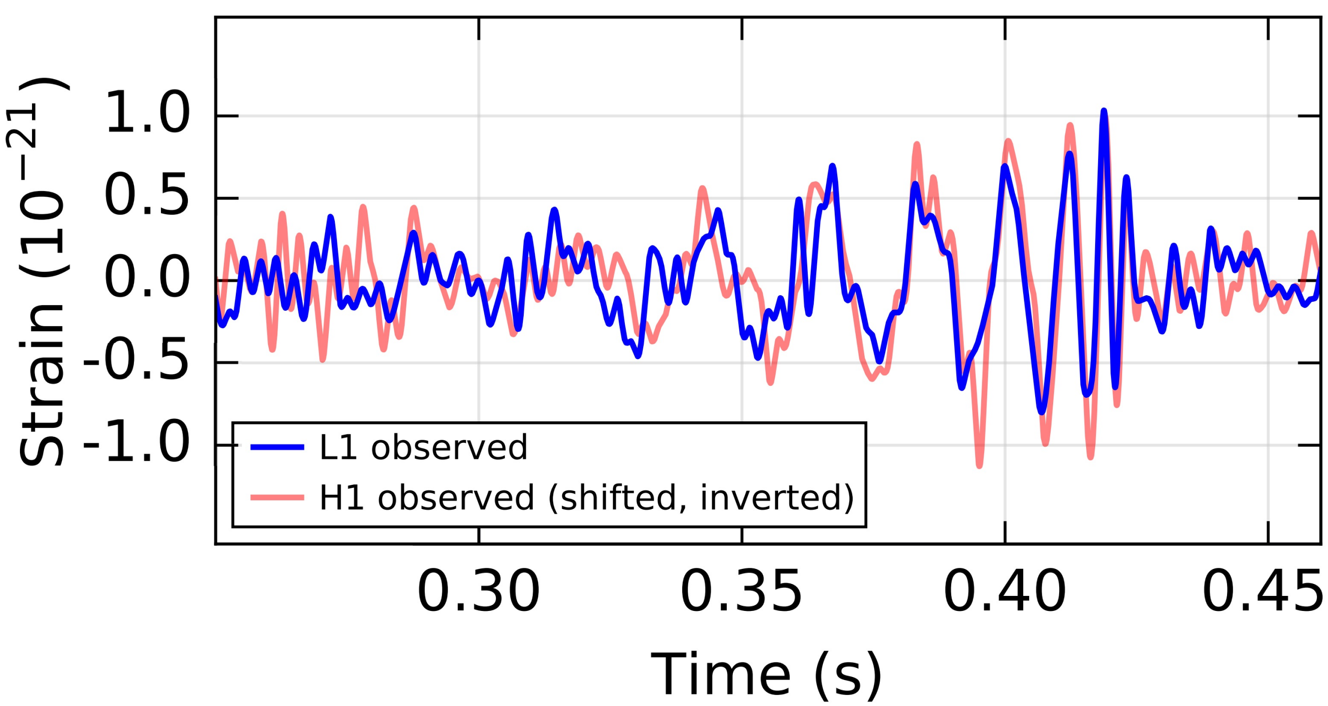
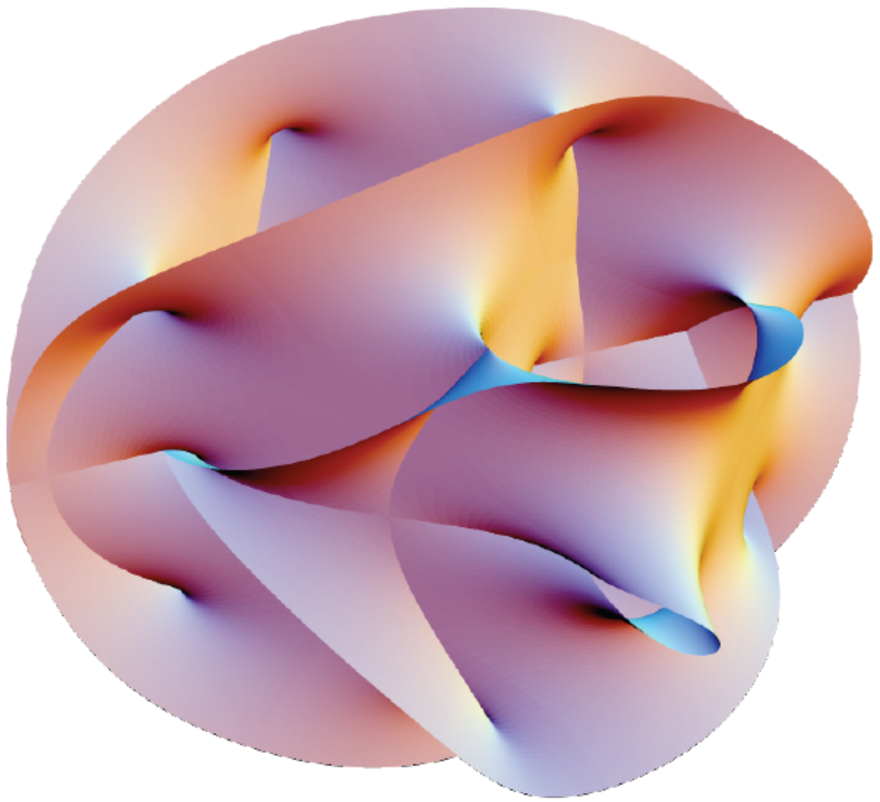
Looking for axions with astrophysical black holes

Sergei Dubovsky
CCPP (NYU)





Solvay Workshop "The dark side of black holes"

Looking for axions with astrophysical black holes

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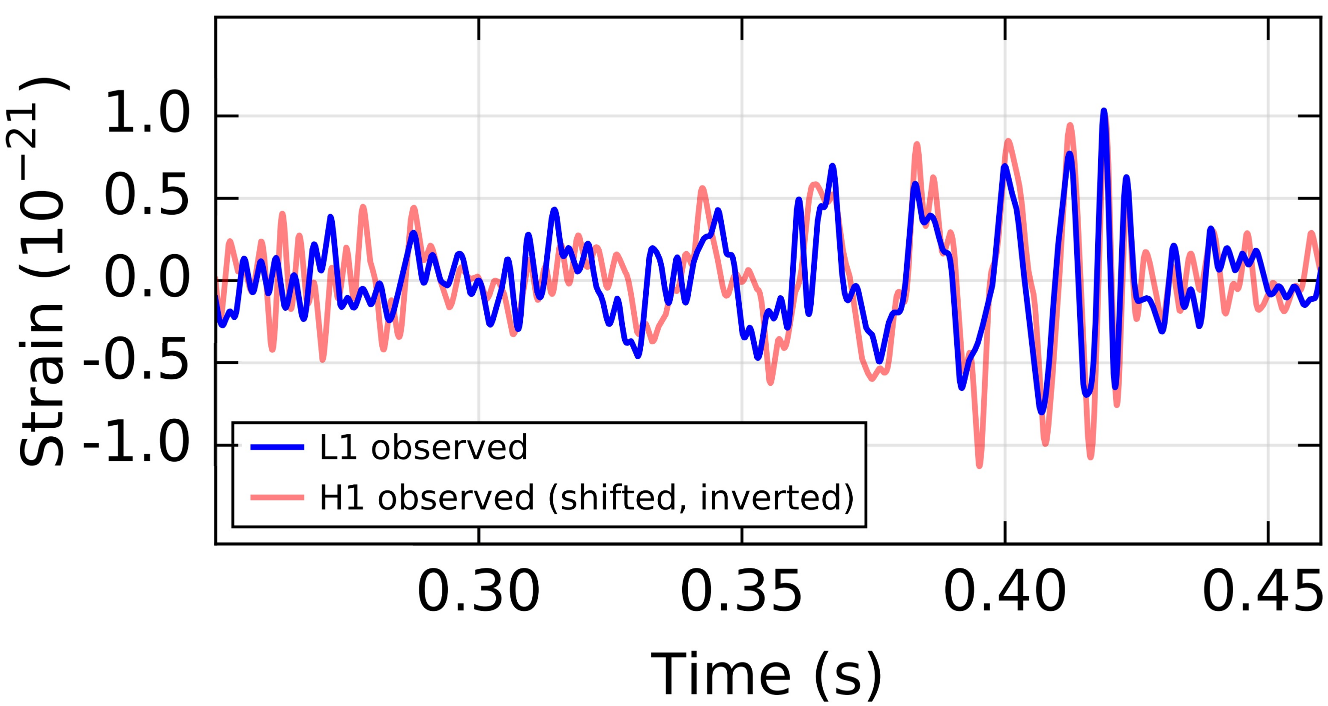
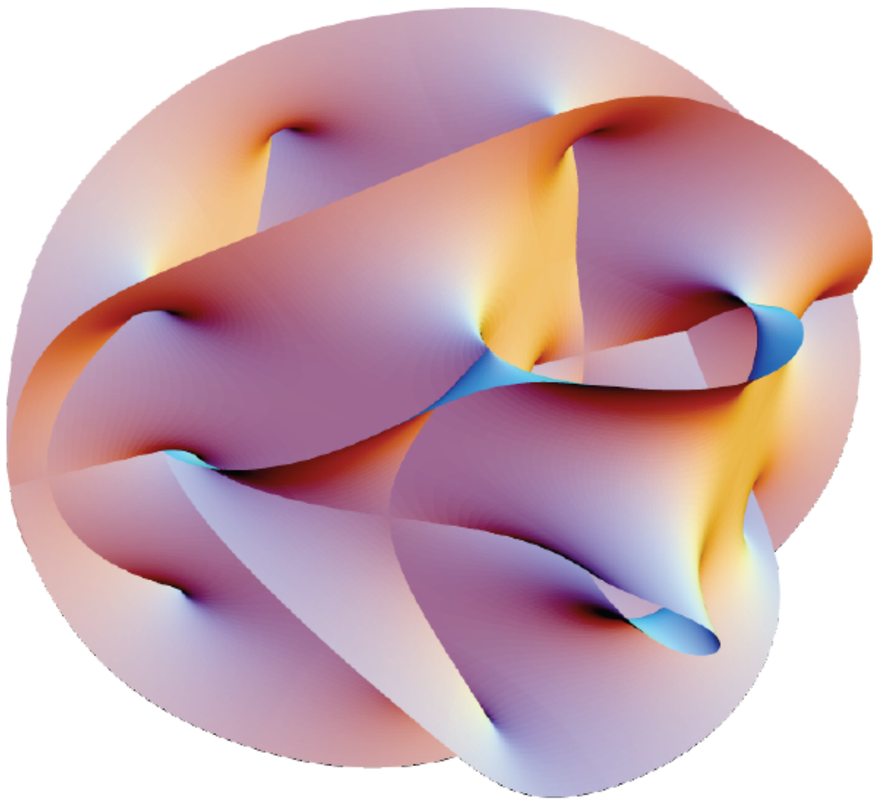




Solvay Workshop "The bright side of black holes"

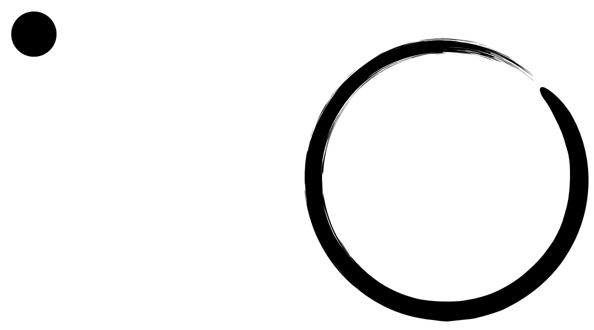
Plan of the Talk

- ✦Brief overview of superradiance

  see a talk by Pani for an up to date detailed story
- ✦Brief overview of axions
- ✦Superradiance and local phase transitions
- ✦Superradiance and supermassive black hole nurturing

