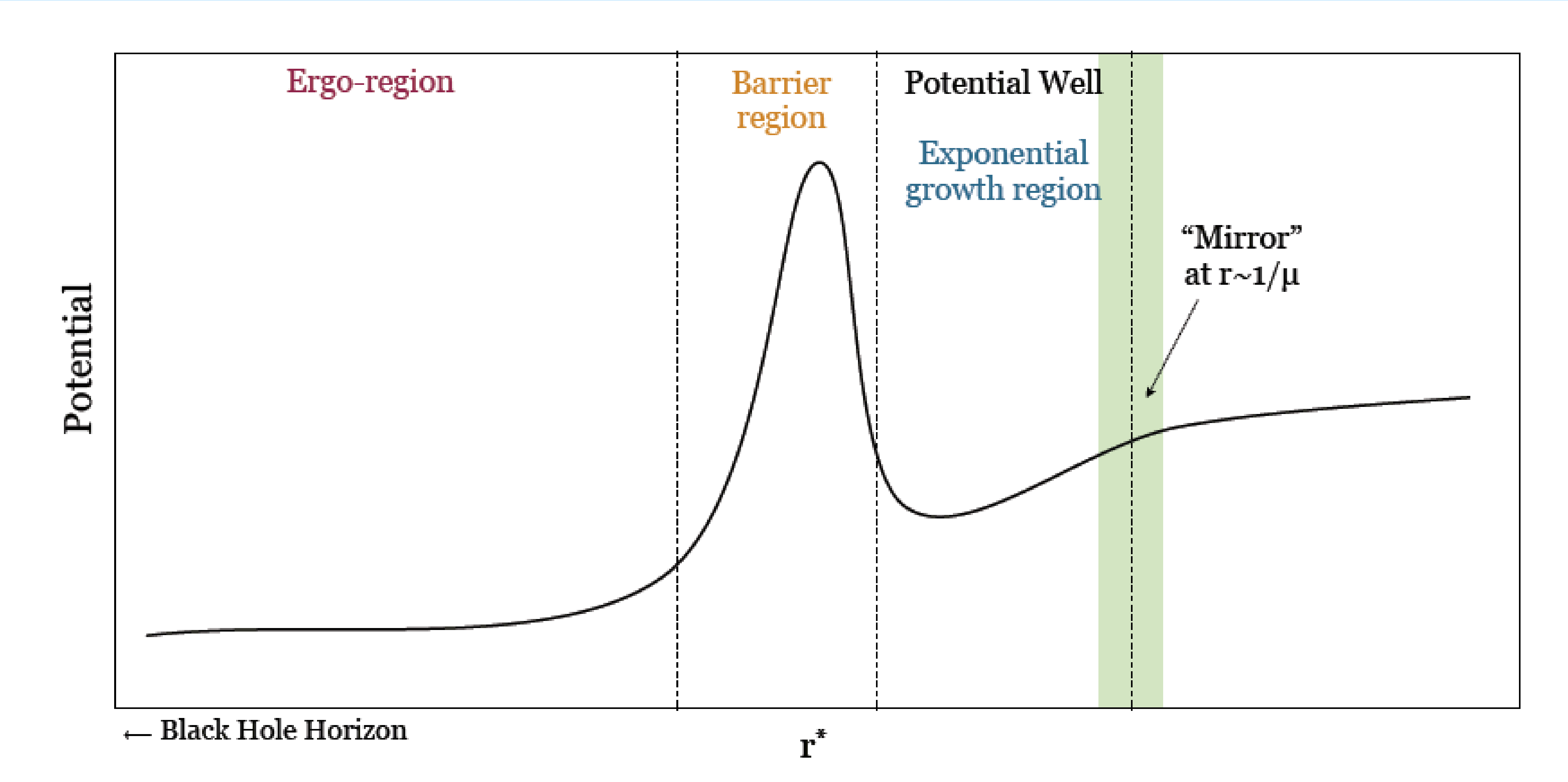
$\delta M < 0$



$\delta J < 0$

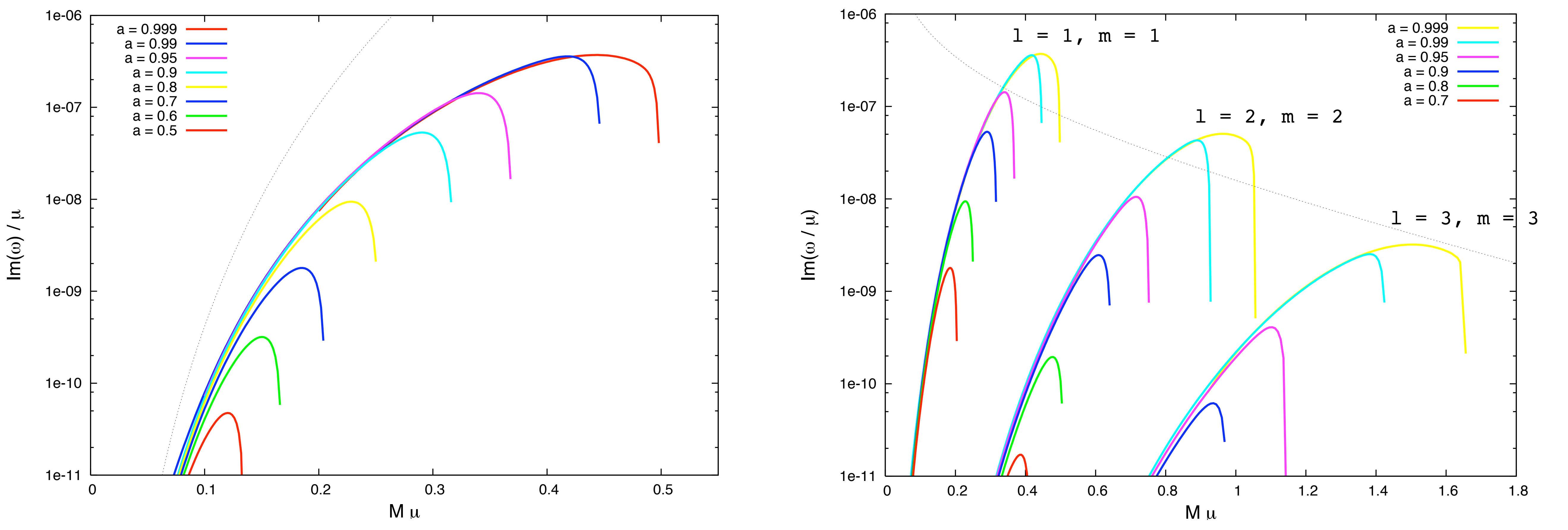
Quantumly, a scalar field in a Kerr background can have bound states with $Im(\omega) > 0$

Damour etal; Zouros & Eardly; Detweiler; Dolan



Only works for massive field with compton wavelength close to BH size

cf. Black hole 'bomb' of Press & Teukolsky



(numerical calculation from Dolan 0705.2880[gr-qc])

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

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

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

A slow process wrt R_g/c, fast compared to accretion

Result is that spin KE of BH gets transferred to orbital ang mom'm of axion cloud

Many potentially observable consequences: (work in progress)

