Detecting Superradiant Dark Photon Strings in Gravitational Wave Experiments

CLAYTON RISTOW, DAWID BRZEMINSKI, ANSON HOOK, JUNWU HUANG

Dark Photon Strings

$$\mathcal{L} = -\frac{1}{4}F^{D\,\mu\nu}F^{D}_{\mu\nu} + \frac{1}{2}\left|D_\mu\Phi\right|^2 - \lambda(|\Phi|^2 - v^2)^2$$

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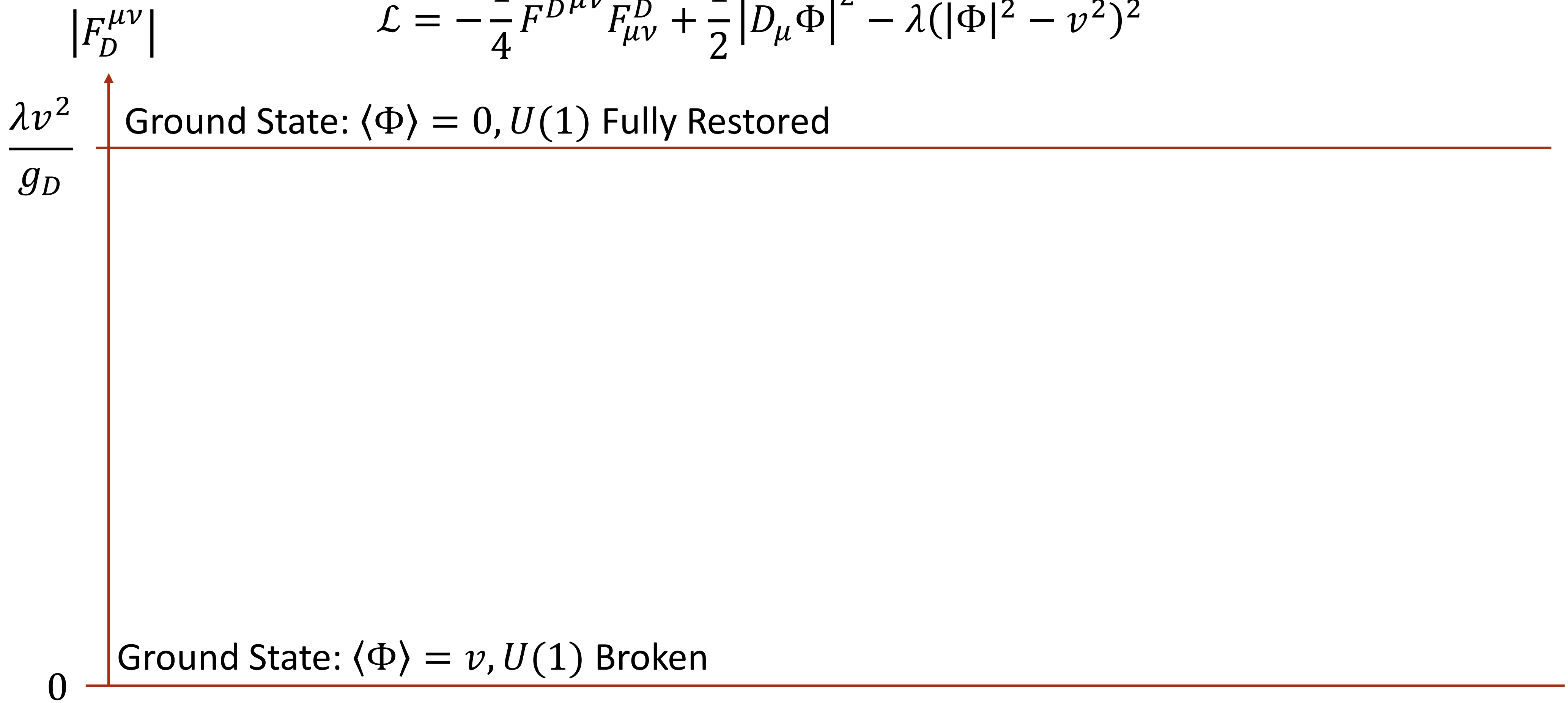

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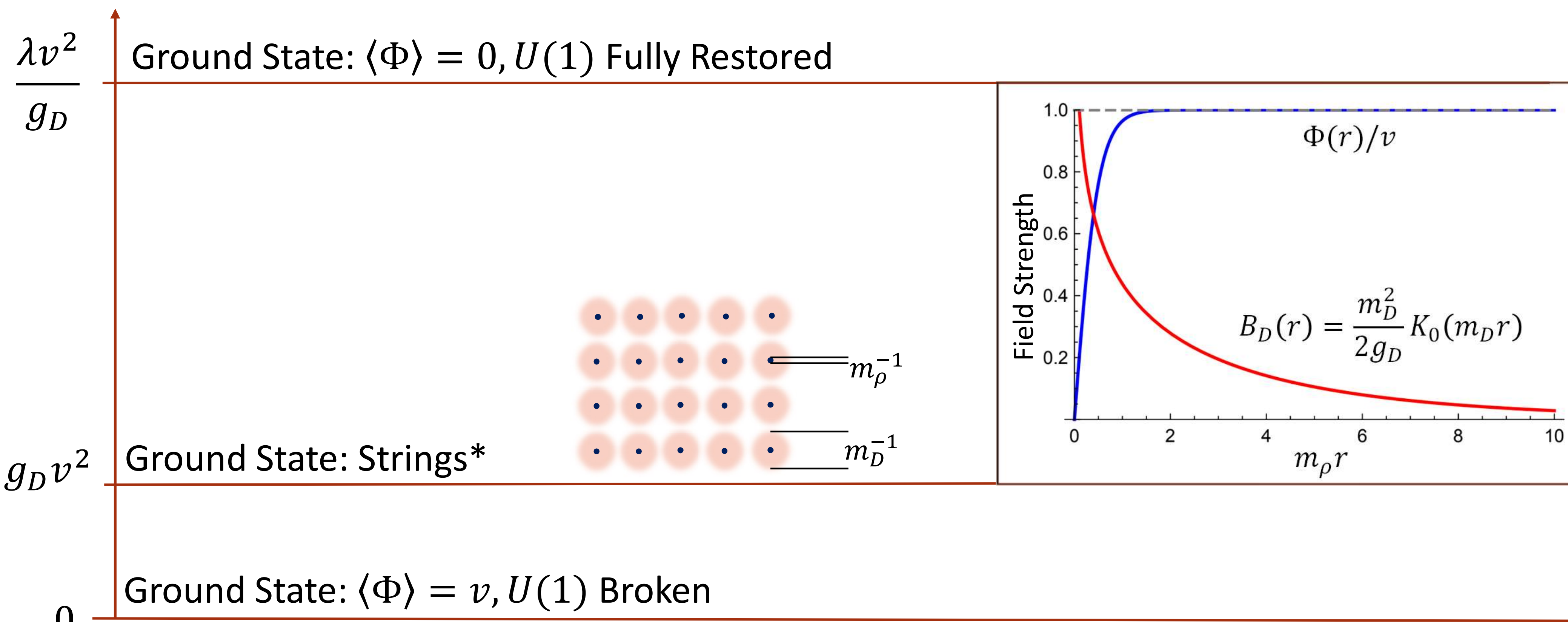

*A. A. Abrikosov, *On the Magnetic properties of superconductors of the second group*, Sov. Phys. JETP 5 (1957) 1174–1182.

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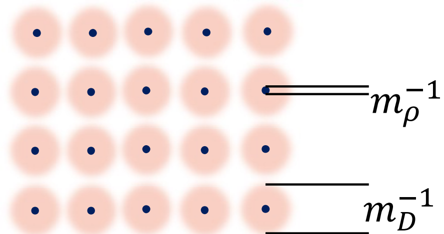
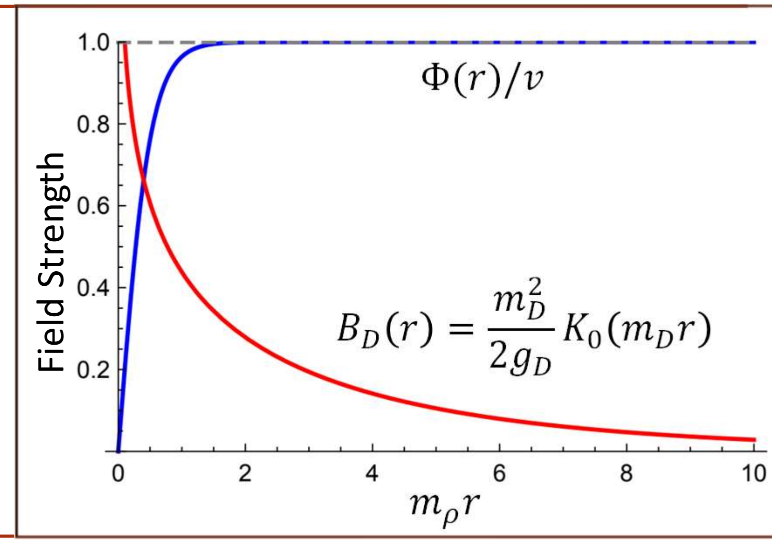
$|F_D^{\mu\nu}|$

$\frac{\lambda v^2}{g_D}$ Ground State: $\langle\Phi\rangle = 0, U(1)$ Fully Restored

$\sqrt{\lambda}v^2$ Superheated Phase Transition



$g_D v^2$ Ground State: Strings*



Ground State: $\langle\Phi\rangle = v, U(1)$ Broken

0

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Answer 2 Questions:

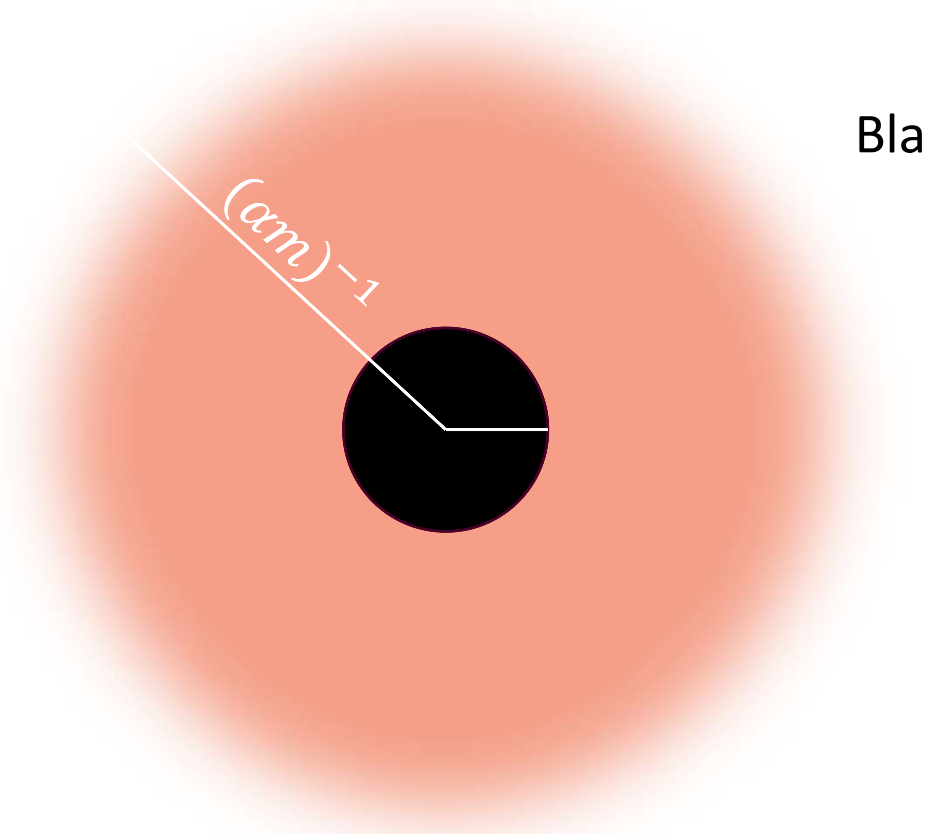
A. How can these strings arrive on earth?
(A: Superradiance)

B. What experimental signals would these strings produce?
(A: Gravitational Wave Experiments $(\mathrm{U}(1)_{\mathrm{B-L}})$)

A. How can these strings arrive on earth?

Superradiance

Bosons spontaneously produced outside a spinning blackhole



Black Hole Spin: a_*

Black Hole Mass: M

Boson Mass: m

If, $m \leq \omega_{BH}$:
Bosons cloud forms by extracting a_*

Superradiance

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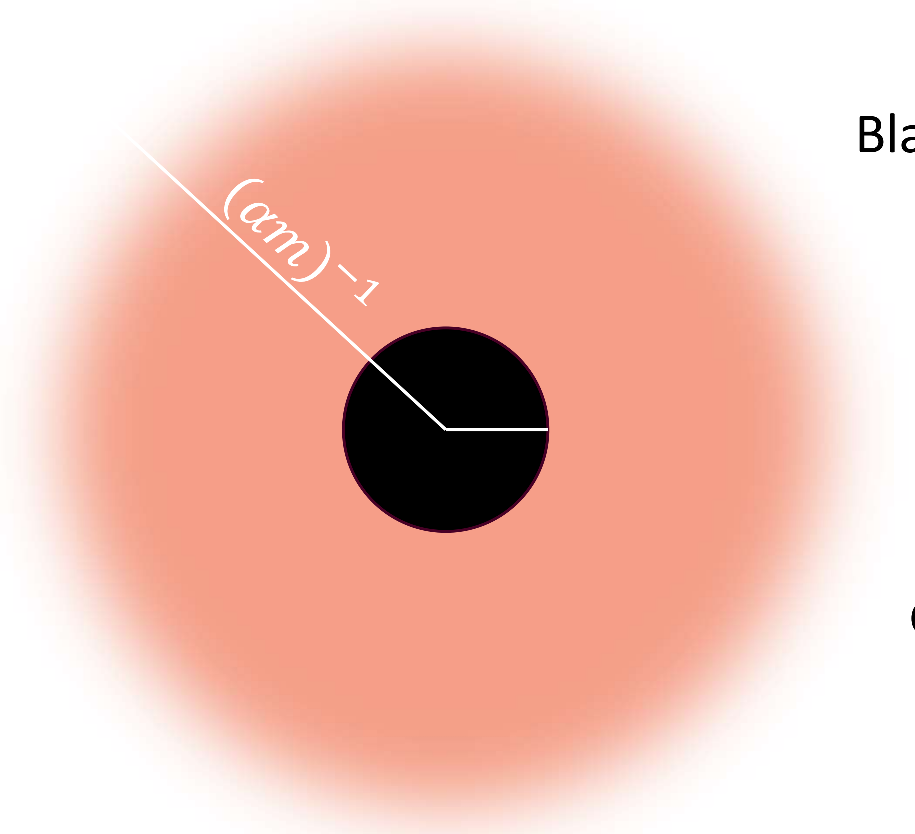

Black Hole Spin: a_* Black Hole Mass: M

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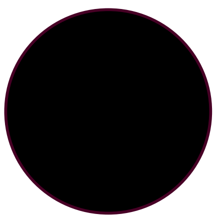
If, $m \leq \omega_{BH}$:
Bosons cloud forms by extracting a_*

Gravitational Atom with fine structure $\alpha = GMm$

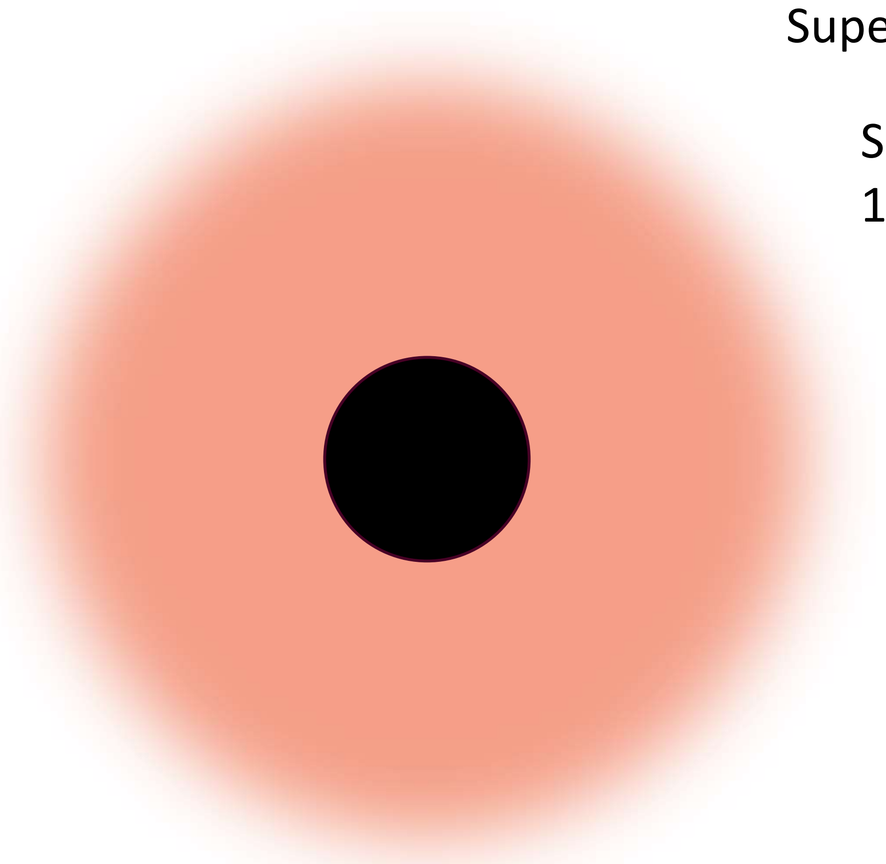
Cloud grows exponentially!

Vector Superradiance

Superradiance Condition: $m_D \leq \omega_{BH}$



Vector Superradiance



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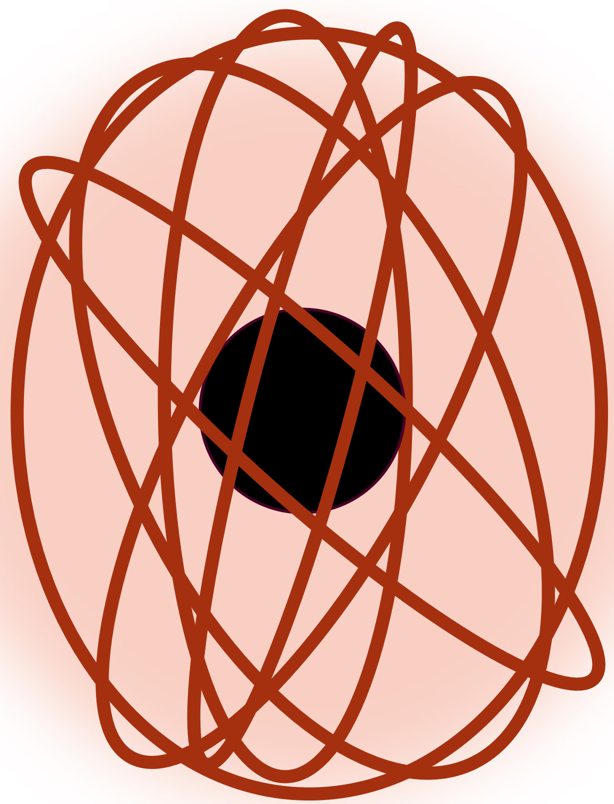
Superradiance Cycle:

1. Cloud Grows at rate $\Gamma_{SR} = 4\alpha^6 m_A$

Vector Superradiance



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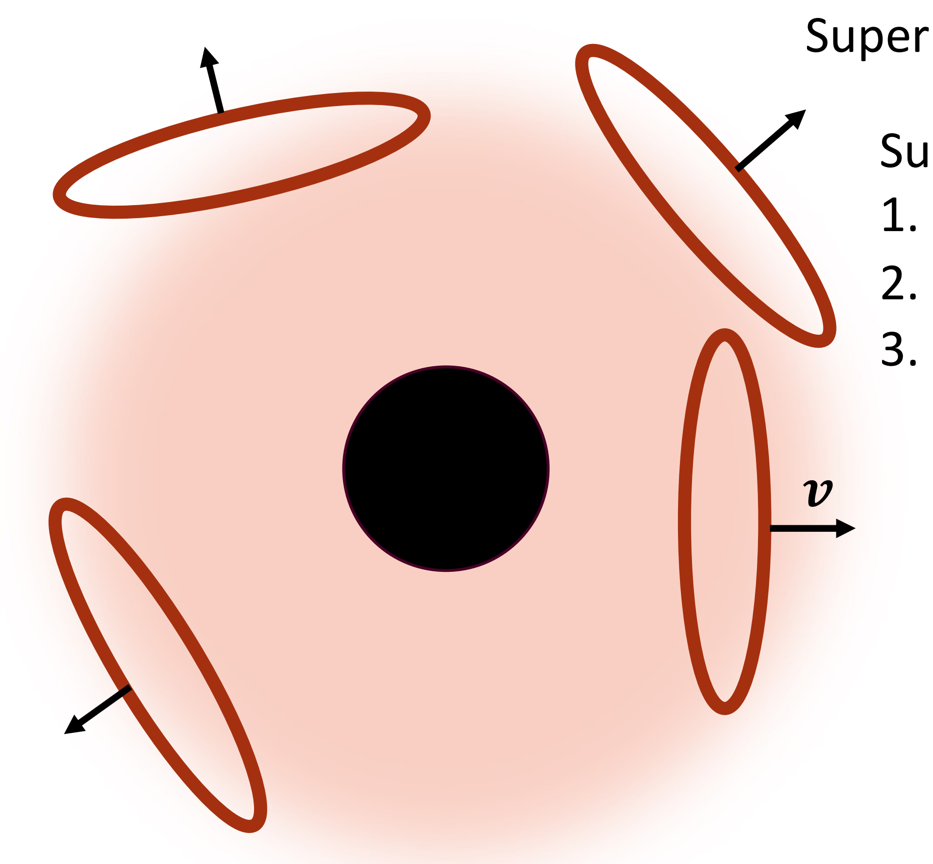
Superradiance Cycle:

1. Cloud Grows at rate $\Gamma_{SR} = 4\alpha^6 m_A$
2. $|F_D^{\mu\nu}| \sim B_{sh} = \lambda^{1/2} v^2$, Strings loops form.

Vector Superradiance



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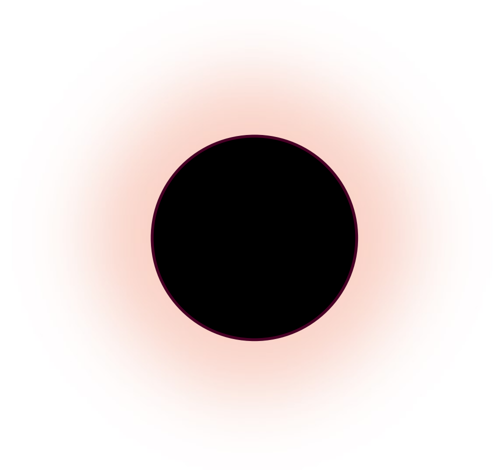

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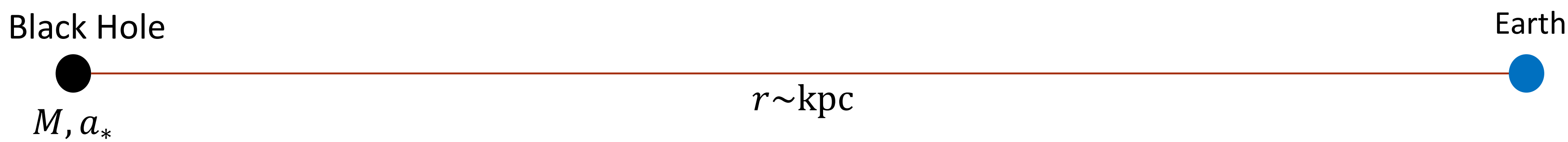
4. Repeat until Superradiance condition is not satisfied

How many of these strings arrive on earth?

String Rates: Single Burst



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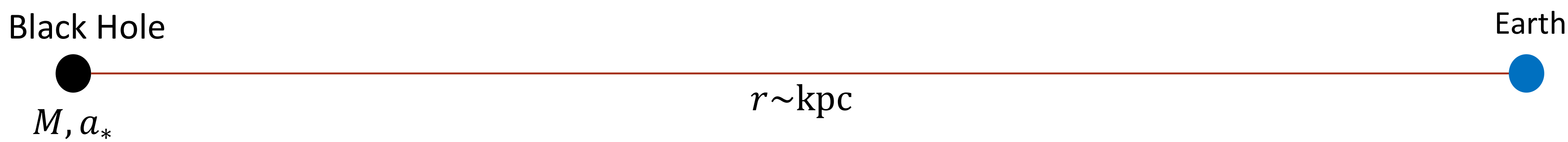

$$\Phi = \frac{N_{Strings}}{4\pi r^2 \Delta t}$$

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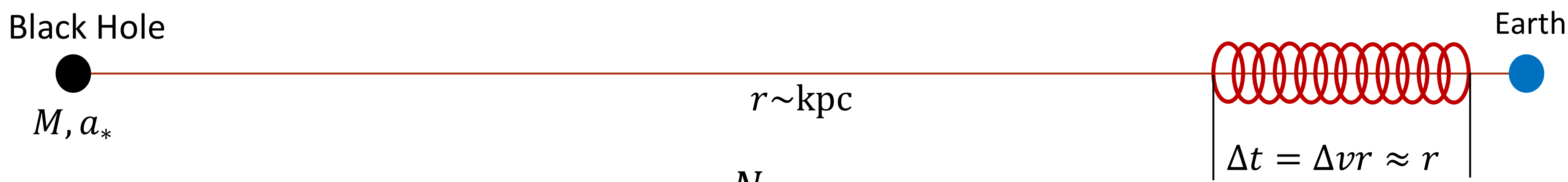

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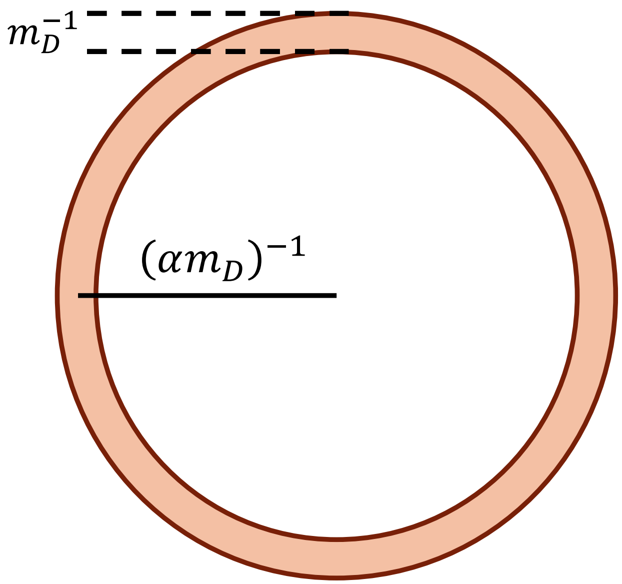
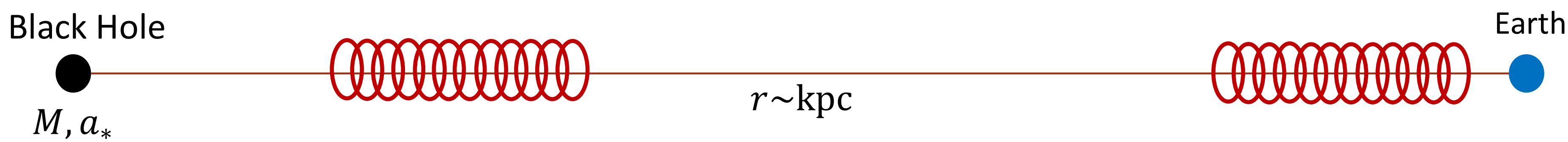


Strings hitting detectors much smaller than m_D^{-1}:

$$\Gamma_{Burst} = A_{string}\Phi \approx \frac{\lambda}{g_D^2}\frac{m_D}{2\pi^2\alpha^3(r m_D)^3}$$

String Rates: Multiple Bursts



Black Hole can repeat this process many times: $N_B = \dfrac{M\alpha\Delta a_*}{V_{cloud} B_{sh}^2}$ $\Delta t_B \approx \dfrac{\mathrm{e-folds}}{\Gamma_{SR}}$

$\Delta t_B \sim m_D^{-7} \sim \text{days} \; - 10^{11}\ \text{yr}$

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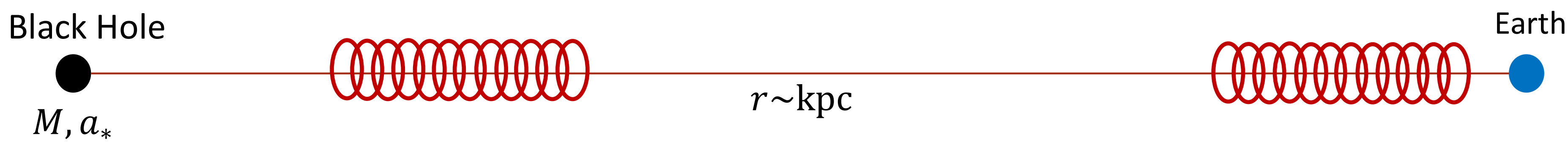

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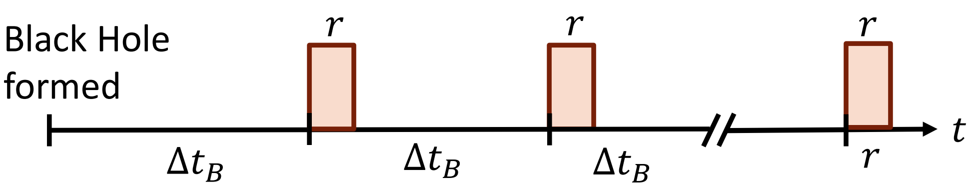
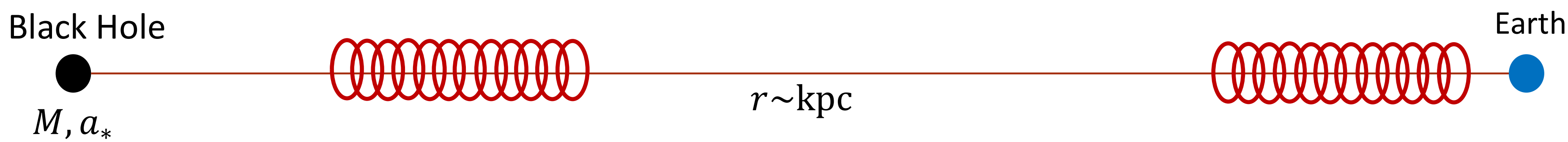
Black Hole's "Superradiant Lifecycle":



Black Hole "lives" for $\tau_{BH} = N_B \Delta t_B + r$.
During that time, it is "on" for $r N_B$