Generic superradiance: rotating absorbing object may serve as a source of energy

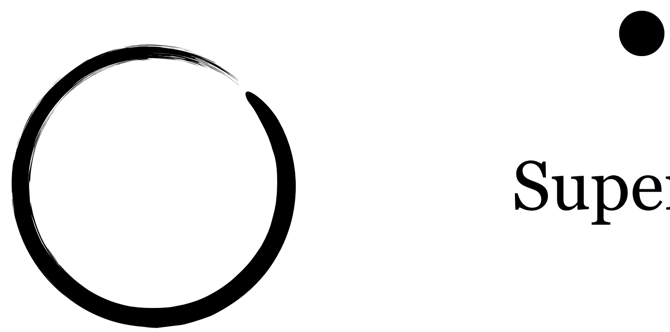
Zeldovich'71



Super-radiant scattering of a massive object

Generic superradiance: rotating absorbing object may serve as a source of energy

Zeldovich'71



Super-radiant scattering of a massive object

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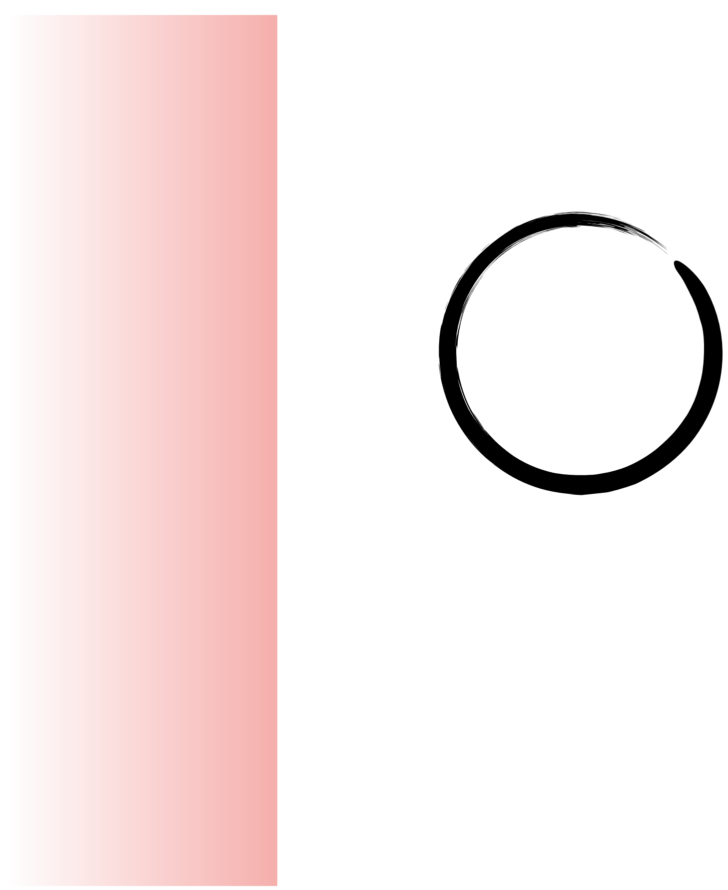
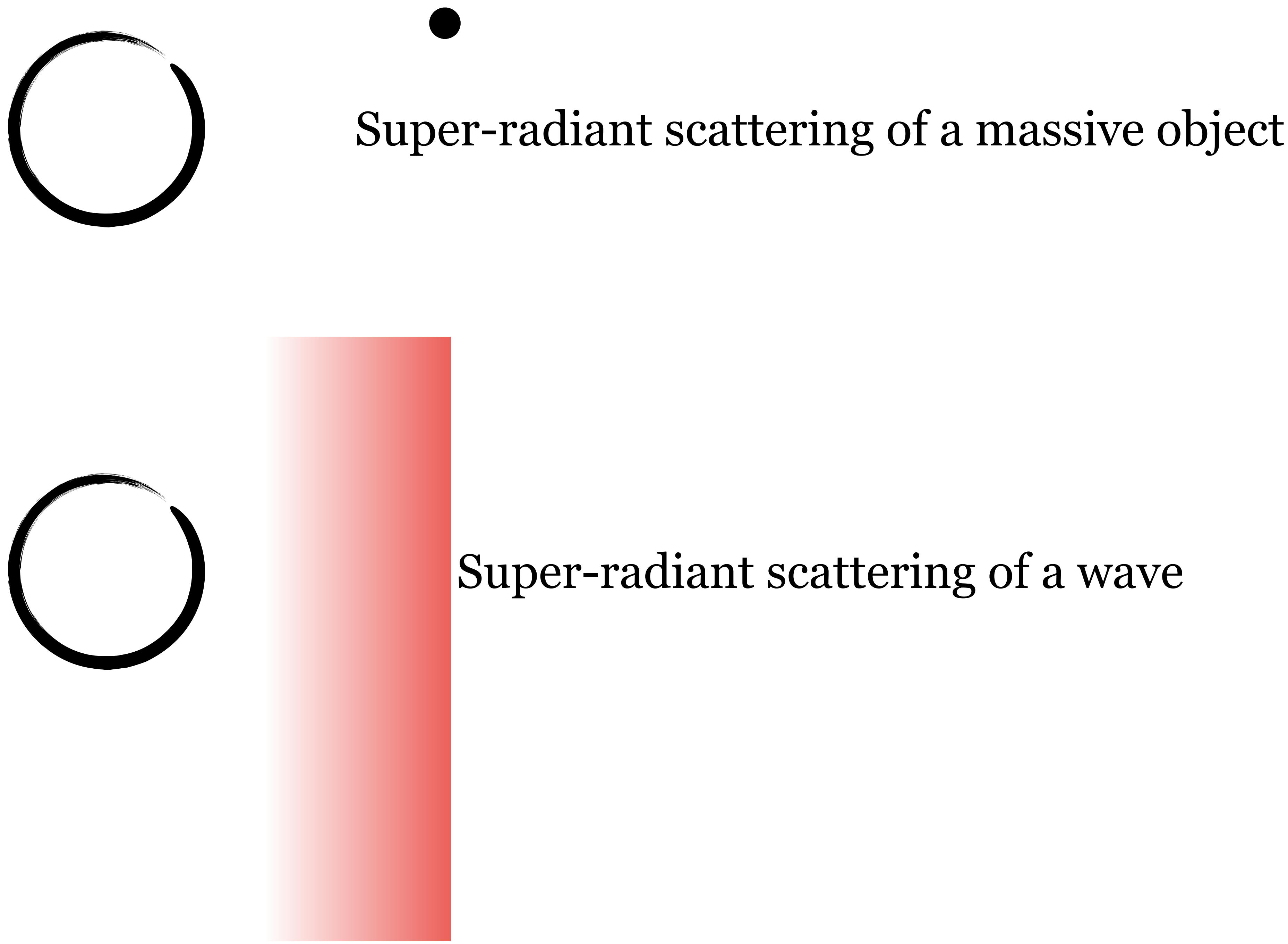
Super-radiant scattering of a massive object



Super-radiant scattering of a wave

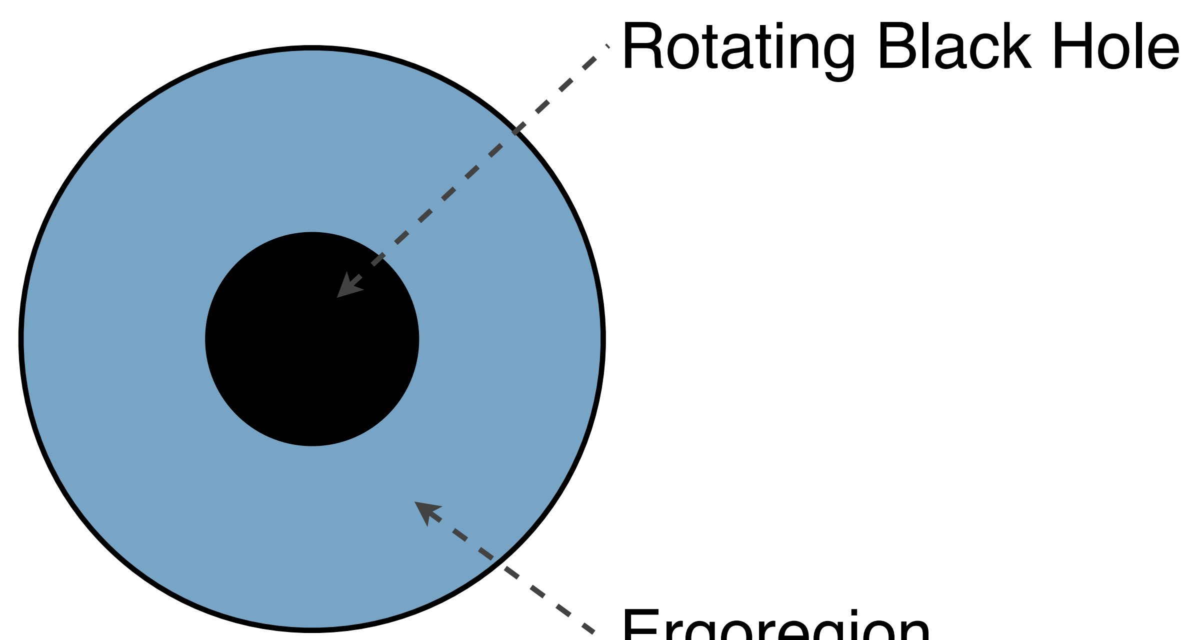
Generic superradiance: rotating absorbing object may serve as a source of energy

Zeldovich'71



Penrose Process

Penrose'69;
Misner'72; Starobinsky'73



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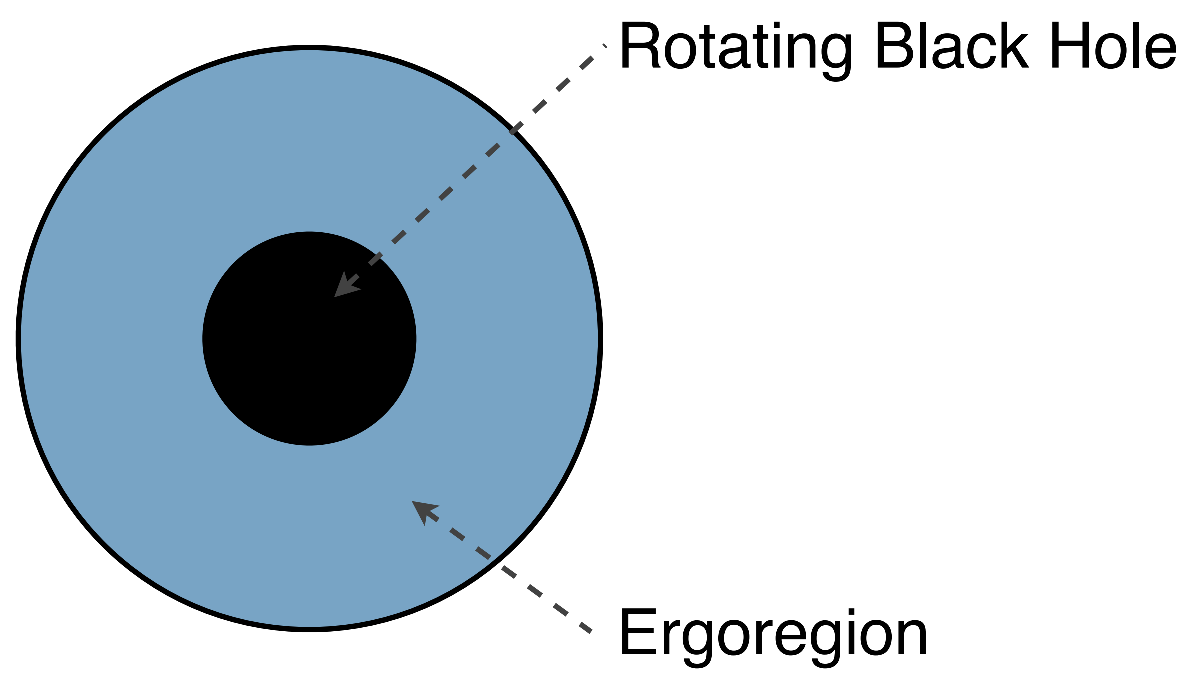
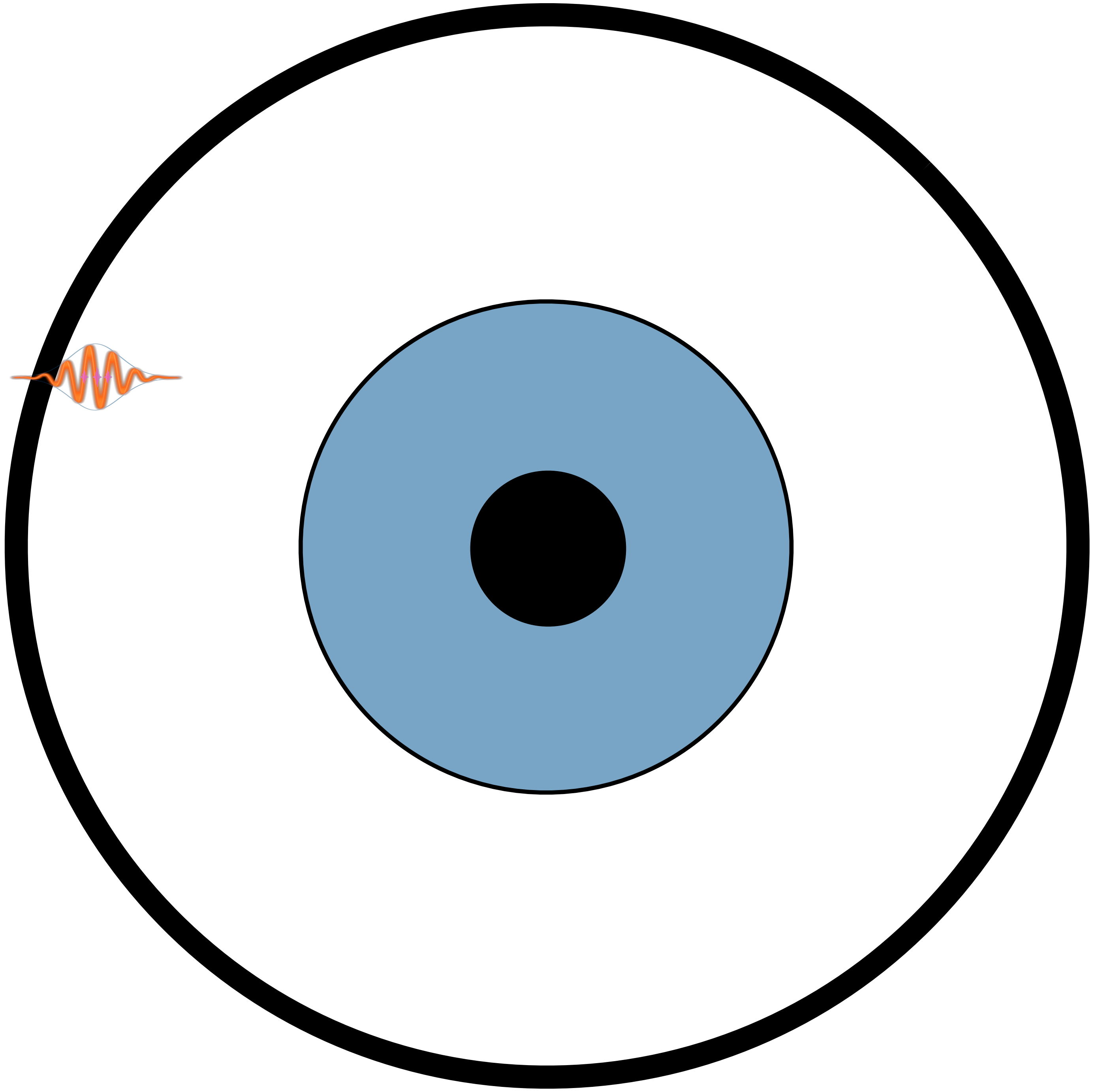


Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

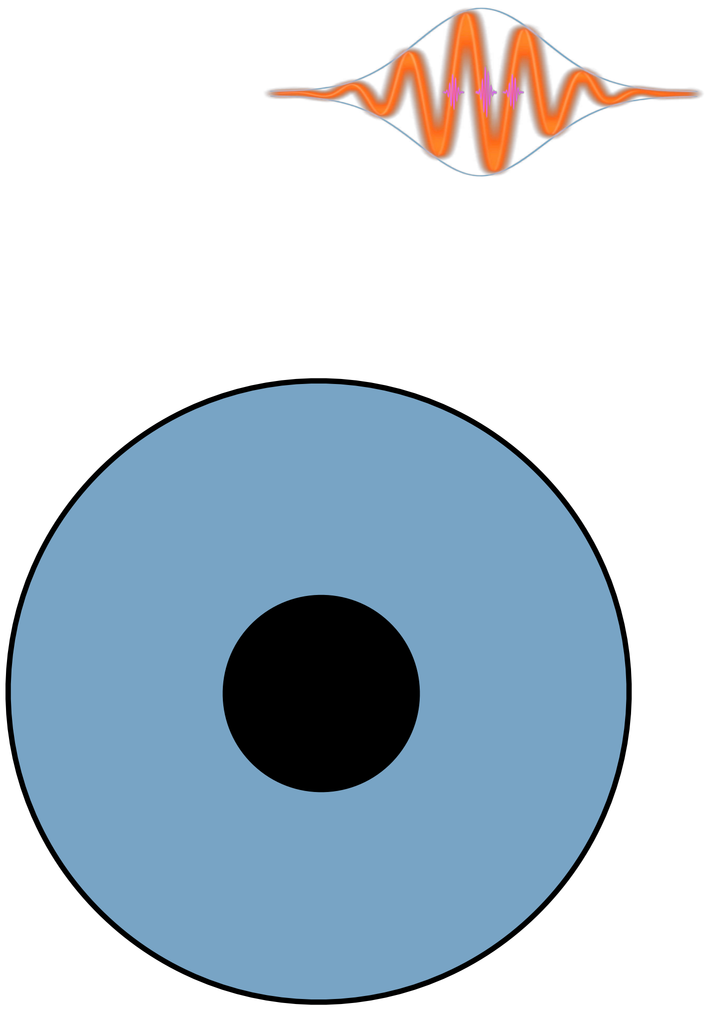
Press & Teukolsky 1972



Photons reflected back and forth from the black hole
and through the ergoregion

Black Hole Bomb

Press & Teukolsky 1972

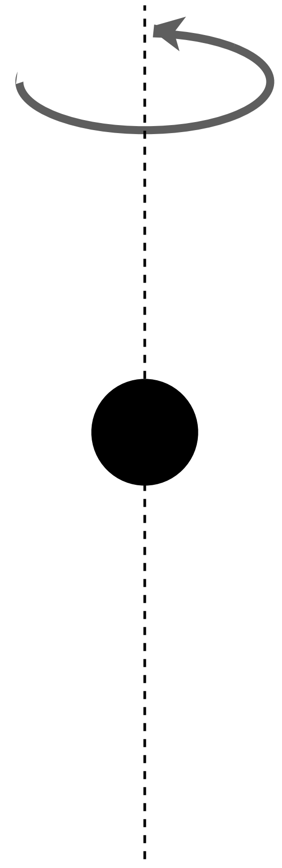


Photons reflected back and forth from the black hole and through the ergoregion

Superradiance for a massive boson

Press & Teukolsky'72

Damour et al.'76; Gaina et al.'78; Detweiler'80; Zouros & Eardley'79;



Particle Compton wavelength comparable to the size of a black hole

$$m \sim 10^{-10} \div 10^{-20}\ eV$$

Superradiance for a massive boson

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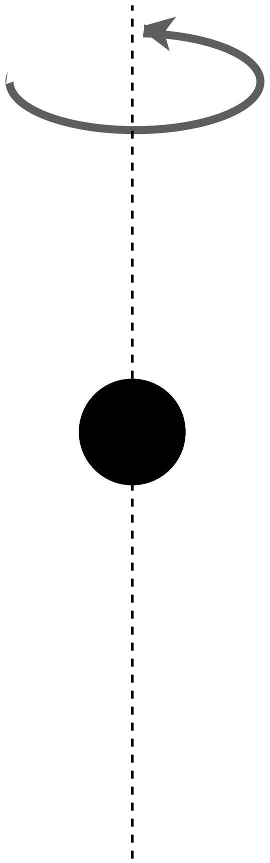

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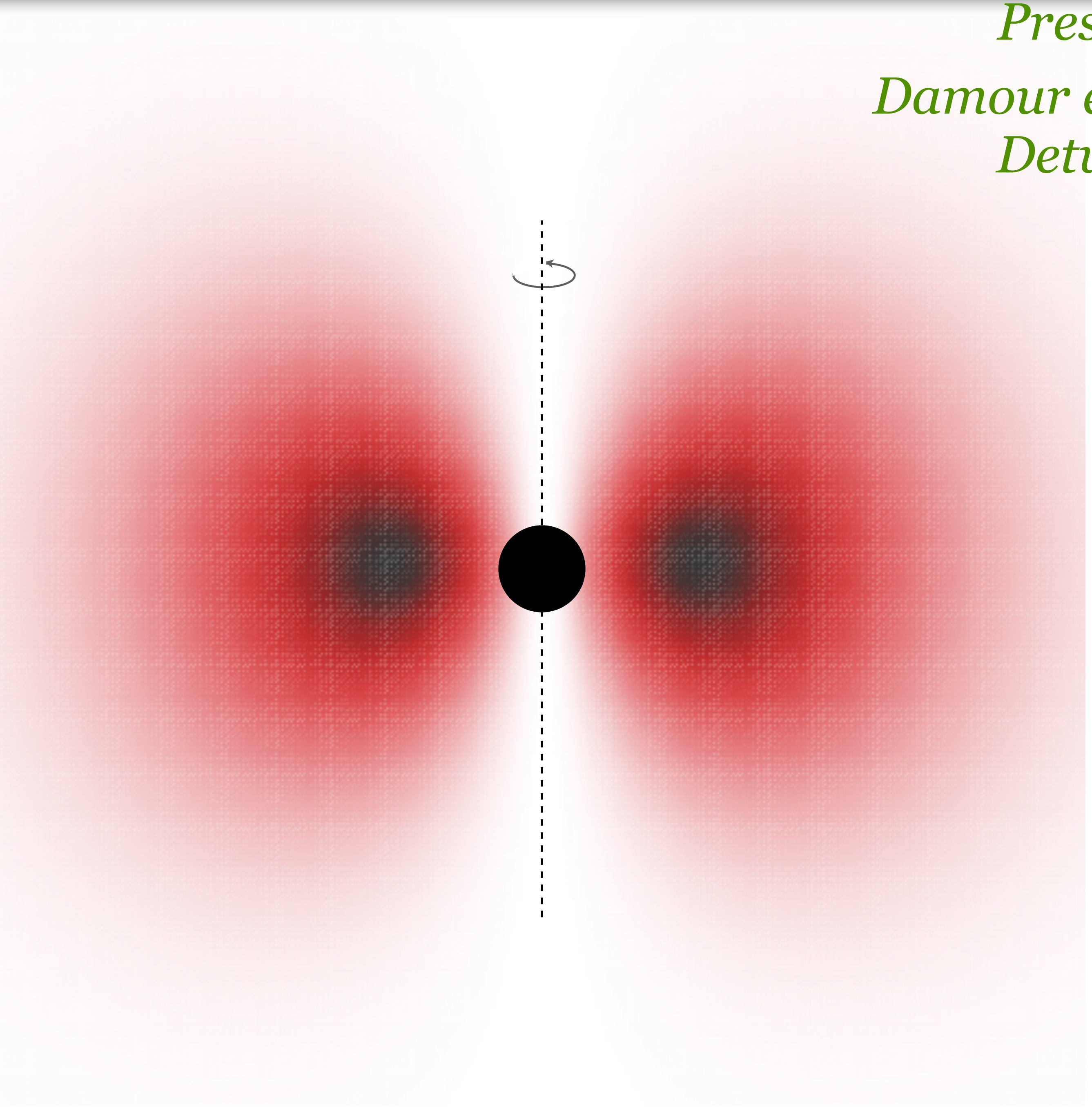


Particle Compton wavelength comparable to the size of a black hole

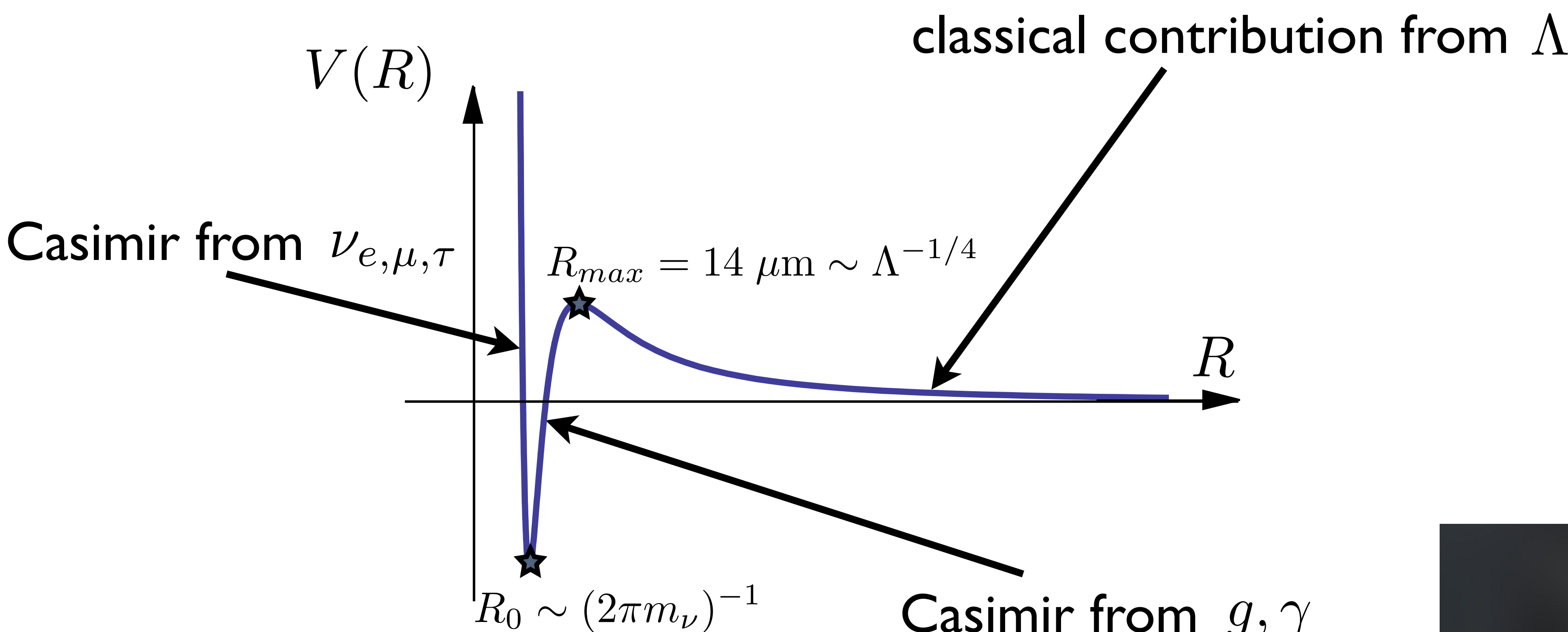
$$m \sim 10^{-10} \div 10^{-20}\ eV$$

Standard Model Landscape

Arkani-Hamed, SD, Nicolis, Villadoro hep-th/0703067

What are the vacua in the Standard Model?