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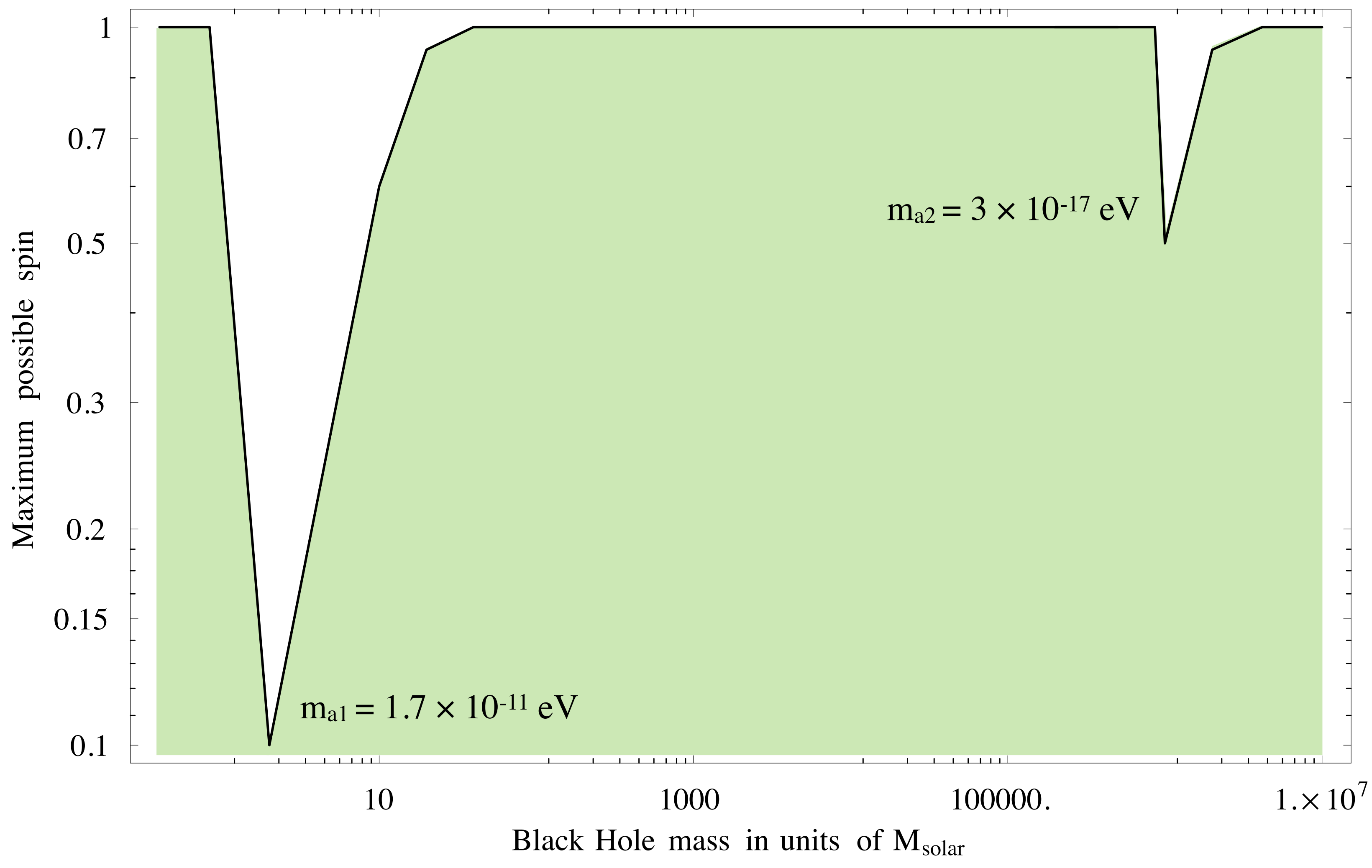