String Rates: Multiple Bursts



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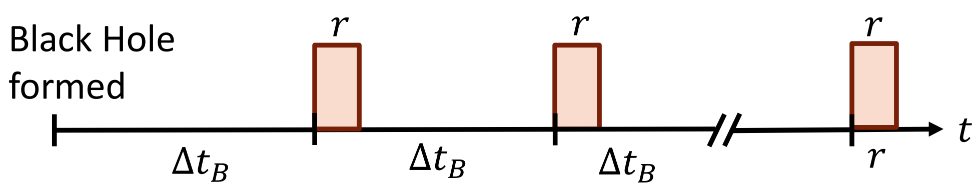

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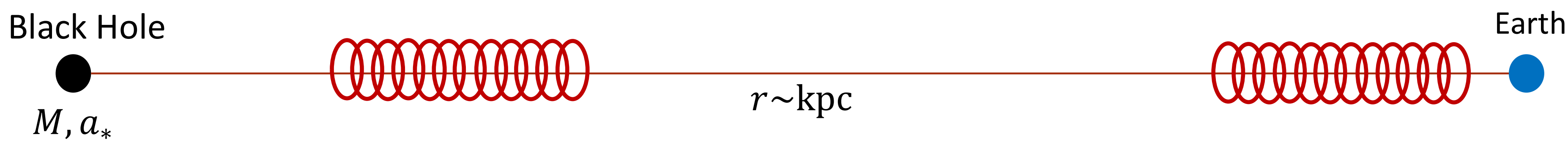
$$\Gamma_{SBH} = N_B^{Eff}\ \Gamma_B \qquad N_B^{Eff} = \frac{\text{"Time On"}}{\tau_{BH}} = \frac{rN_B}{\Delta t_B N_B + r}$$

String Rates: Multiple Bursts



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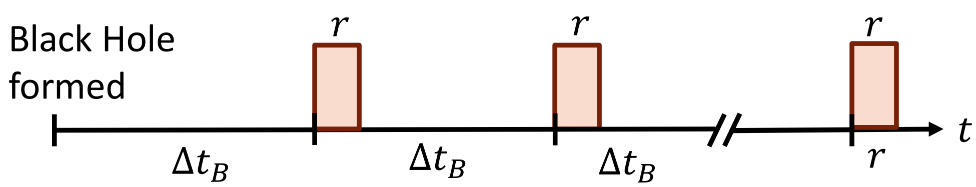

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Sum over all blackholes:

$$\Gamma_{Tot}(\lambda/g_D^2, m_D) = \left\langle N_{BH} N_B^{Eff}\, \Gamma_{Burst} \right\rangle_{M, a_*, r}$$

String Rates

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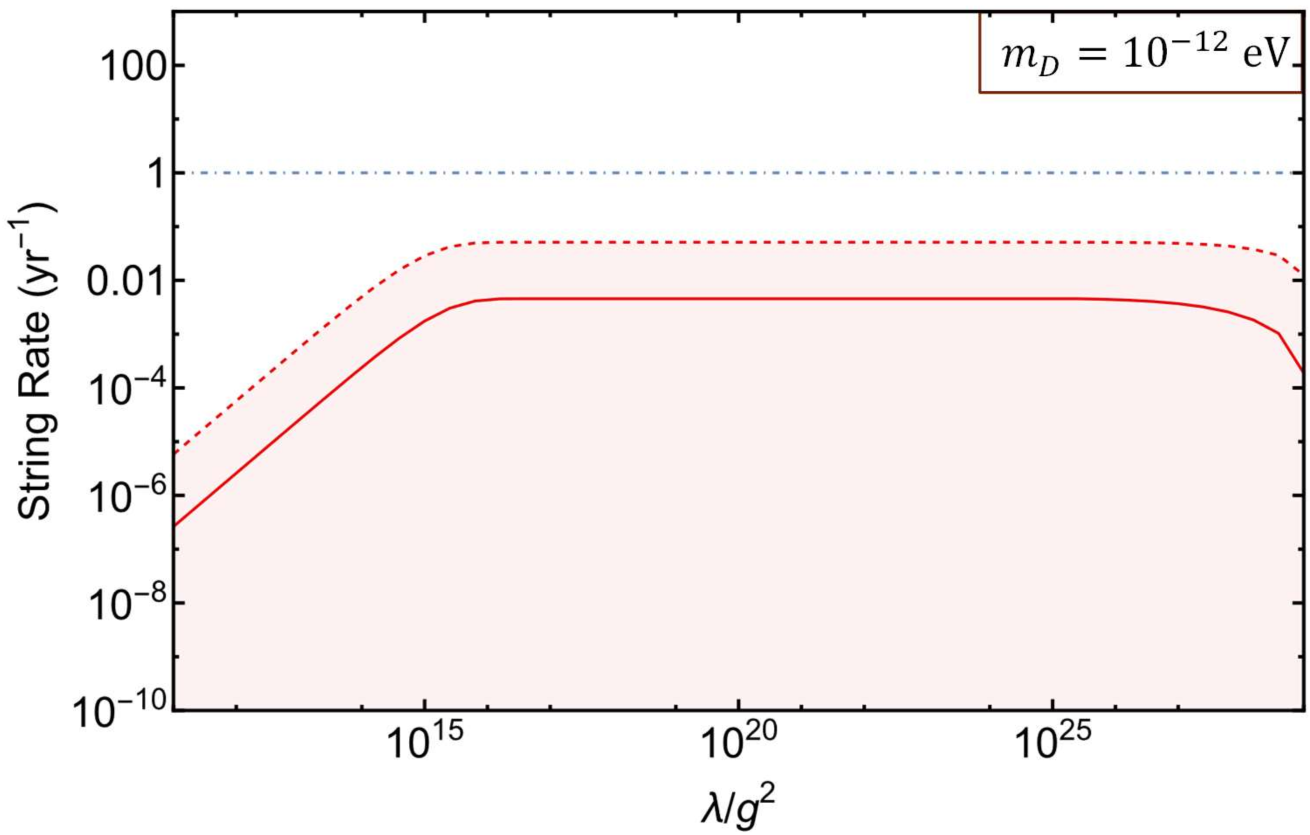

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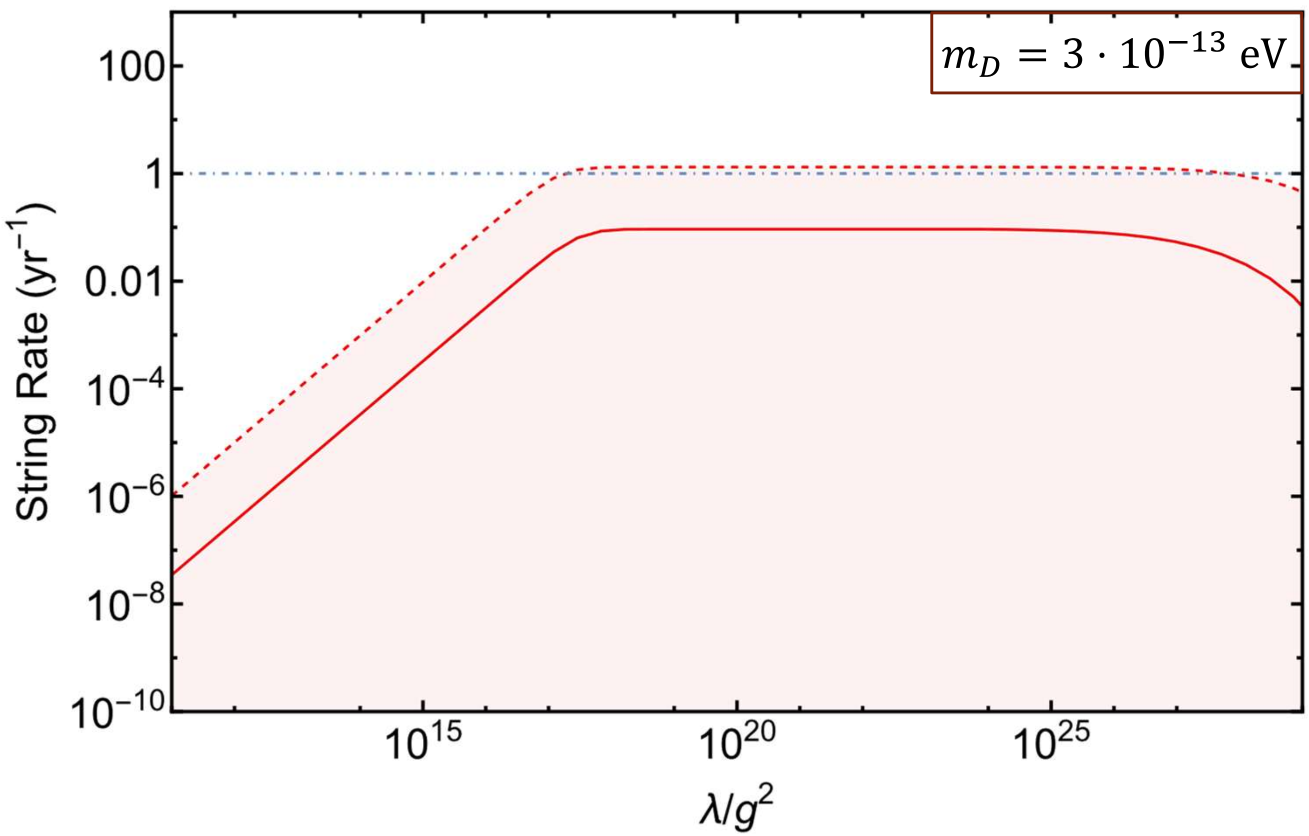