Radion Potential

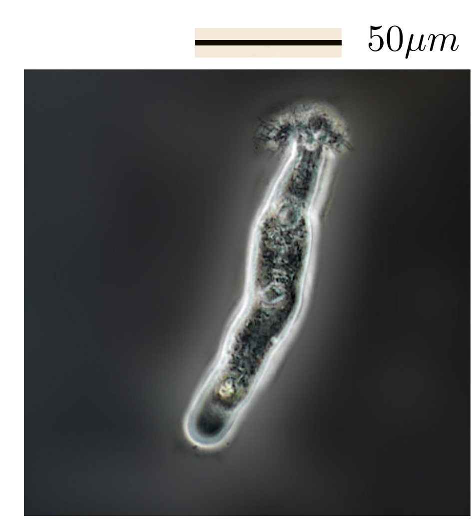


$AdS_3 \times S_1$

vacuum with

$$2\pi R_0 \approx 20\mu\text{m}$$

$$l_{AdS} \approx 3.7 \cdot 10^{27} cm$$



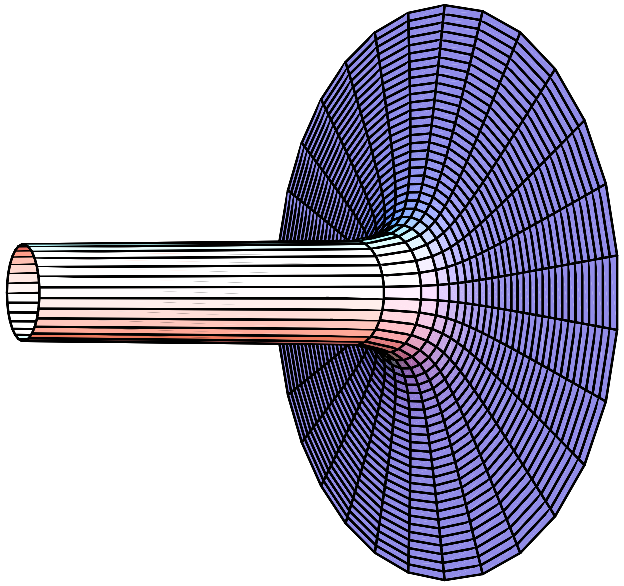
Trichamoeba sp.

typical habitant of the SM Landscape

Many More Vacua

Extremal Reissner-Nordstrom black holes connect between flat and $AdS_2 \times S_2$ vacua

$$ds^2 = (1 - \frac{r_h}{r})^2 dt^2 - \frac{dr^2}{(1 - \frac{r_h}{r})^2} - r^2 d\Omega_2^2$$



Particles in $AdS_3 \times S_1$ vacuum

- All of the Standard Model
- Radion (a cousin of graviton) with

$$m_R \sim \frac{R_0^{-2}}{M_{Pl}} \sim 10^{-40}\mathrm{GeV}$$

- Axion (a cousin of photon/Aharonov-Bohm flux) with

$$m_a \sim eR_0^{-2}\mathrm{e}^{-2\pi R_0 m_e} \sim \mathrm{e}^{-10^8}$$

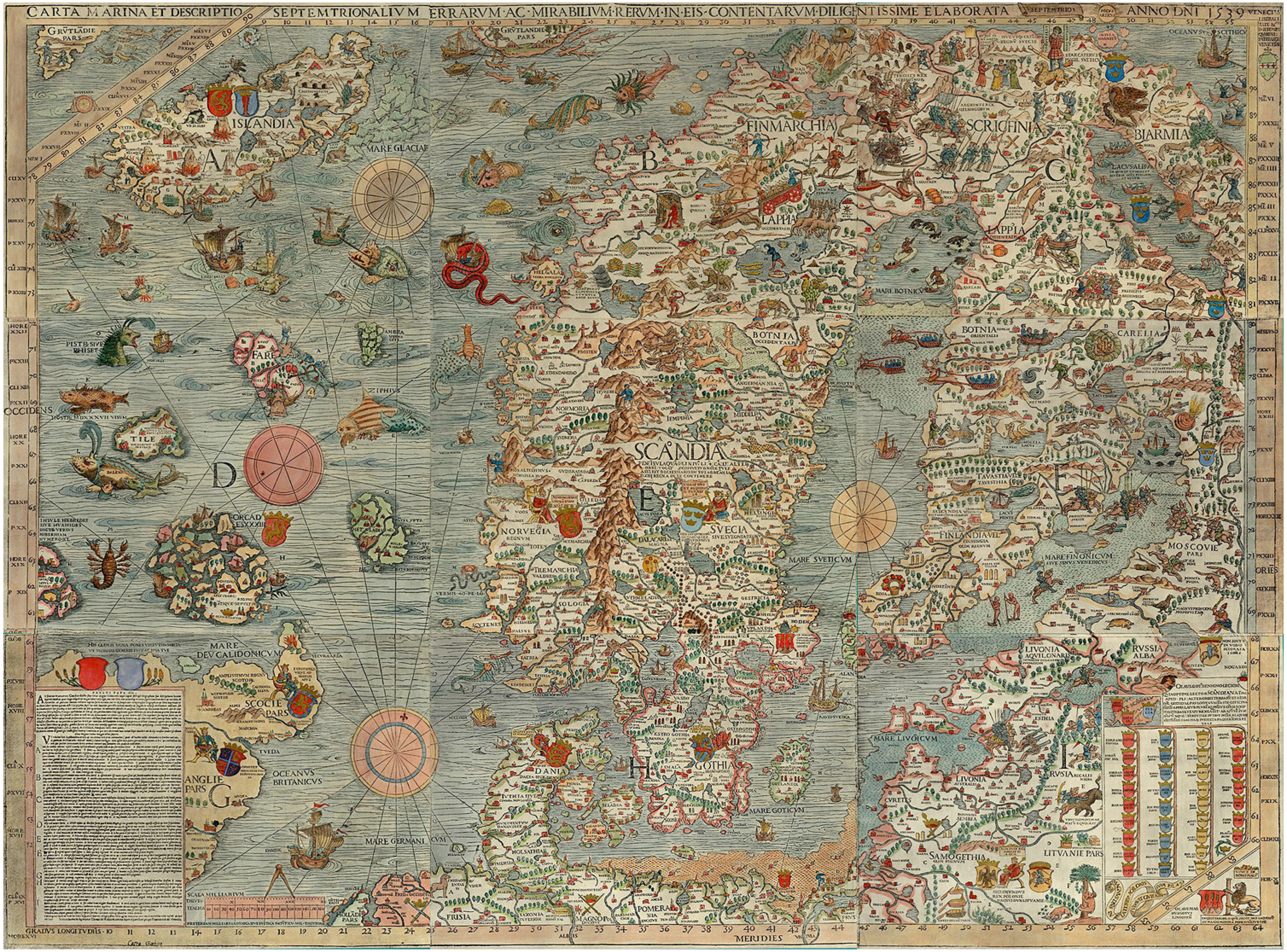
$$f_a^2 \sim \frac{1}{2\pi R_0 e^2}$$

Exponentially light axion comes from power-like small f_a

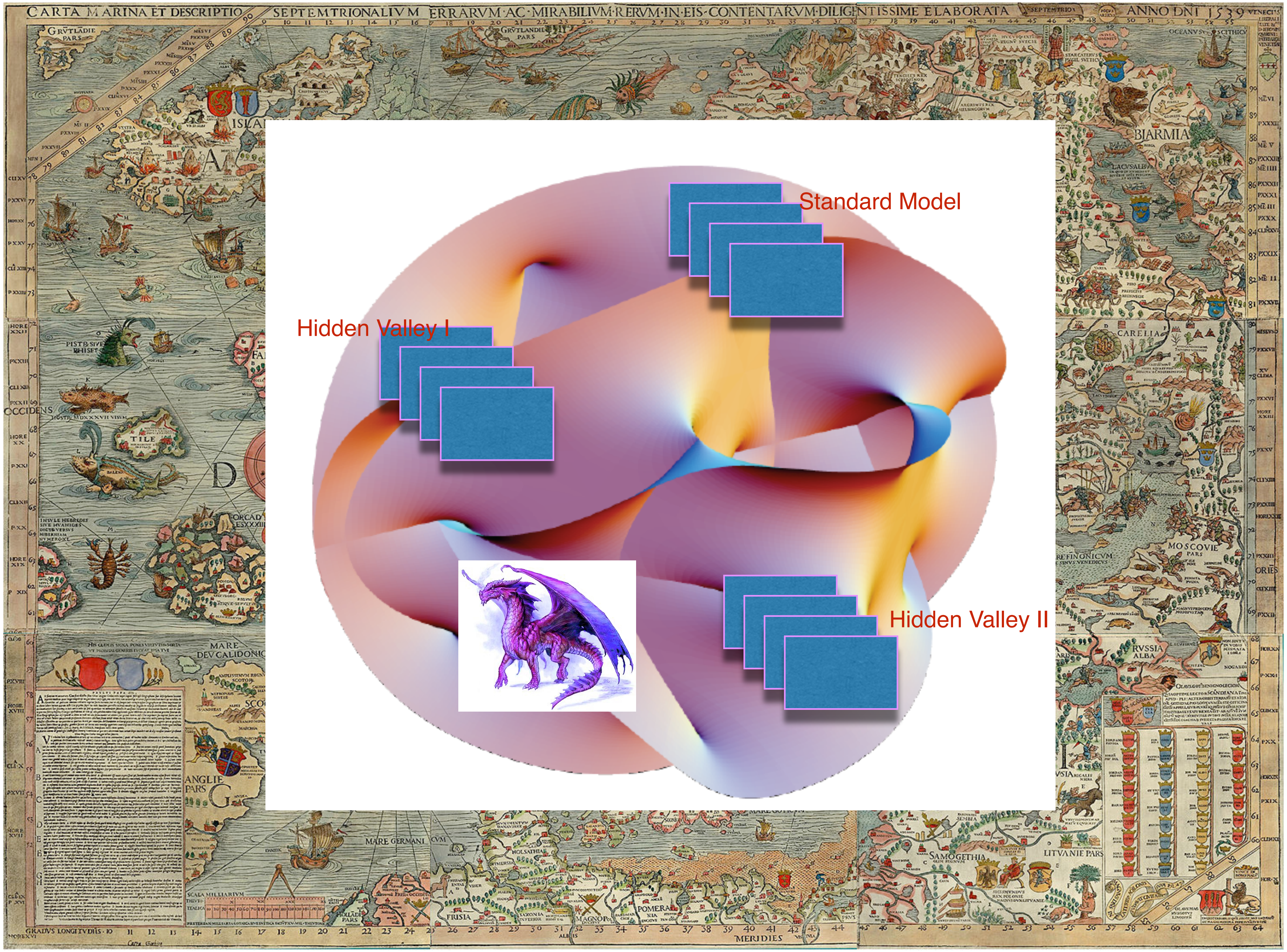
String Lanscape:

Plenitude (‘$\sim 10^{500}$ ‘) of vacua

Ultimate Unification of Fundamental Physics and Geography



CARTA MARINA ET DESCRIPTIO SEPTEMTRIONALIVM TERRARVM AC MIRABILIVM RERVM IN EIS CONTENTARVM DILIGENTISSIME ELABORATA ANNO DNI 1539
ISLANDIA
MARE GLACIALE
FINMARCHIA
BIARMIA
LAPPIA
BOTNIA
CARELIA
SCANDIA
NORVEGIA
SVECIA
MARE SVETICVM
FINLANDIA
MARE FINONICVM
MOSCOVIE PARS
TILE
ORCADES
MARE DEVCALIDONICVM
SCOCIE PARS
ANGLIE PARS
OCEANVS BRITANICVS
MARE GERMANICVM
DANIA
GOTHIA
MARE GOTICVM
LIVONIA
MARE LIVONICVM
RVSSIA ALBA
SAMOGETHIA
LITVANIE PARS
FRISIA
POMERANIA
MERIDIES
OCCIDENS



In both cases no reasons to apply Occam's razor

Axions in String Theory

Exactly the same story! Starting from a higher dimensional theory, and very small and very complicated internal compact manifold

$$\mu_a \propto e^{-\frac{M_{Pl}}{f_a}}$$

suggests

$$\frac{M_{Pl}}{f_a} \sim 100$$

the same factor is suggested by gauge coupling unification

The QCD axion

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

Non-pert QCD gives potential $V(a)$ of height $\Lambda^4_{QCD} = \mu^4 \exp(-8\pi/\alpha_s(\mu))$

$\Longrightarrow$ Axion is a pseudo-Nambu-Goldstone boson

$$m_a \sim \frac{\Lambda^2_{QCD}}{f_a} \sim 6 \times 10^{-10} \mathrm{eV} \left(\frac{10^{16} \mathrm{GeV}}{f_a} \right)$$

Minimum of potential leads to axion vev such that

$$\theta_{eff} \equiv \frac{\langle a(x) \rangle}{f_a} + \bar{\theta} = 0$$

solves strong CP!