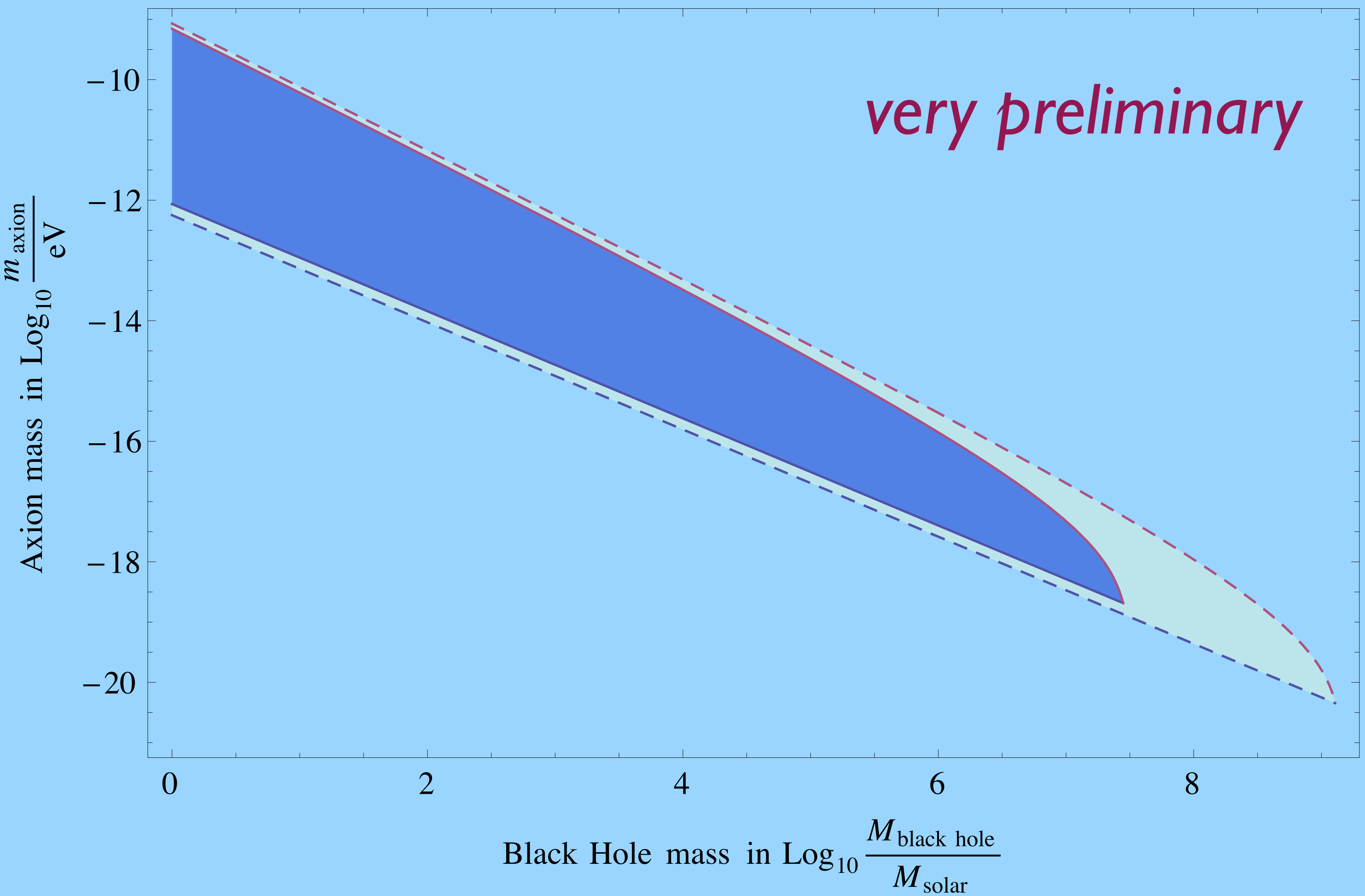
- Accelerated growth of BH's due to increased accretion rate while in low-spin regime