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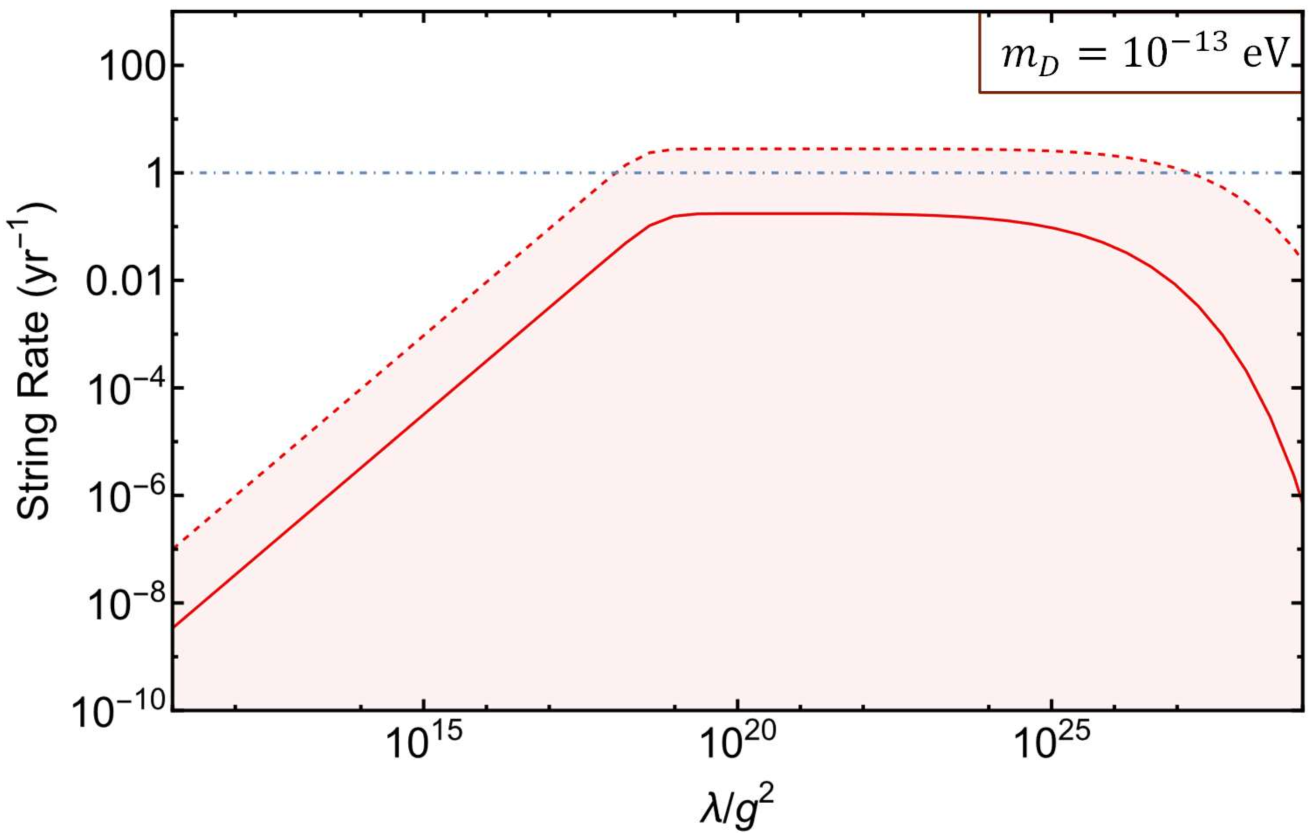

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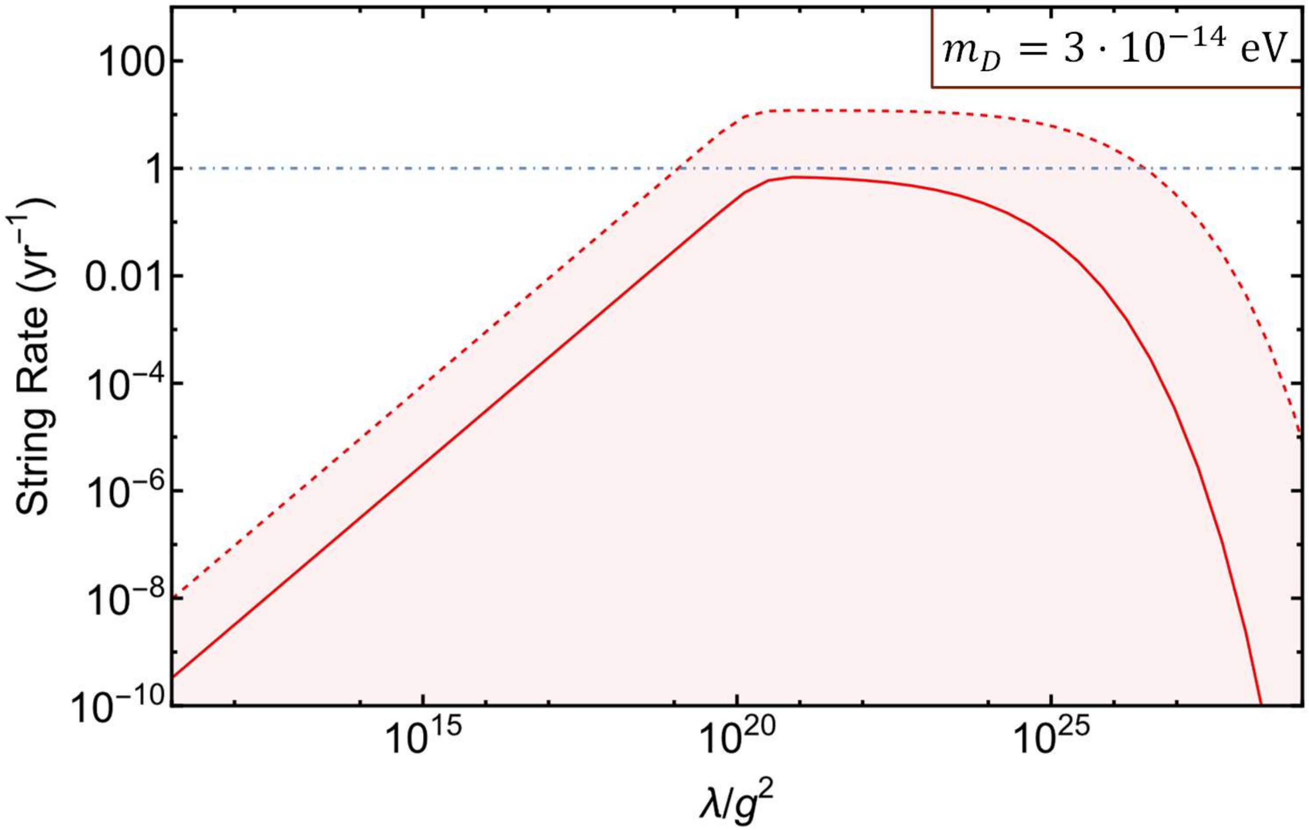

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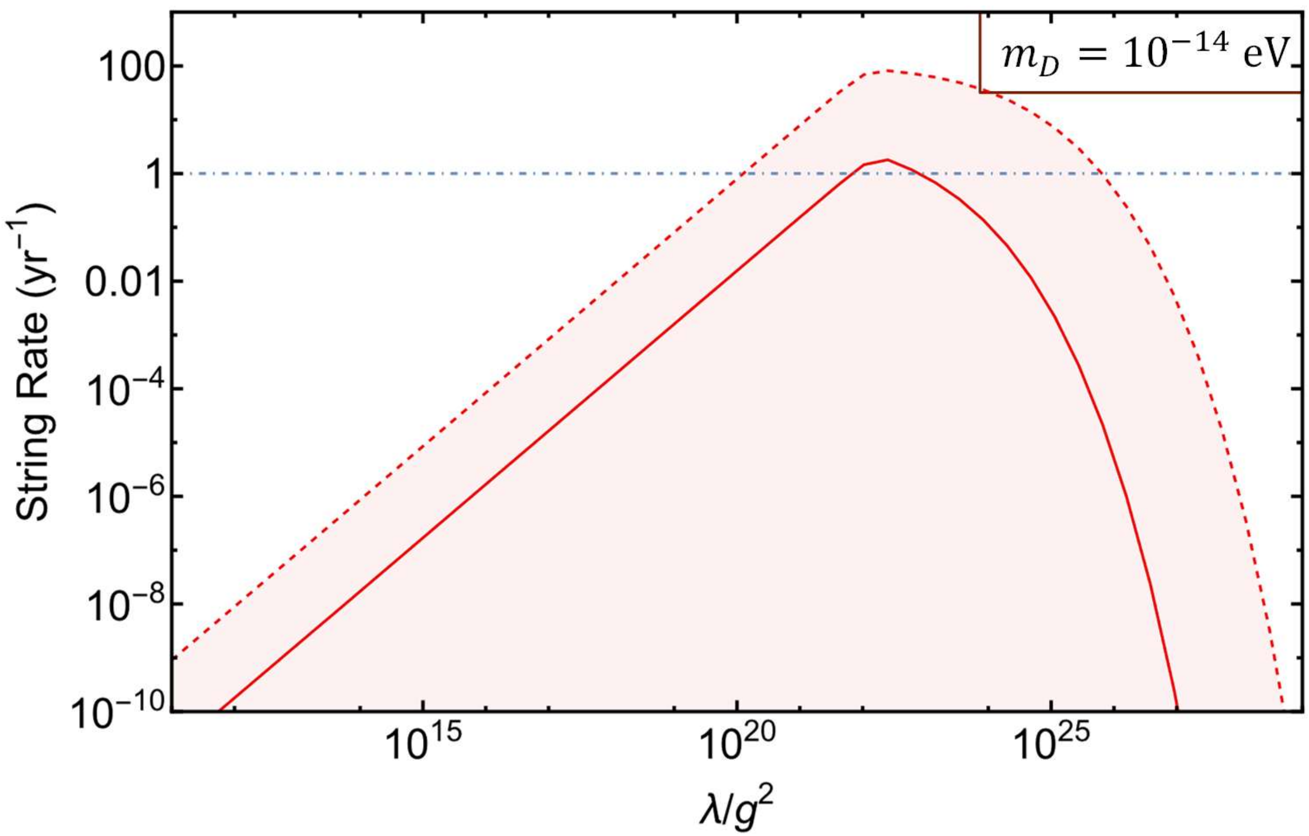