Gravitational Atom in the Sky

Arvanitaki, Dimopoulos, SD, Kaloper, March-Russel 0904.4720
Arvanitaki, SD 1004.3558

Far from the Black Hole: Newtonian Potential

$$\alpha_{EM} = \frac{e^2}{4\pi} \qquad \longrightarrow \qquad \alpha = G_{\rm N} M_{\rm BH} \mu_a = R_g \mu_a$$

$$E_{\rm binding} = -\frac{\alpha_{EM}^2 m_e}{2n^2} \qquad \longrightarrow \qquad E_{\rm binding} = -\frac{\alpha^2 \mu_a}{2n^2}$$

$$\text{fermions} \qquad \longrightarrow \qquad \text{bosons}$$

Occupation number

$$1 \qquad \longrightarrow \qquad 10^{75}$$

Superradiance Parametrics

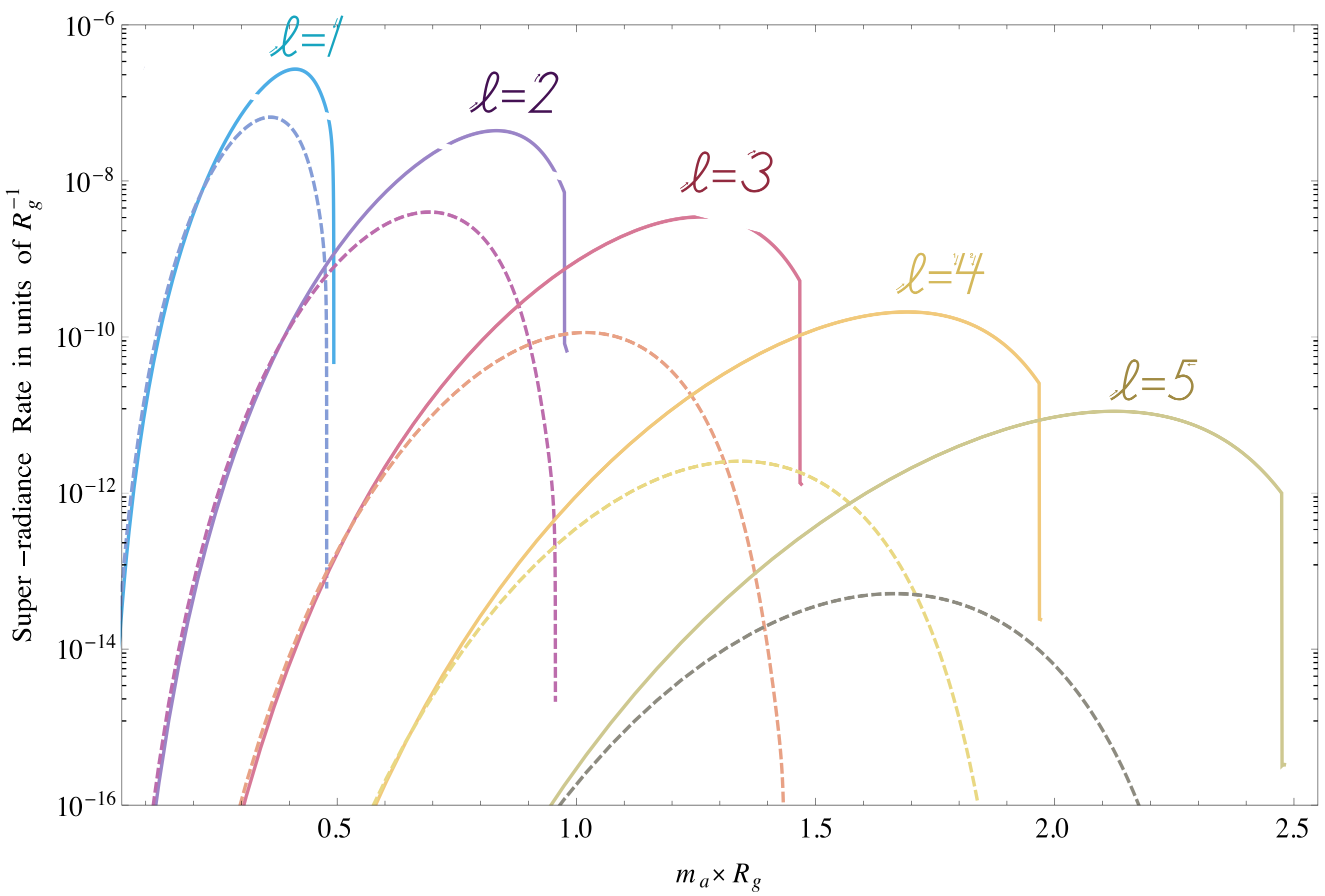
Superradiance Condition

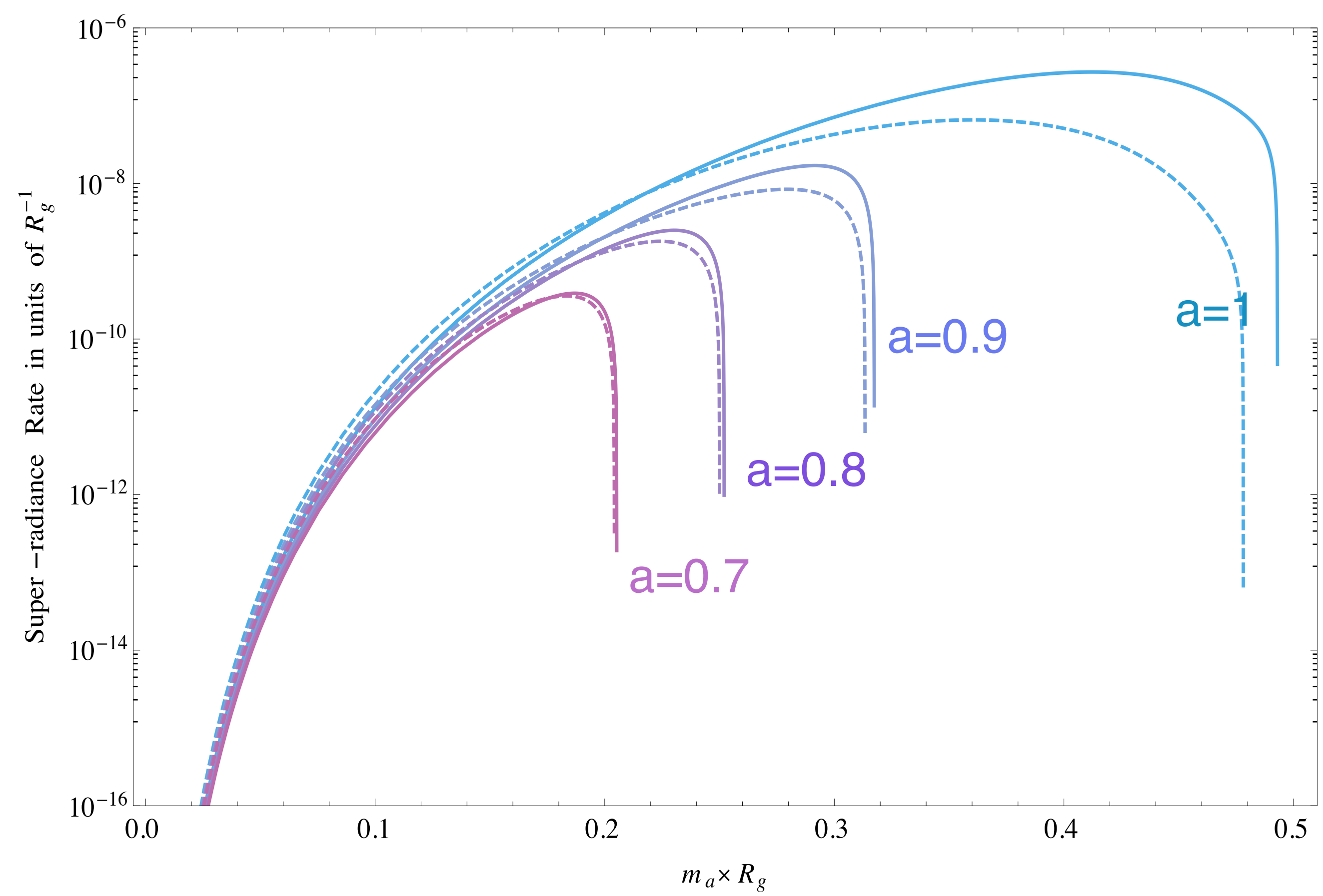