Black hole Regge plot



Black Hole Physics



Limits from current data:

several stellar mass highly-rotating BH's "observed"

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

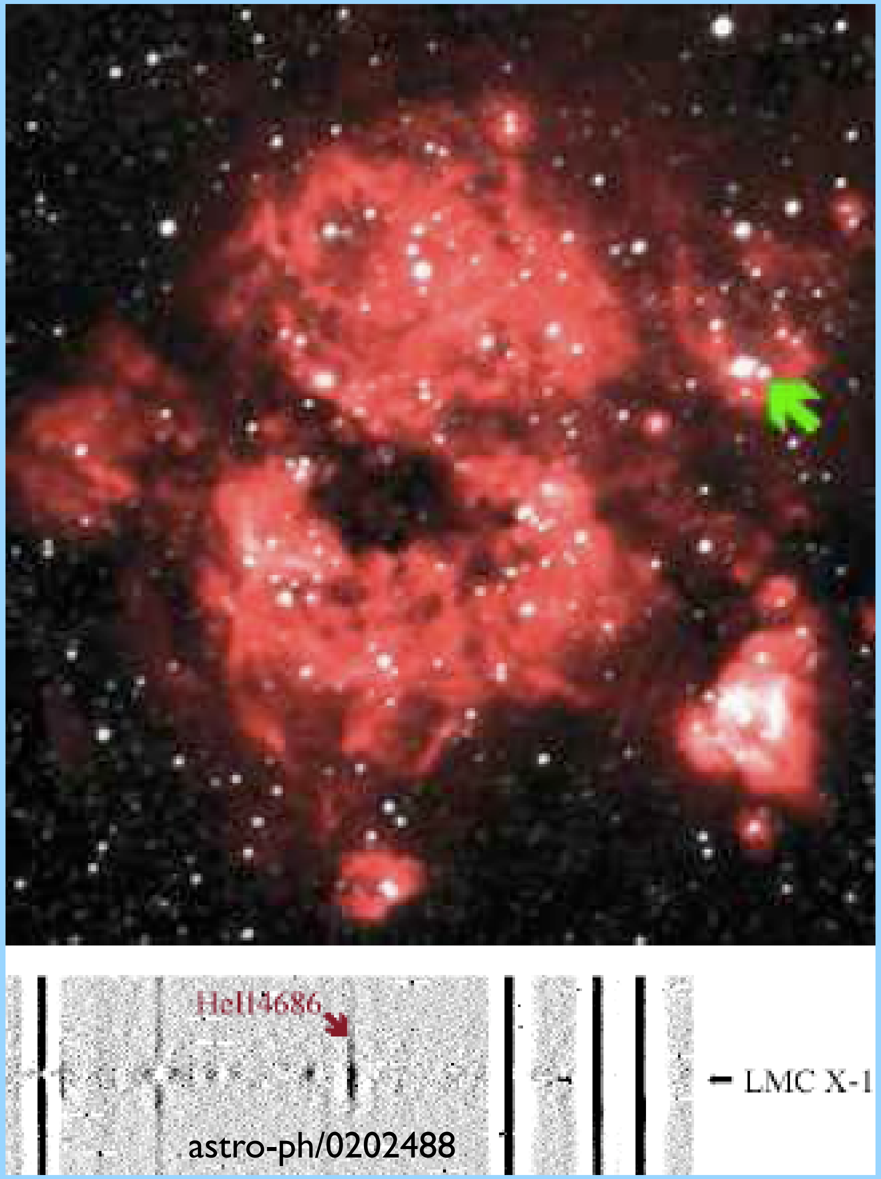
Reach for the QCD axion

detector for the GUT scale QCD axion:

LMC X-1

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

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



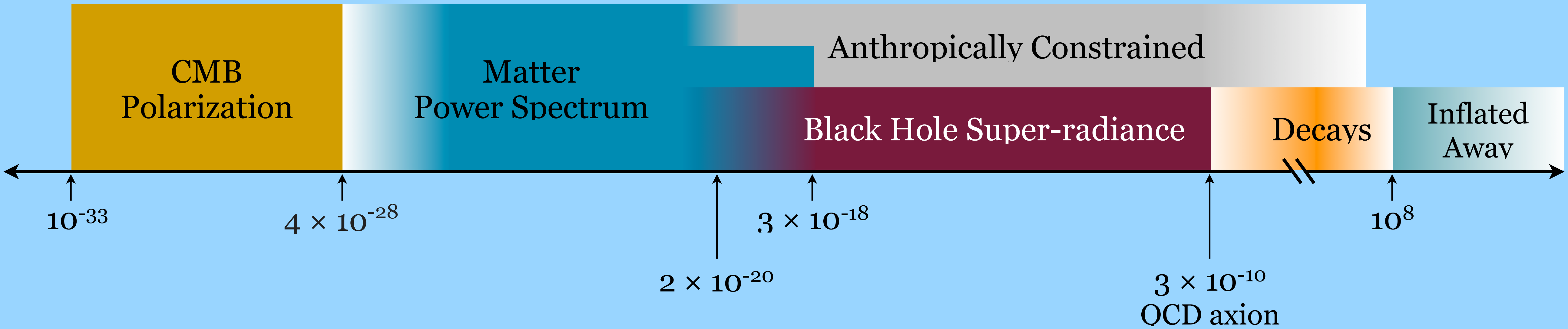
$2 M_\odot,\ \ a/R_g \sim 1$ would probe string value $f_a \sim 2 \times 10^{16}\mathrm{GeV}$