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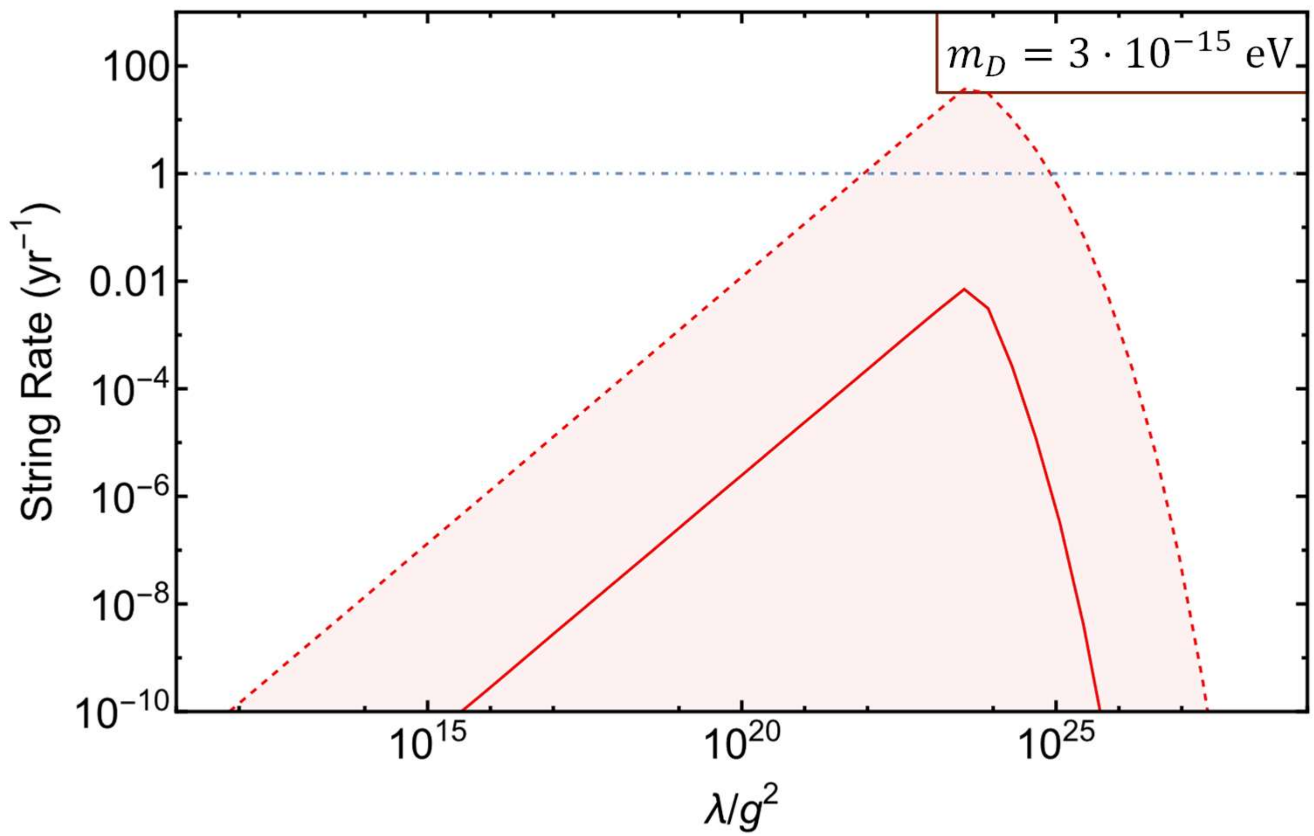

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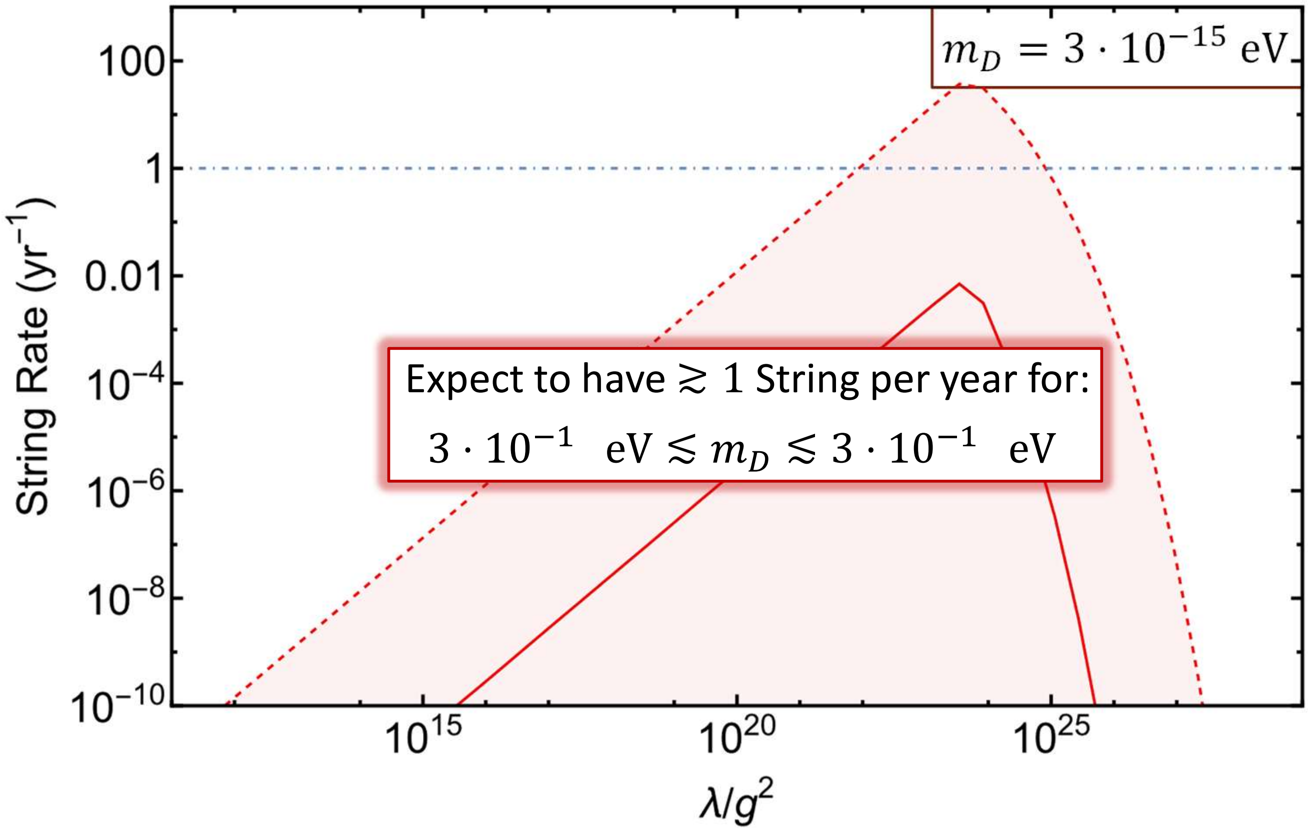
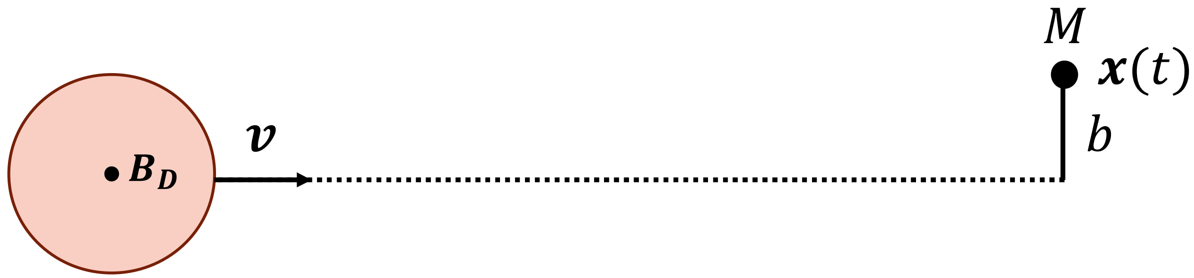


B. What experimental signals do these strings produce?

Observing Dark Photon Strings

Take a $U(1)_{B-L}$ dark photon.



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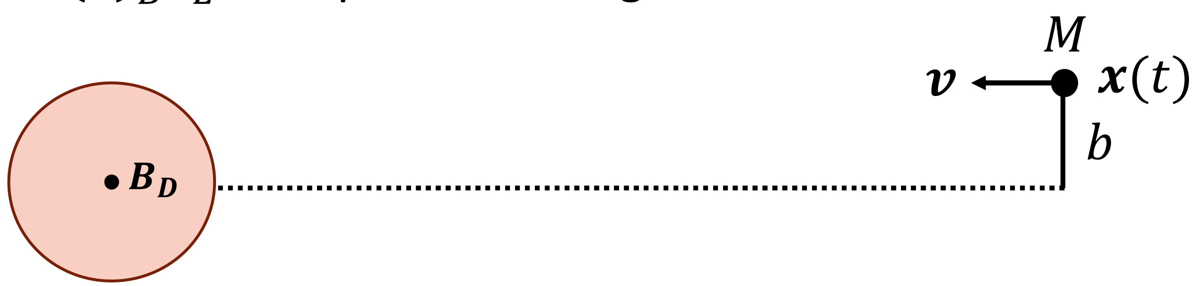

Mass experiences an acceleration

$$\boldsymbol{a} = \frac{Q_D}{M}(\boldsymbol{v} \times \boldsymbol{B_D})$$

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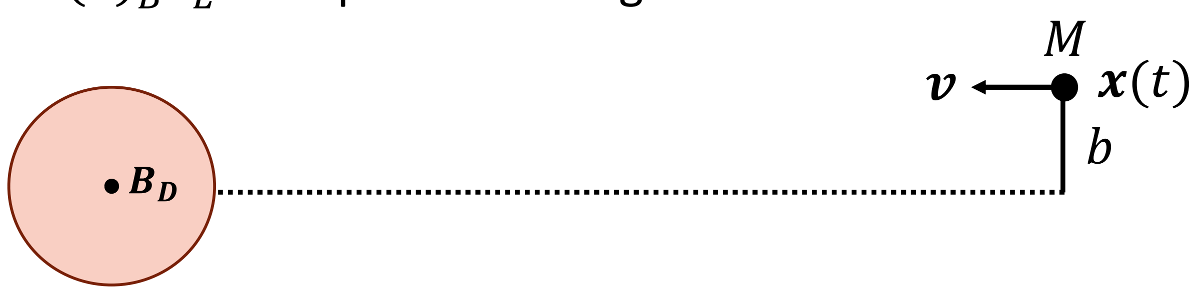

Mass experiences an acceleration

$$\boldsymbol{a} = \frac{Q_D}{M}(\boldsymbol{v} \times \boldsymbol{B_D})$$

Equal numbers of protons and neutrons:

$$\frac{Q_D}{M} = \frac{g_D}{2m_p}$$

$$B(r) = \frac{m_D^2}{2g_D} K_0(m_D r)$$

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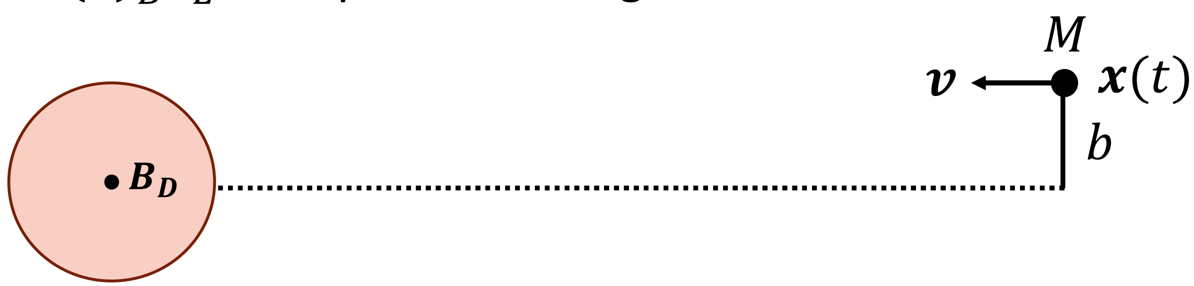

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$\longrightarrow$ Effect is independent of g_D!