$$\omega_{\text{axion}} < m\,\Omega_+$$

$$\mu_a + E_{\text{binding}} < m\frac{a}{2R_g(1+\sqrt{1-a^2})}$$

m : magnetic quantum number

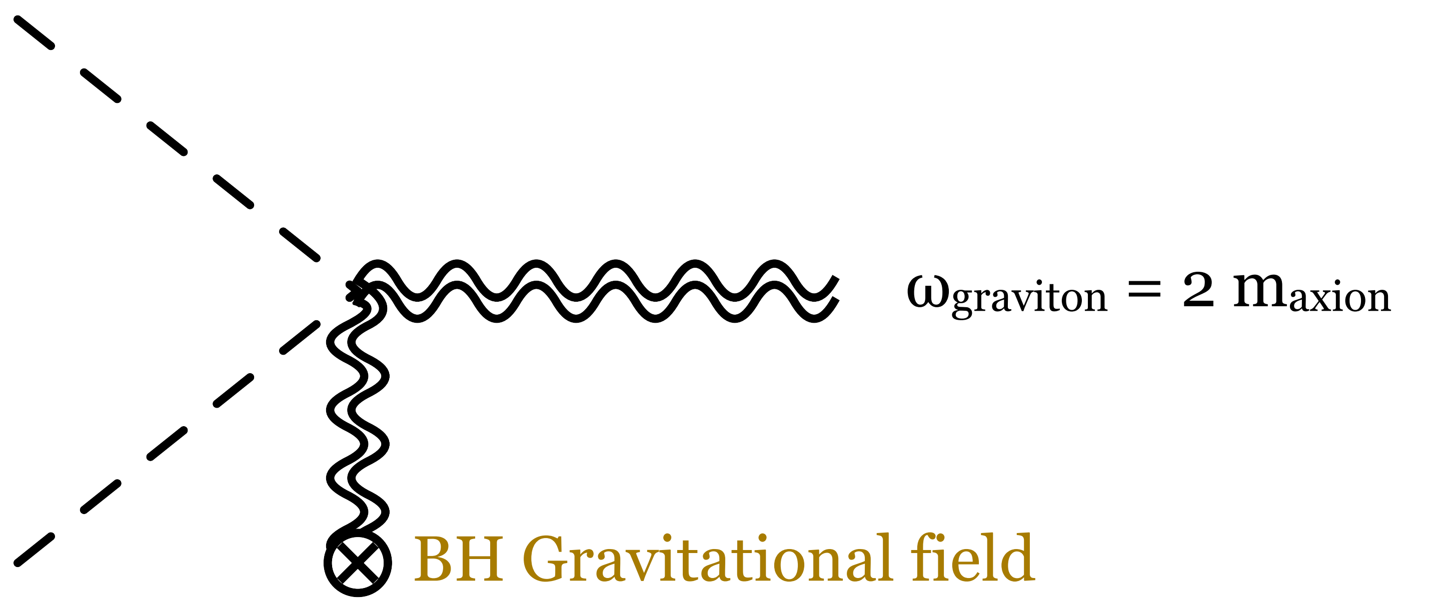
a : BH spin, between 0 and 1



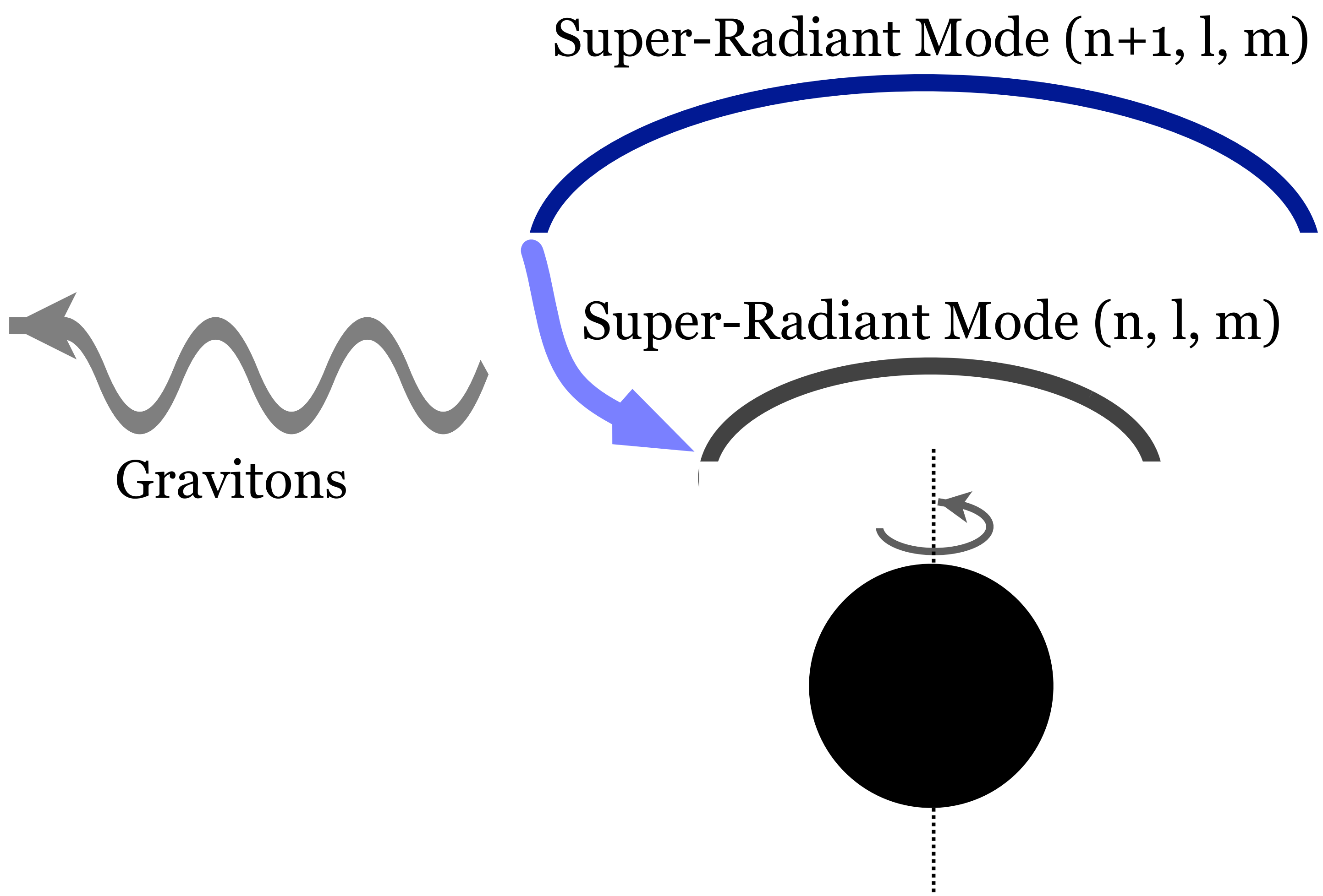


Maximum superradiance rate for level with min. l, max. m

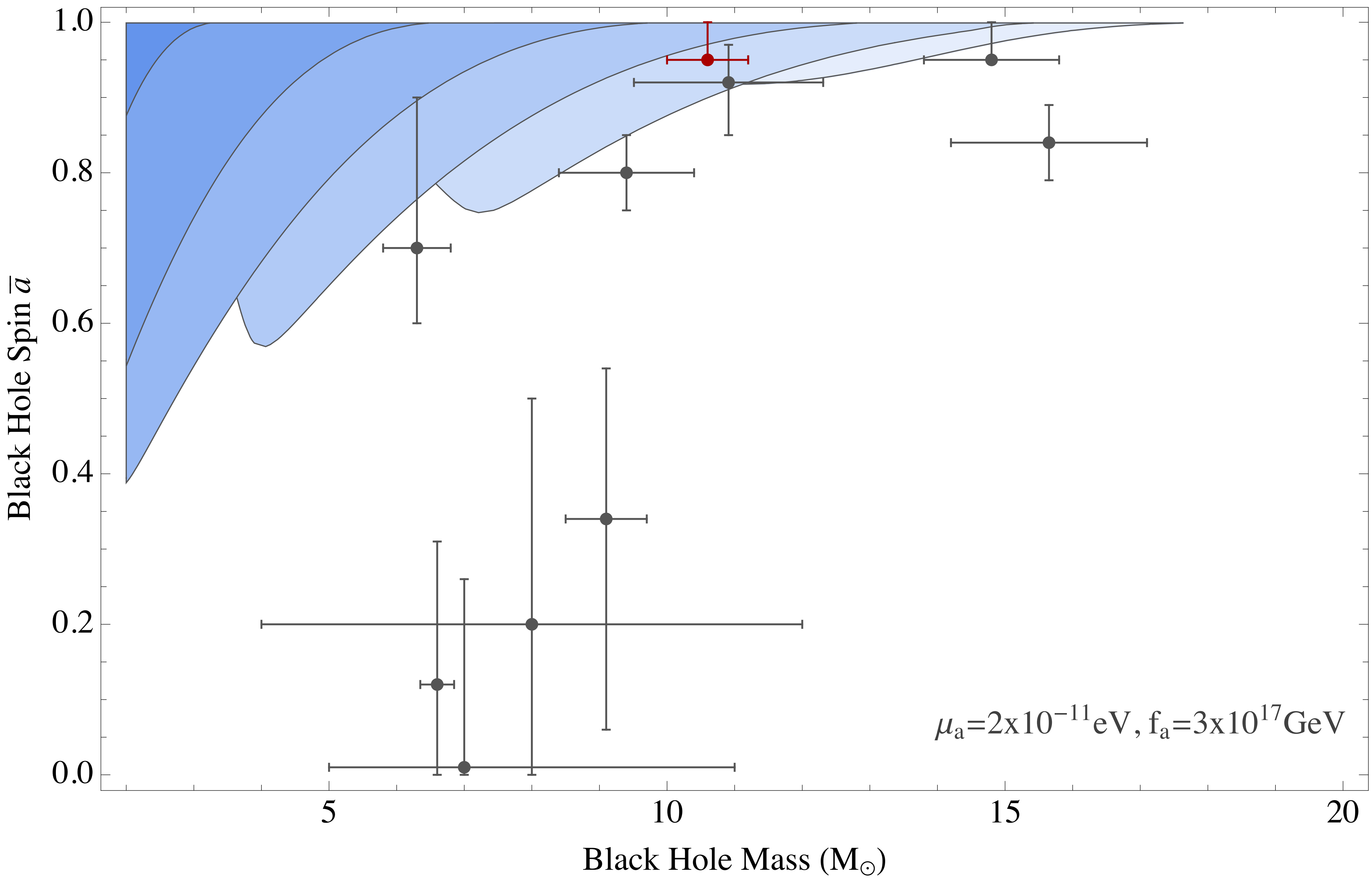
Axion annihilations



Graviton Transitions

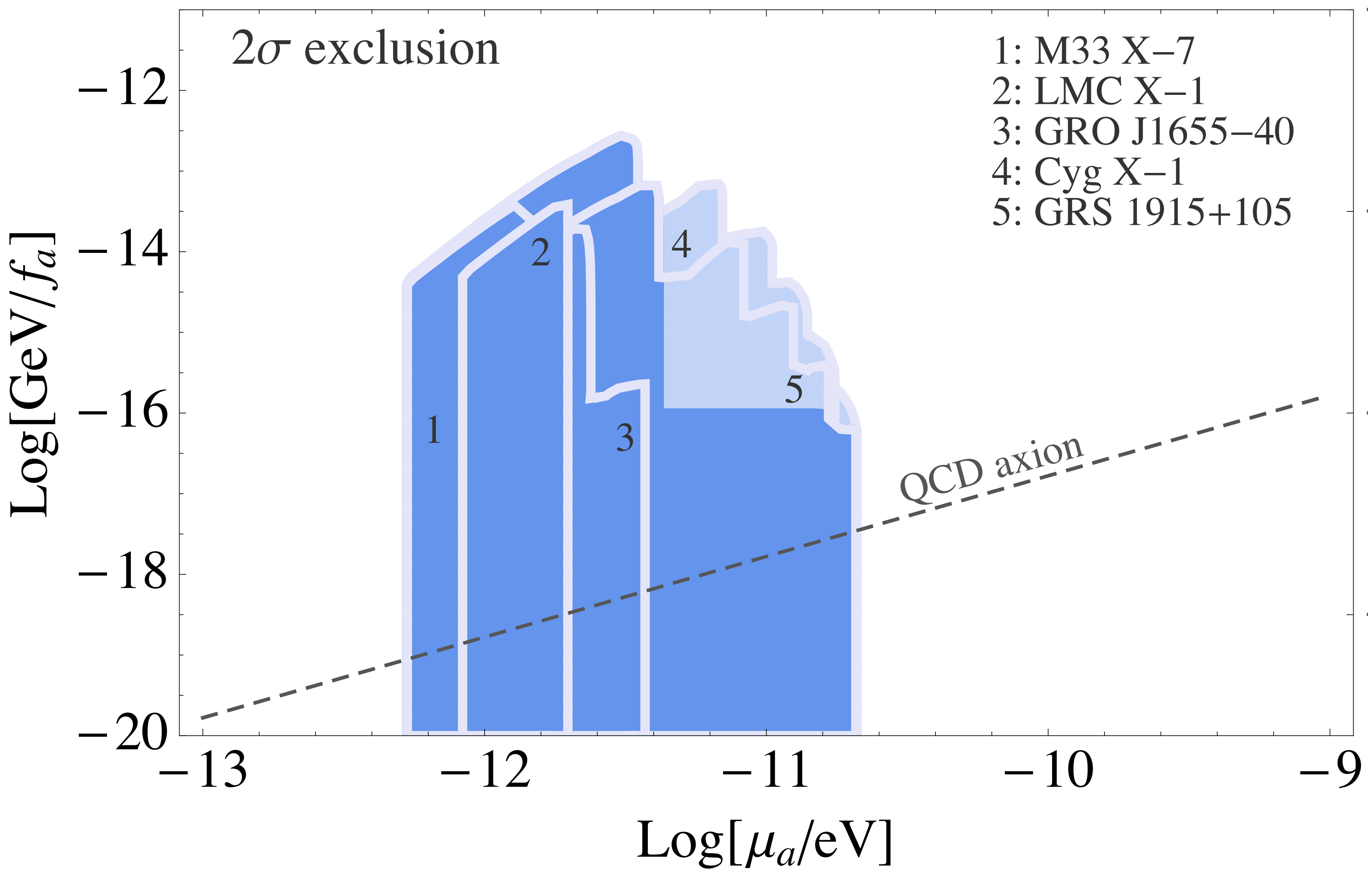


Spin Gap for the QCD Axion



Combined Exclusion Plot

Arvanitaki, Baryakhtar, Huang 1411.2263



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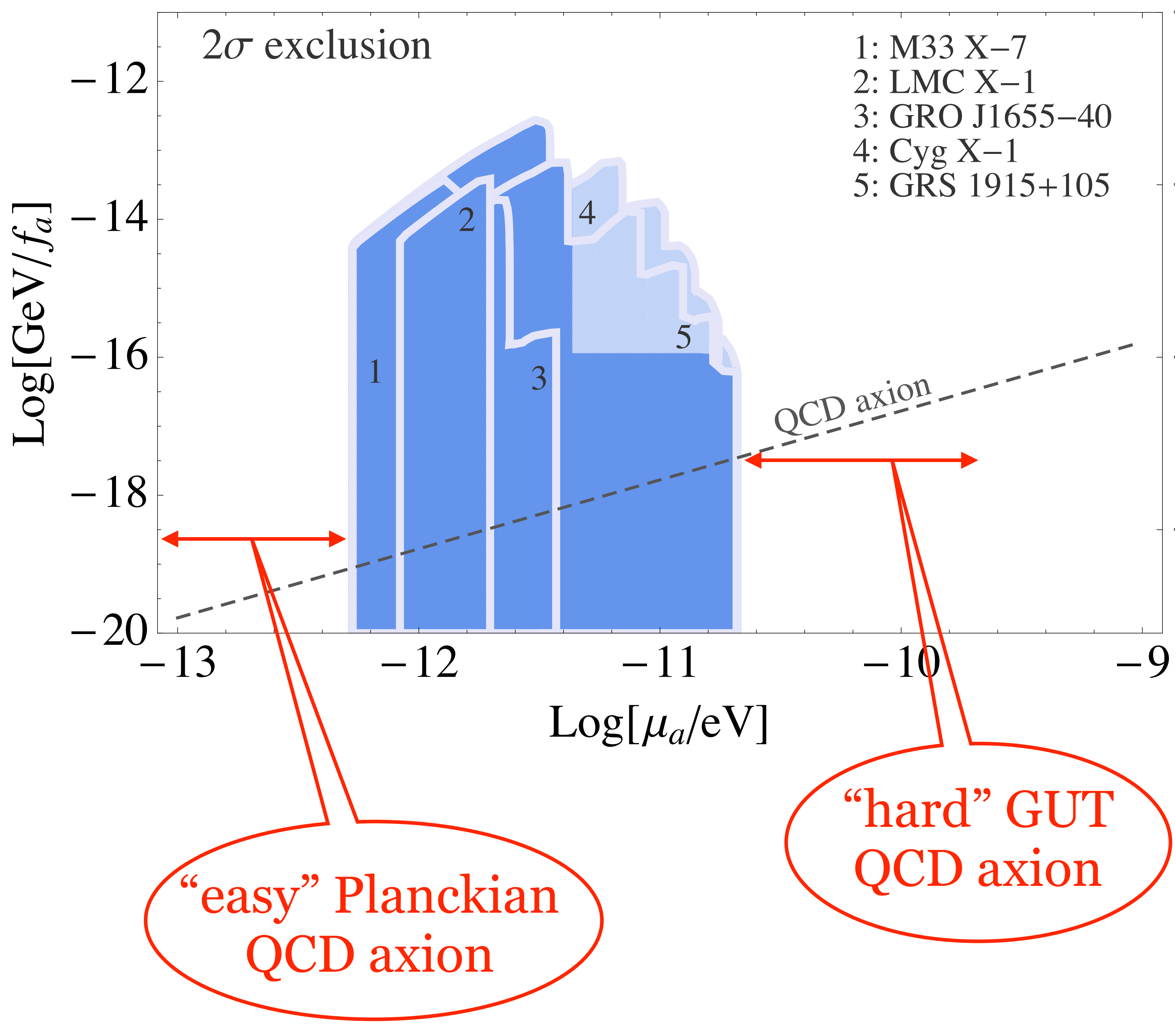
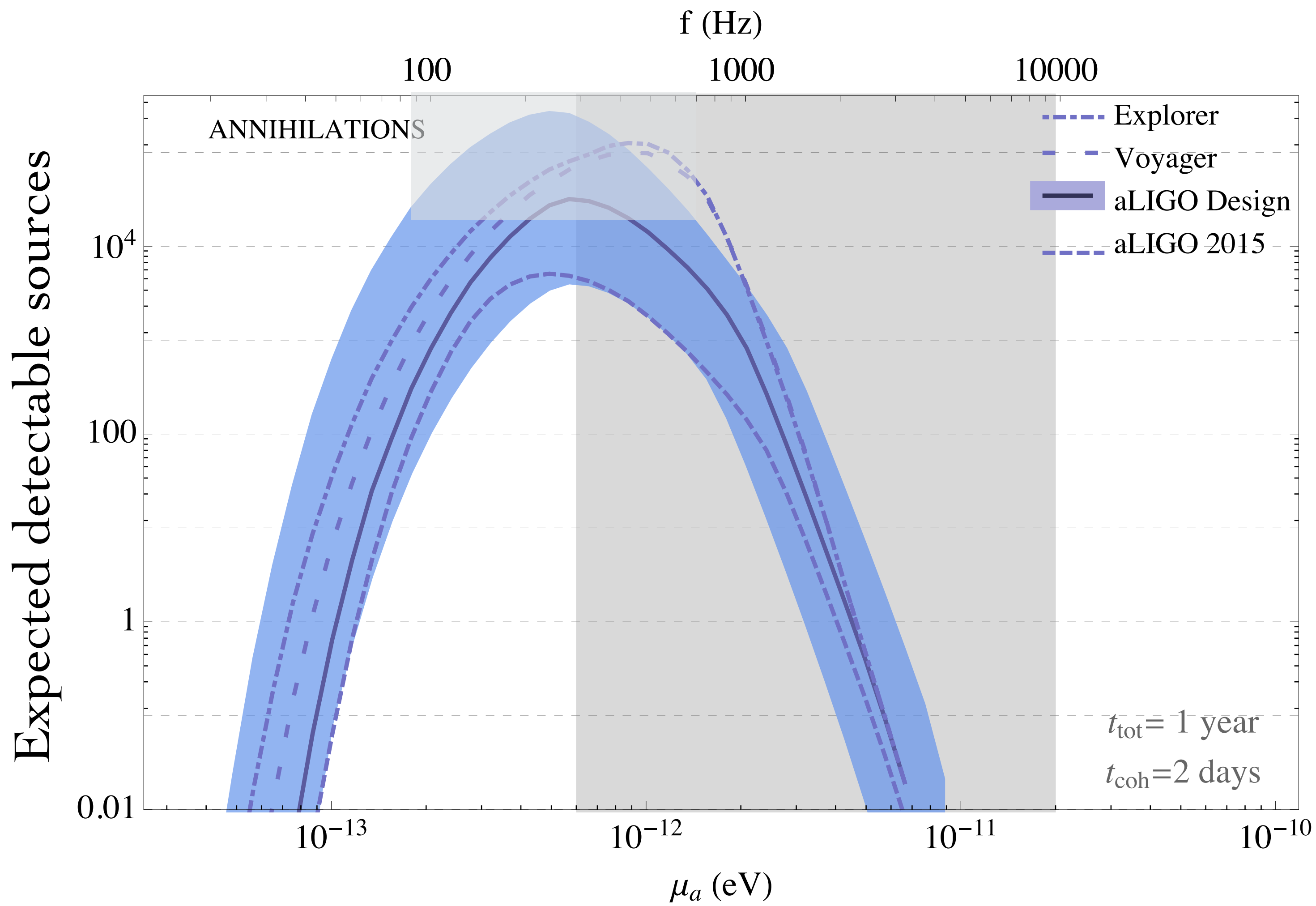