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

have a chance to observationally explore the topology of the compactification manifold

Asides:

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



Photi- & Photini-verse

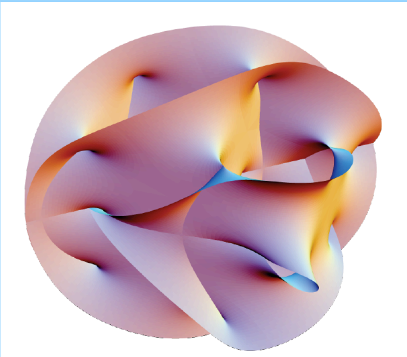
Many U(1)'s can also arise

RR antisymmetric forms

$C_4 \quad (IIB)$

$C_3 \quad (IIA)$

compactification →



many (few10's-100's)
KK zero modes from topology (cohomologies)

eg, $X_i^\mu = \int_{\Sigma_i^3} C_4$

Inherits gauge symm from underlying 10d abelian gauge symm of RR field

Important property of RR U(1)'s: typically no light charged states

due to fact that arise from multi-index fields that naturally couple to branes (Polchinski) not point particles

Uniquely couple to us via kinetic mixing with $U(1)_Y$

$$\Delta\mathcal{L} = -\frac{1}{4}\begin{pmatrix} X^i_{\mu\nu} & B_{\mu\nu} \end{pmatrix} \mathcal{F} \begin{pmatrix} X^{i\mu\nu} \\ B^{\mu\nu} \end{pmatrix}$$

$$\mathcal{F} = \begin{pmatrix} f_{ij} & \epsilon_i \\ \epsilon_j^T & 1 \end{pmatrix}$$

$\mathcal{F}$ non-decoupling & sensitive to UV physics

BUT can be diagonalized (Holdom): b/c of absence of light charged states U(1)'s entirely decouple from us

only remnant: hypercharge norm changes: $g_Y \to \frac{g_Y}{\sqrt{1-\sum_i \epsilon_i^2}}$

No signals from photons

BUT the photini are coupled

difference is that they are massive from susy-breaking

$$\delta\mathcal{L} = iZ_{ij}\lambda_i^\dagger \not{\partial}\lambda_j + m_{ij}\lambda_i\lambda_j$$

and both kinetic and mass-mixing with bino are possible

Mass eigenstates interact with MSSM states via "bino portal"

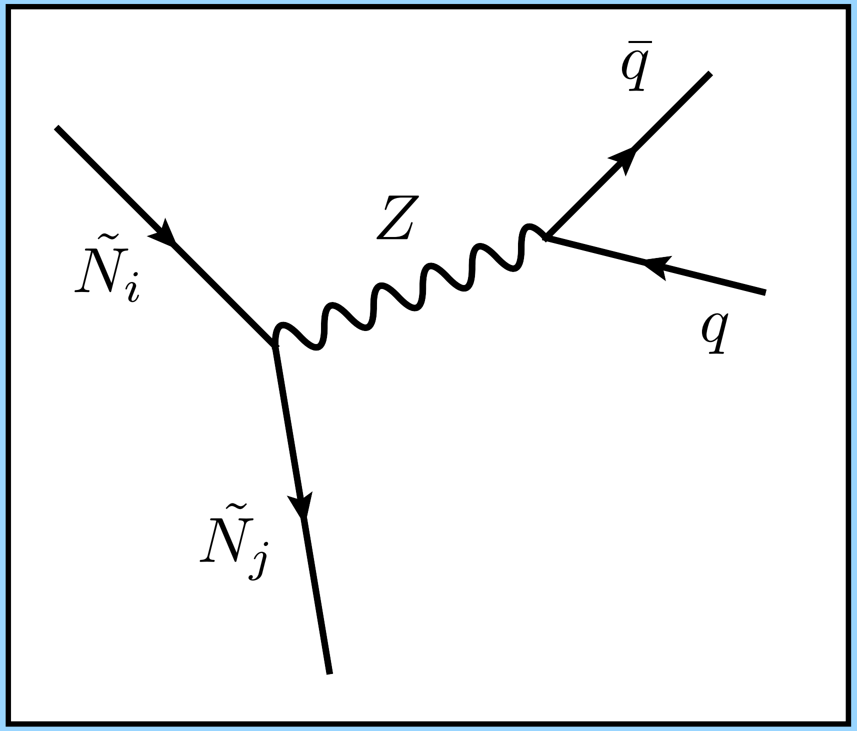
Let $\tilde{N}_I$ be mass e'states $I, J = 1, ..., n+4$

$$\tilde{N}_I = f_{IJ}\lambda_J$$

$$\lambda_I = (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u, \tilde{\gamma}_1, ..., \tilde{\gamma}_n)$$