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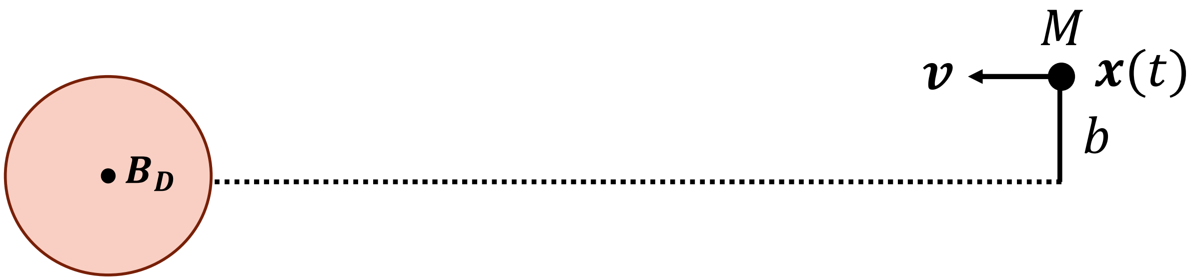

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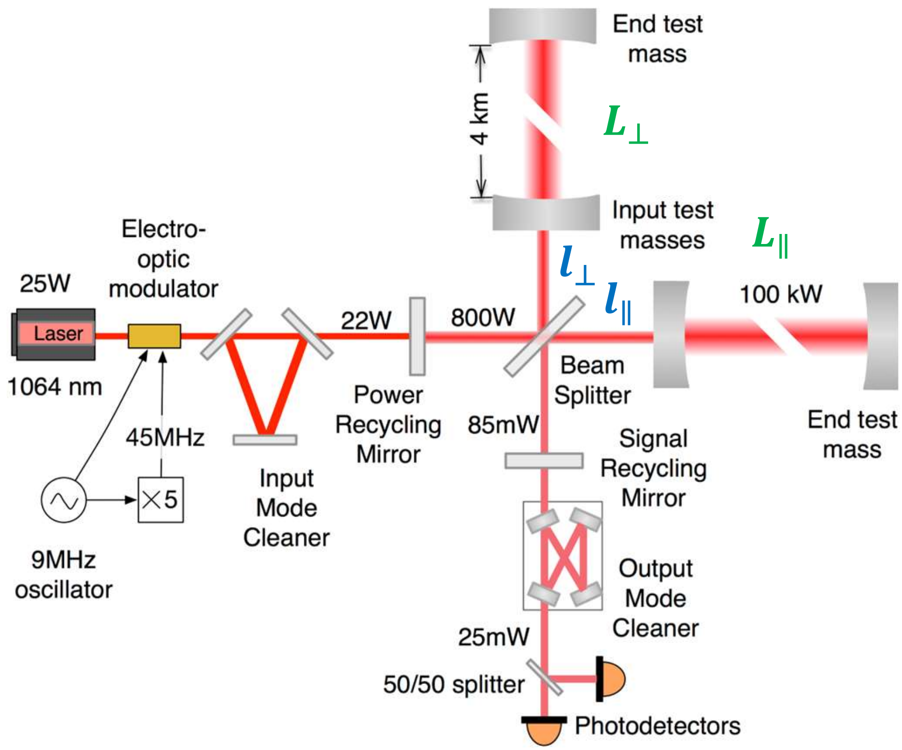
Equal numbers of protons and neutrons: $$\frac{Q_D}{M} = \frac{g_D}{2m_p}$$

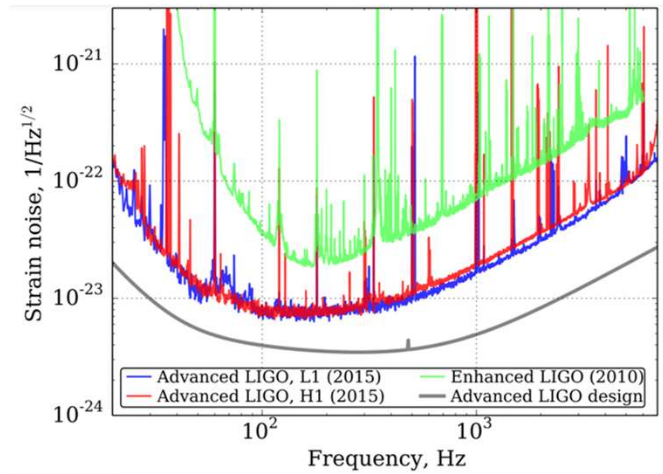
$$B(r) = \frac{m_D^2}{2g_D} K_0(m_D r)$$ ⟶ Effect is independent of g_D!

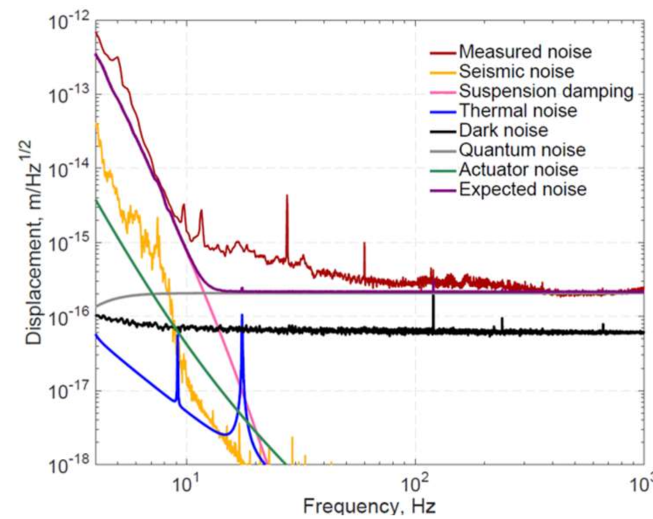
Solve equations of motion:

$$x(t) = \int \frac{d\omega}{2\pi}\, e^{i\omega t}\, \tilde{x}(\omega) \qquad \tilde{x}(\omega) = -\frac{\pi m_D^2 v}{8m_p\omega^2\sqrt{\omega^2 + m_D^2 v^2}}\, \mathrm{e}^{-\frac{b}{v}\sqrt{\omega^2+m_D^2 v^2}}$$

LIGO



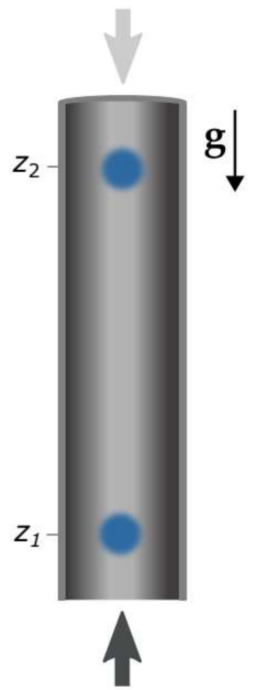


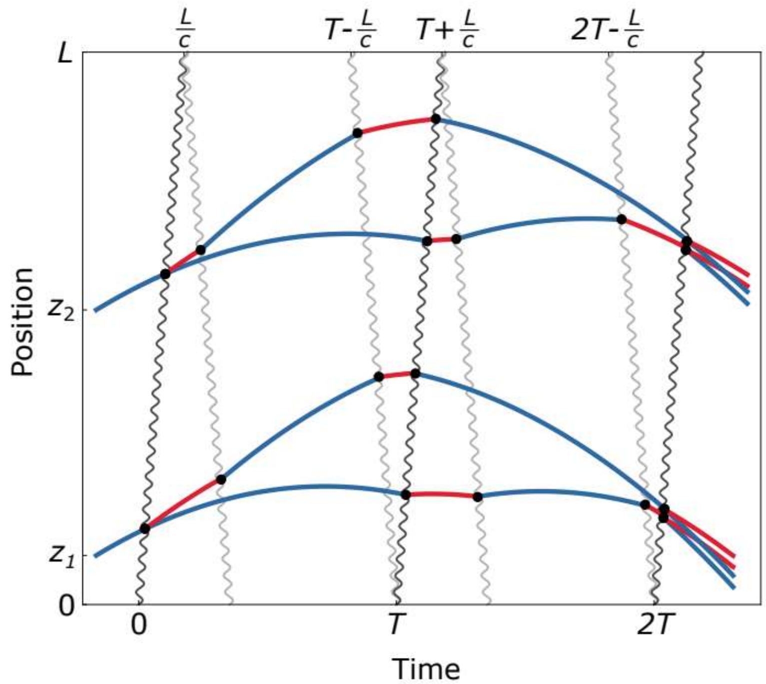


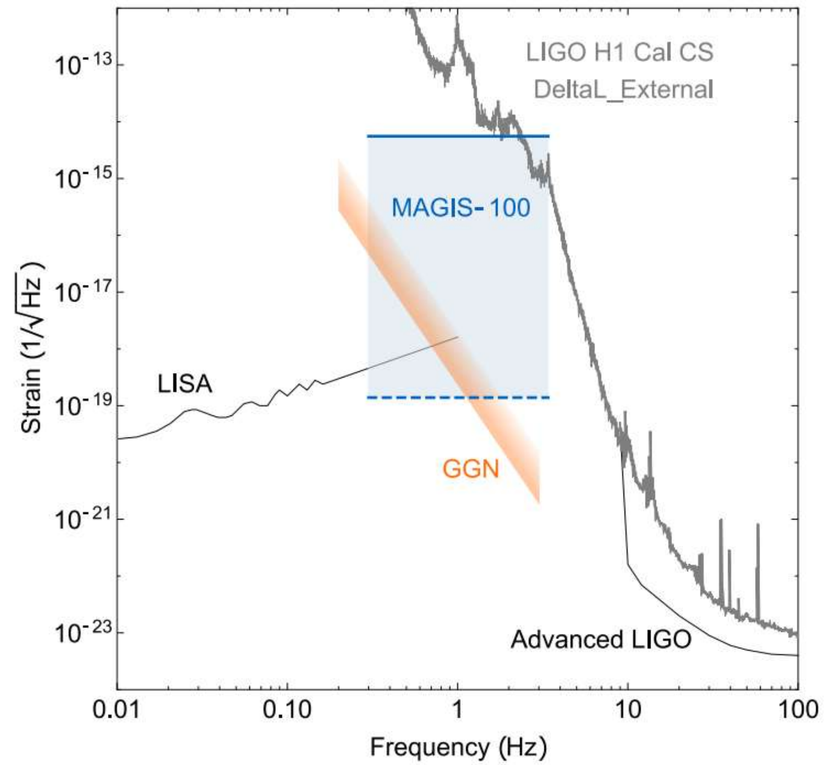
LIGO measures displacement $l_\parallel - l_\perp$ (Michaelson Displacement) and strain $h = \frac{L_\perp - L_\parallel}{L_0}$