Expected Events from Annihilations

Arvanitaki, Baryakhtar, Dimopoulos, SD, Lasenby 1604.03958

Large uncertainties coming from tails of BH mass distribution

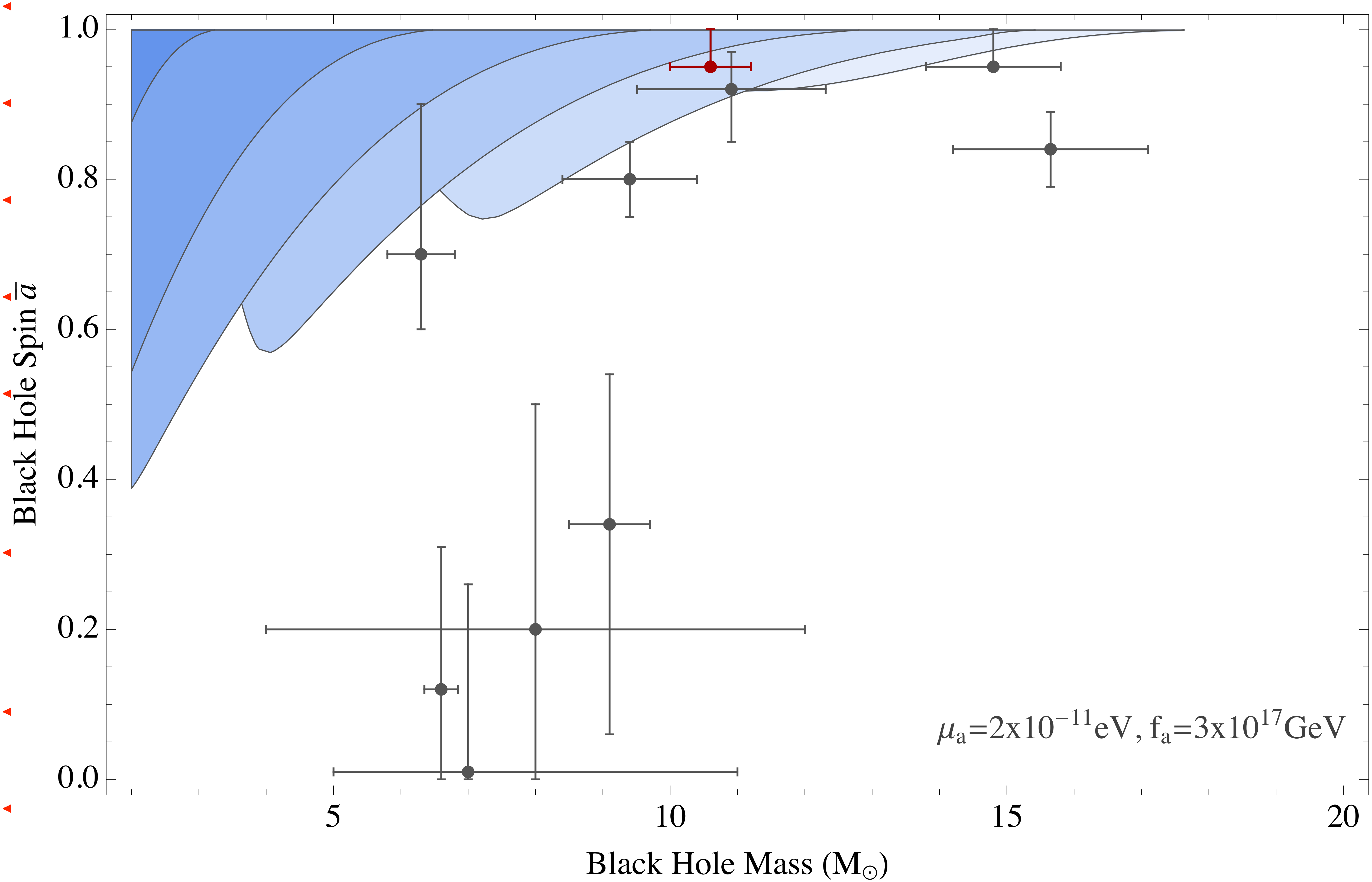


Pessimistic: flat spin distribution and 0.1 BH/century

Realistic: 30% above spin of 0.8 and 0.4 BH/century

Optimistic: 90% above spin of 0.9 and 0.9 BH/century

GUT QCD axion



GUT QCD axion

- Running out of BHs. $l>1$, large α regime
- Spindown and annihilations signals are too small
- Most conservative from theory viewpoint
- Need to think how to go for high frequencies

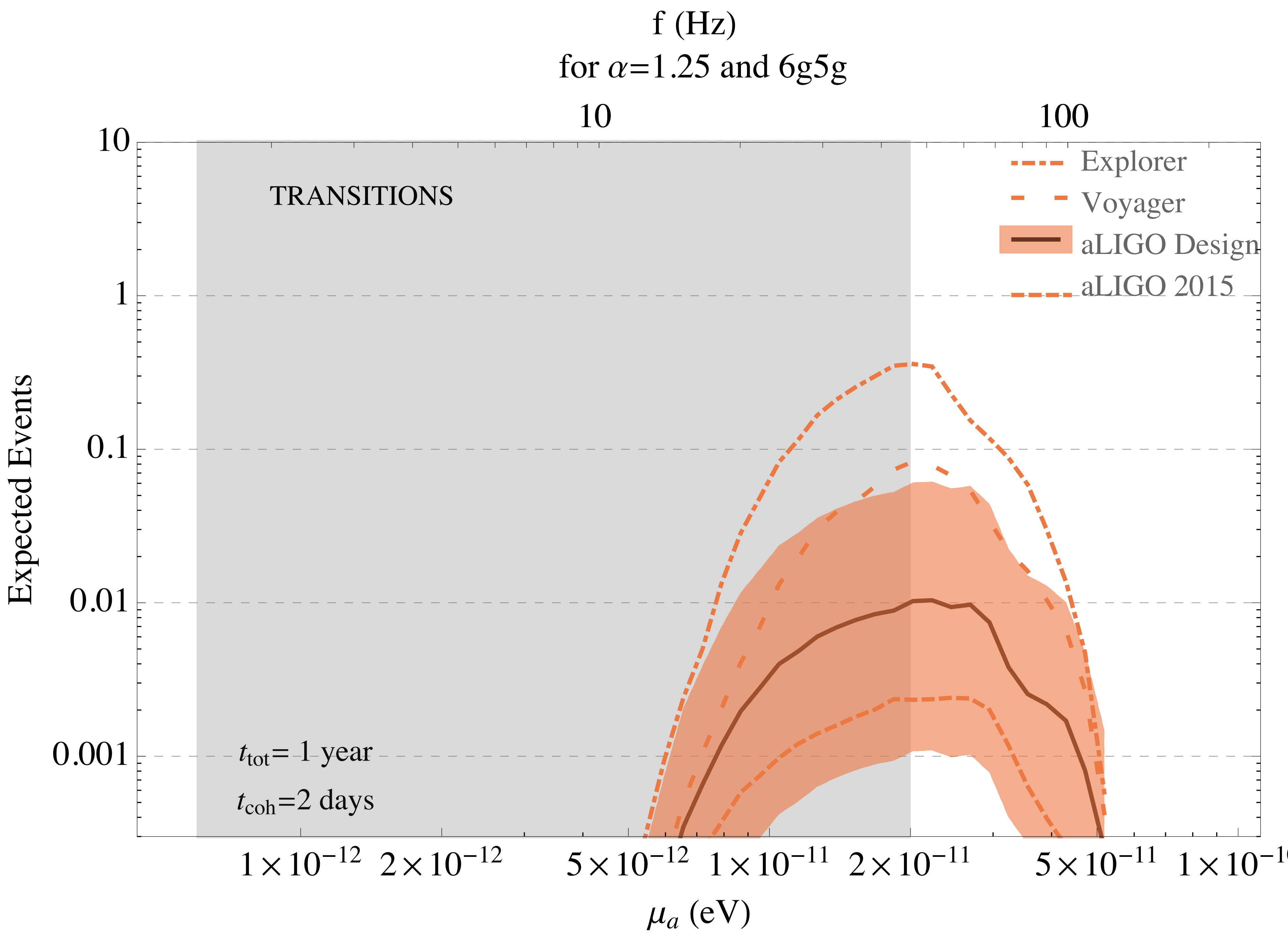
Arvanitaki, Geraci 1207.5320

- Need to understand axion non-linearities. Bosenova burst?
- Need to look for possible ways to transmit GW power into lower frequencies:
- 6g-5g transitions?
- Resonances in binary systems?

Baumann, Sheng Chia, Porto 1804.03208

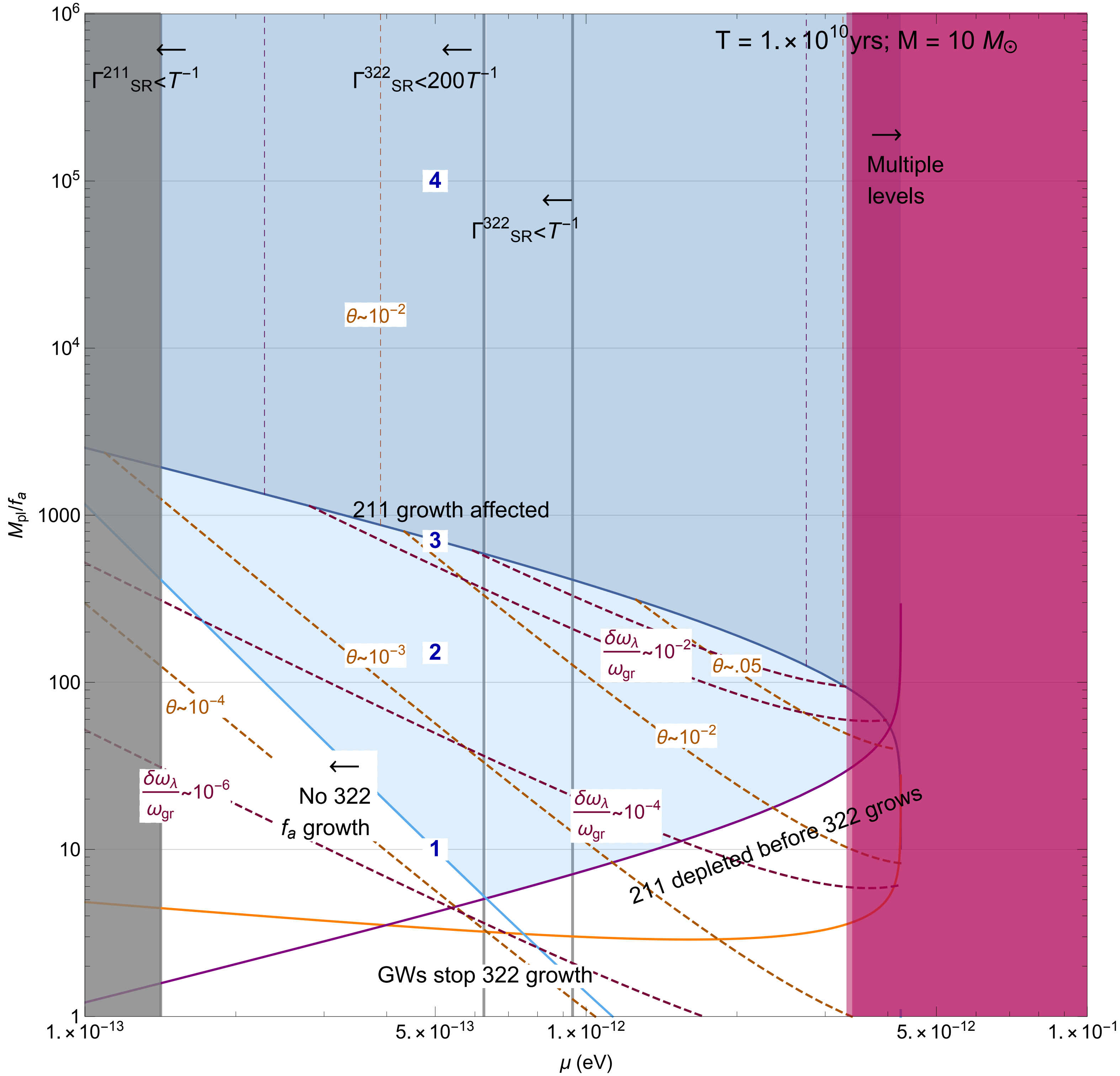
Transition Events Estimates

- Lower number of observable sources due to signal duration



Non-linear dynamics is hard...