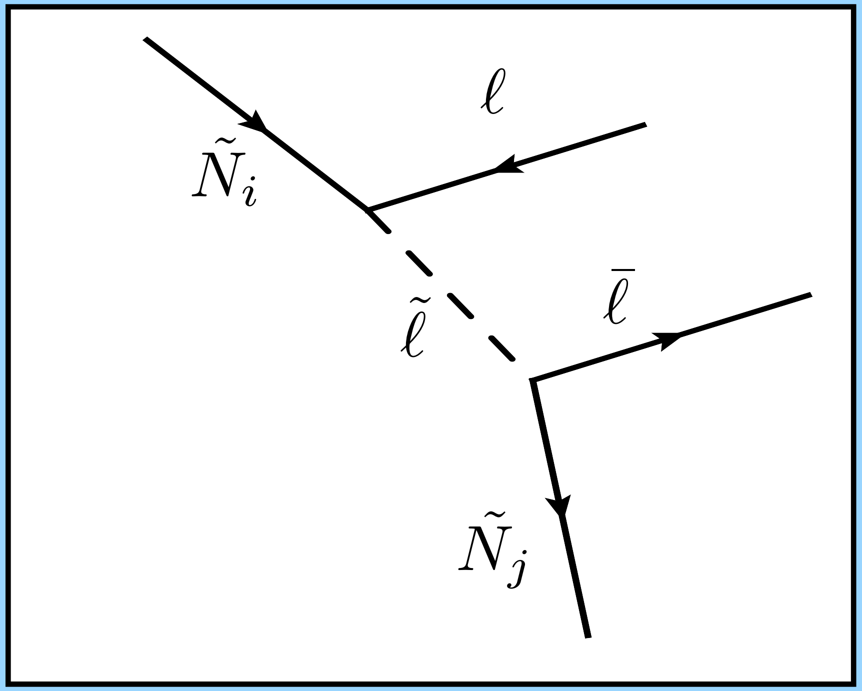
Inter-photini decays

$$f_{i1} \simeq \epsilon_i \frac{m_i}{m_1 - m_i} \qquad f_{i(2,3,4)} \simeq f_{1(2,3,4)} \epsilon_i \frac{m_i}{m_1 - m_i}$$



$$\Gamma^{Z^*}(\tilde{N}_i \rightarrow \tilde{N}_j + f\bar{f}) \simeq$$

$$\frac{\alpha_W^2 \times \text{MSSM mixings}}{192\pi^3} (\epsilon_{eff,ij})^4 \left(\frac{M_i M_j}{M_{\tilde{B}}^2}\right)^2 \frac{(\delta m)^5}{m_Z^4}$$



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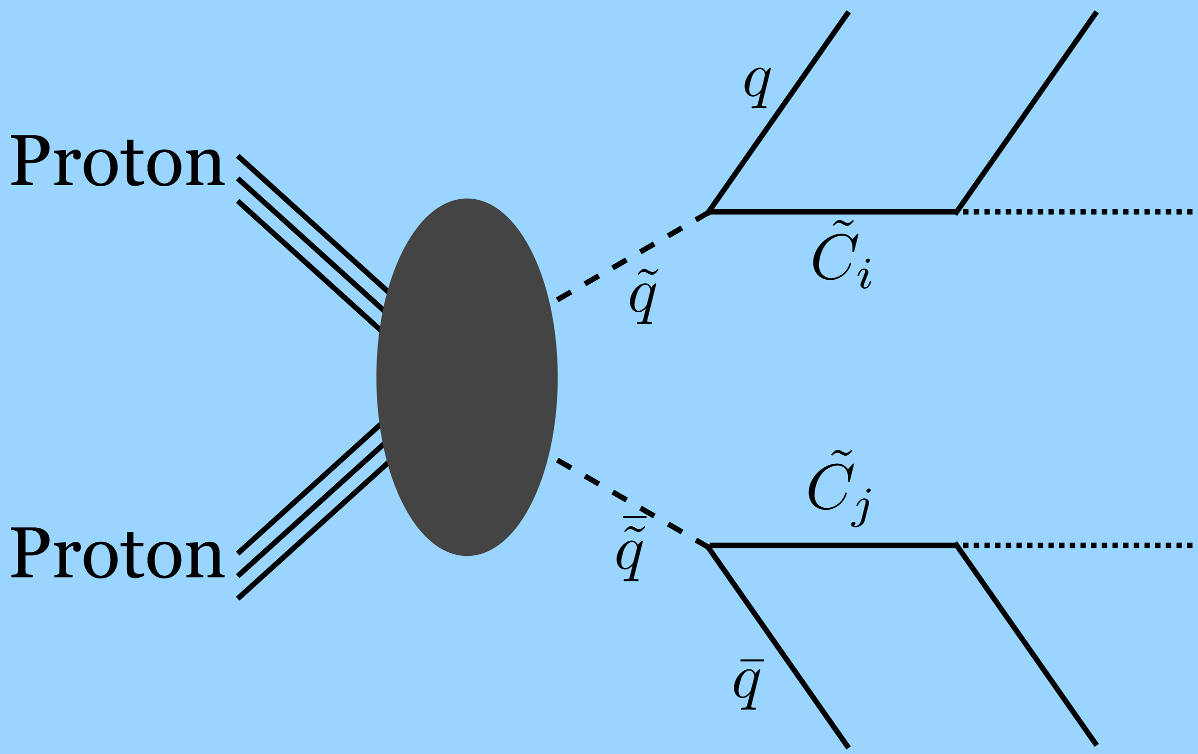
Cascade decays at the LHC