Baryakhtar, Galanis, Lasenby, Simon in progress



Remaining 10 orders of magnitude in masses:

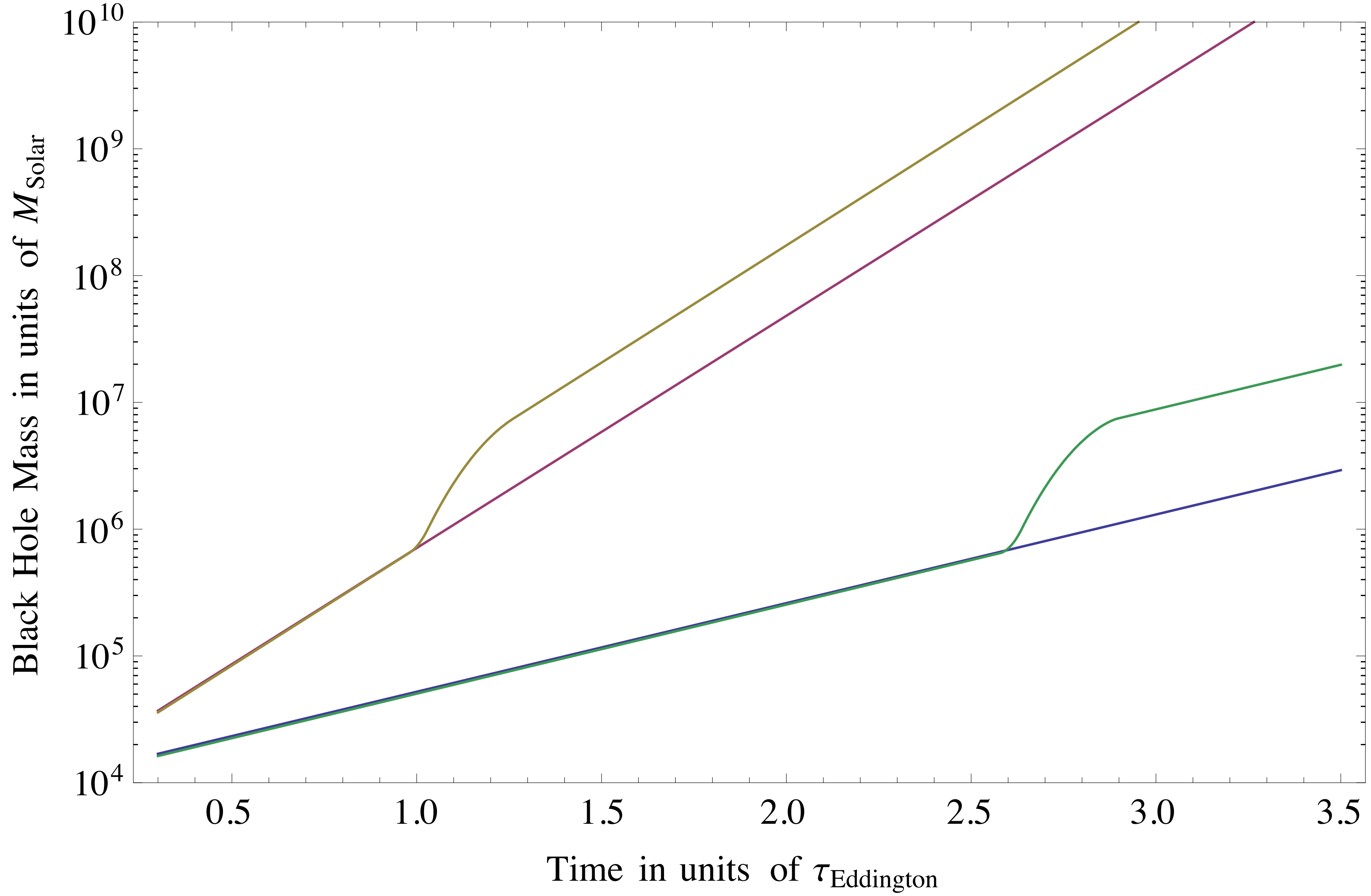
Many ways to be inventive!

Effects on BH accretion rate

Arvanitaki, SD 1004.3558

Axion spins BH down and accelerates the accretion rate

$$\frac{dM}{dt} = \frac{1-\epsilon_M(\bar{a})}{\epsilon_M(\bar{a})}\frac{M}{\tau_E} + \dot{M}_{sr}$$



Superradiant Creates Huge Field Values

Setup:

SD, Gorbenko, 1012.2893

✦Axion, coupled to QCD-like sector.
At least 3 light quark flavors with close masses.
Pure glue also works.

✦Some portal, allowing for hidden pions to annihilate into SM. Simplest example: dark photon with kinetic mixing.

Effective action describing axion and mesons:

$$\mathcal{L} = \frac{F_\pi^2}{4} \mathrm{Tr}\, \partial U^\dagger \partial U + \frac{\Lambda^3}{2} Tr \left(M \mathrm{e}^{-i\theta/N} U + M \mathrm{e}^{i\theta/N} U^\dagger \right)$$

Axion Monodromy

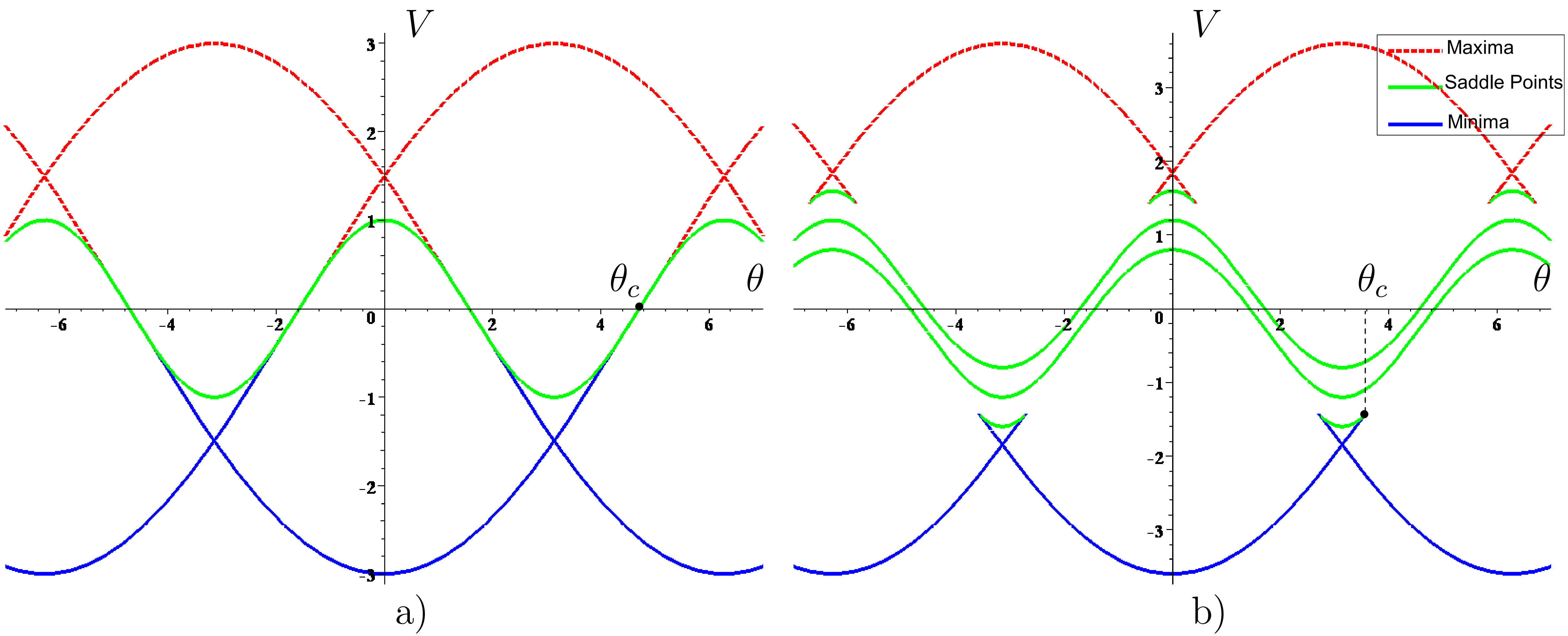


Figure 1: Extrema of the axion potential at $N = 3$ for equal quark masses (left), and for mass ratios 1:1.2:1.4 (right).

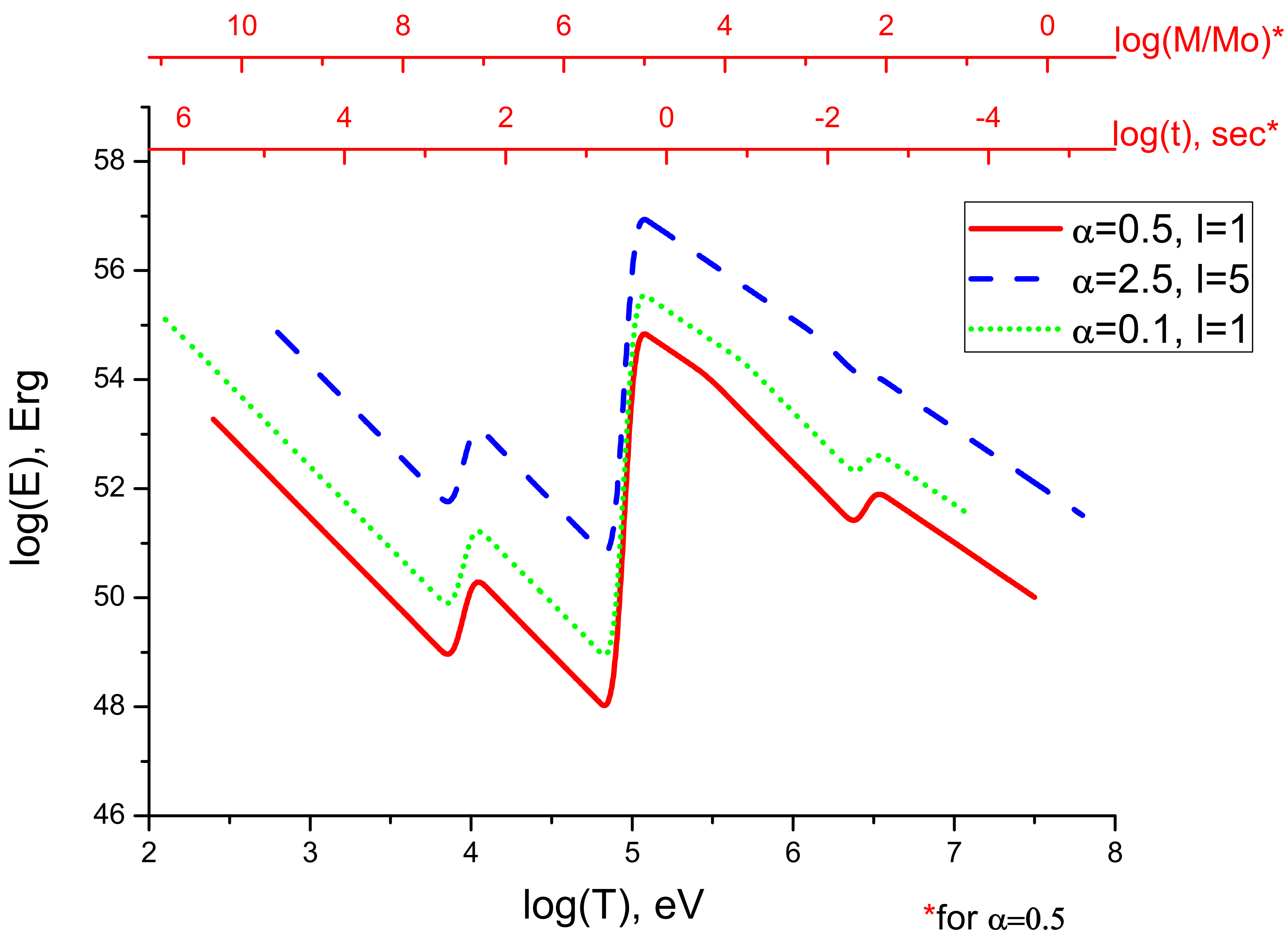


Figure 2: A total energy release as a function of a characteristic temperature of a fireball for different values of parameters α and l. Two red axes on top represent a corresponding black hole mass and time scale for $\alpha = 0.5$, $l = 1$. For the blue line a black hole mass is 5 times larger than the value on the red axis and a time scale is 5 times longer. For the green line a black hole is 5 times lighter and a time scale is $\sim 5^{1/3}$ times longer.

What about QCD itself?

What happens to nuclear physics at large θ?

Conclusions

- ✦Superradiance opens lots of opportunities to brighten up black holes
- ✦Lots of analytical and numerical work still needs to be done to fully understand this phenomenon and to make a full use of these opportunities