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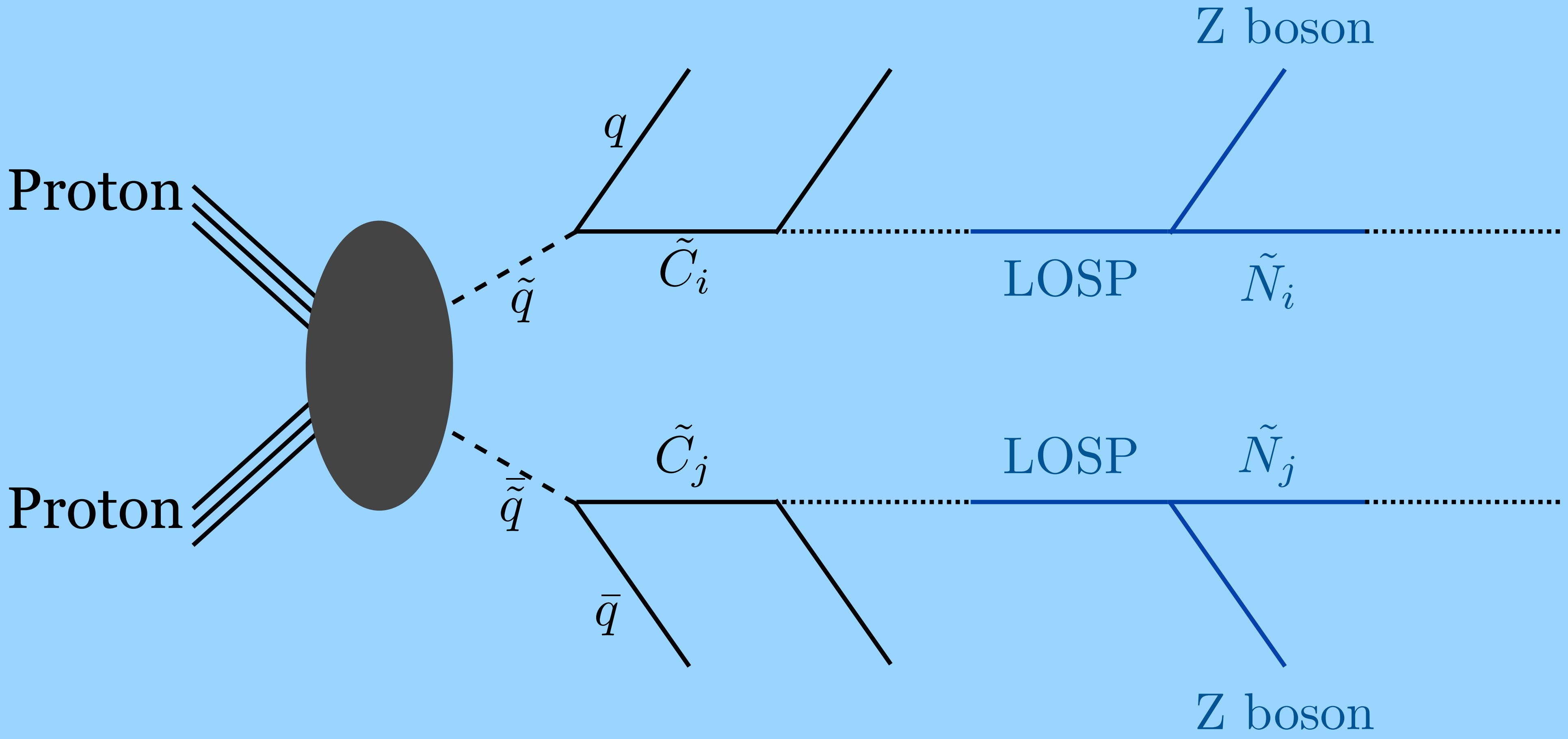

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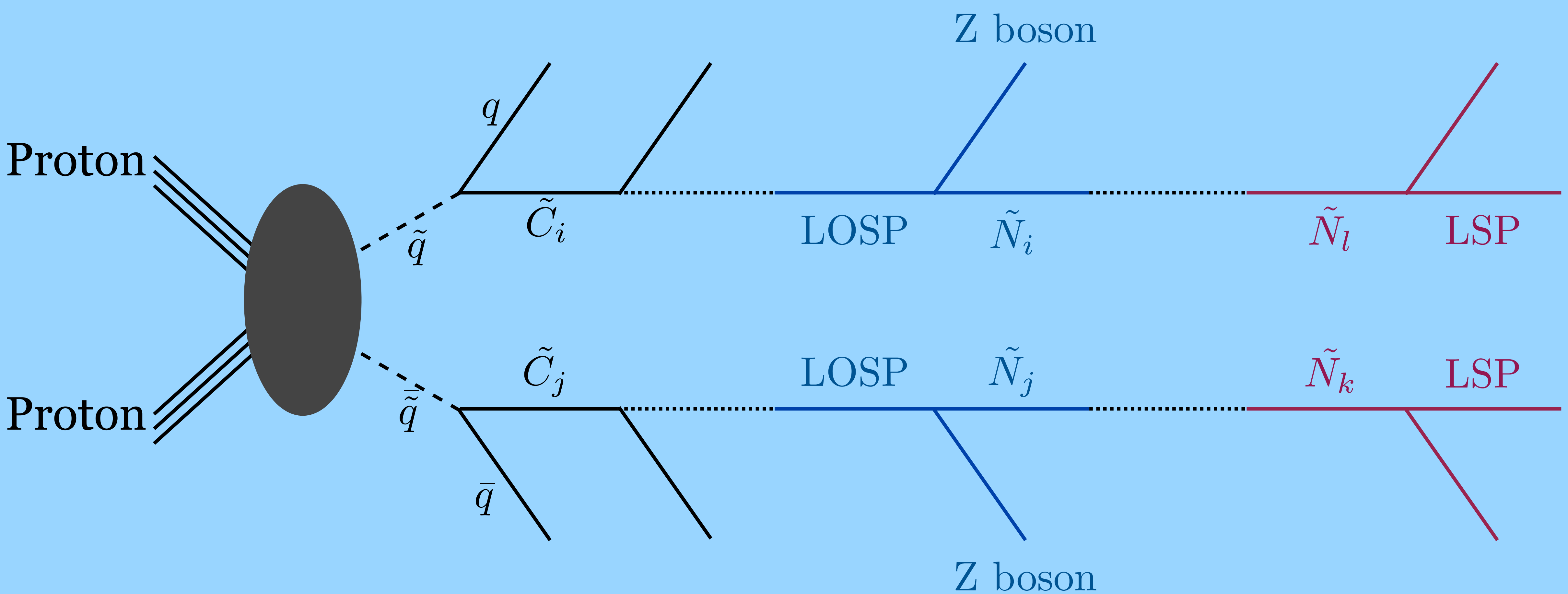
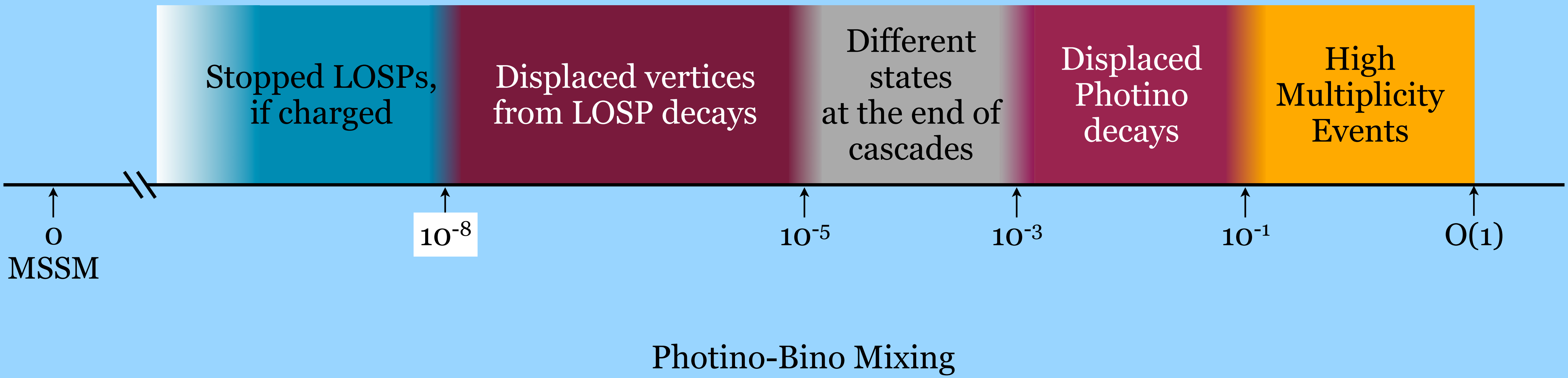


Photini signatures at the LHC



Gottfried Wilhelm Leibniz

The Principle of Plenitude:

"This best of all possible worlds will contain all possibilities, with our finite experience of eternity giving no reason to dispute nature's perfection."