B. P. Abbott et al., *Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy*, Phys. Rev. D 93 (2016), no. 11 112004

MAGIS-100





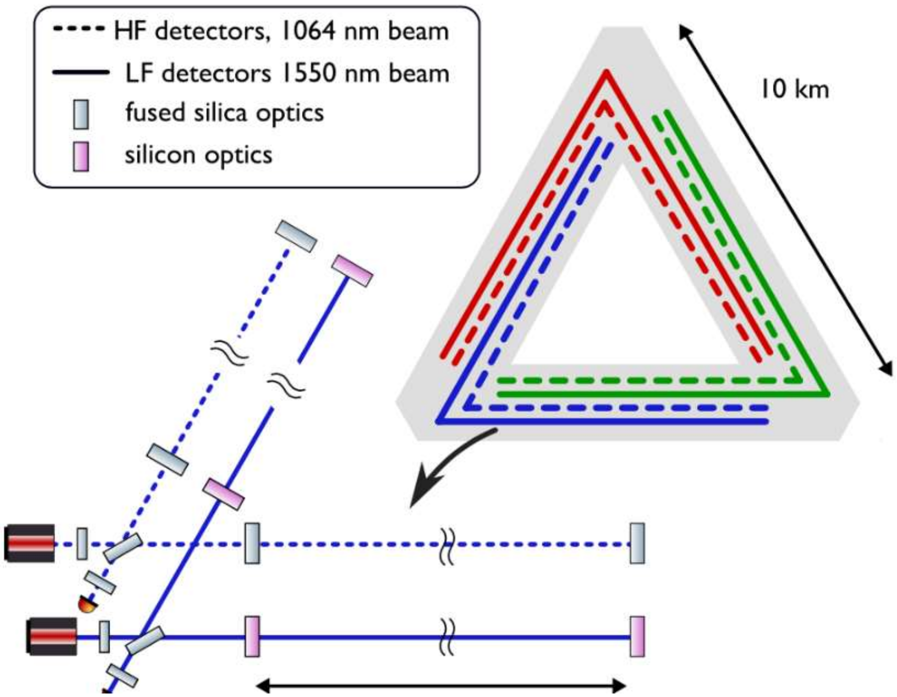


MAGIS-100 will measure strain $h = \frac{z_2 - z_1}{L_0}$

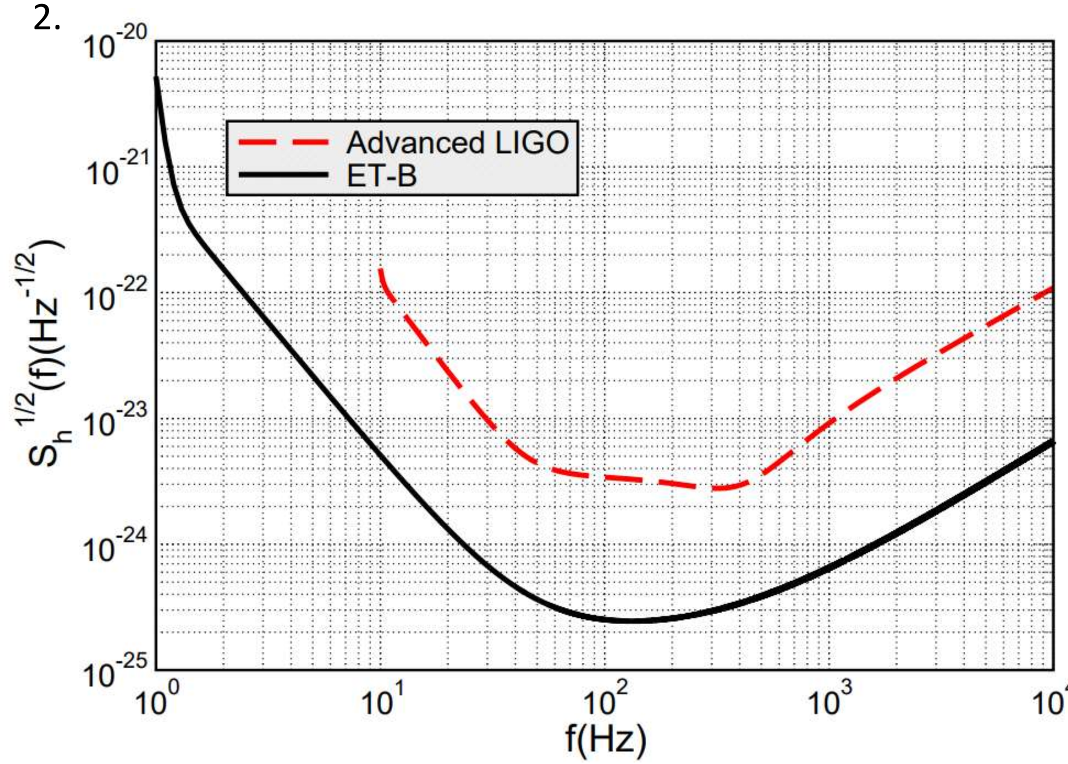
MAGIS-100 Collaboration, M. Abe et al., *Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)*, Quantum Sci. Technol. 6 (2021)

Einstein Telescope

1.



2.

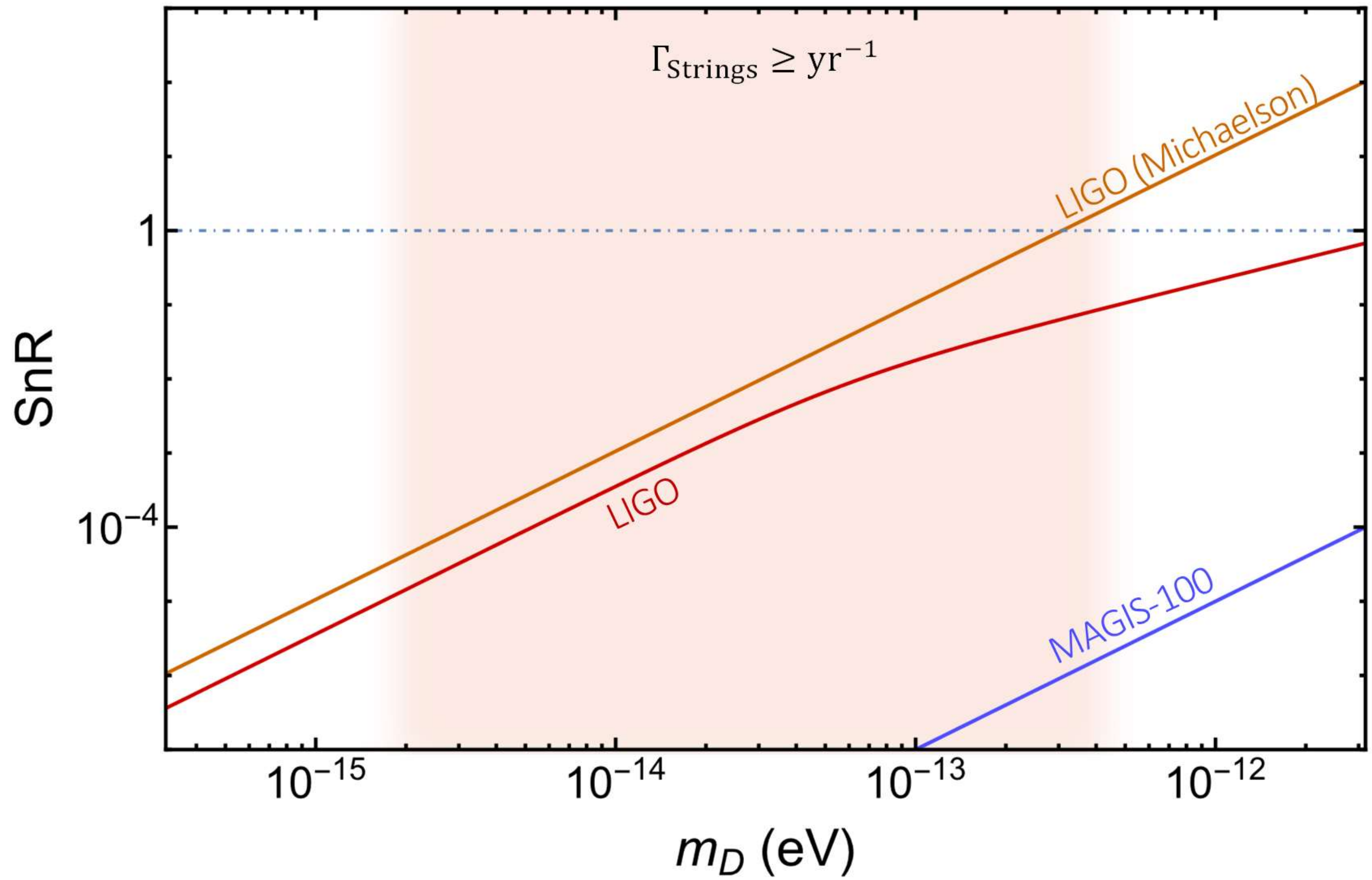


Einstein Telescope will measure strain h

1. S. Rowlinson, A. Dmitriev, A. W. Jones, T. Zhang, and A. Freise, Feasibility study of beam-expanding telescopes in the interferometer arms for the einstein telescope, Phys. Rev. D103 (Jan, 2021)

2.Type equation here. E. A. Huerta and J. R. Gair, Intermediate-mass-ratio-inspirals in the Einstein Telescope: I. Signal-to-noise ratio calculations, Phys. Rev. D 83 (2011) 044020

Signal to Noise Ratio



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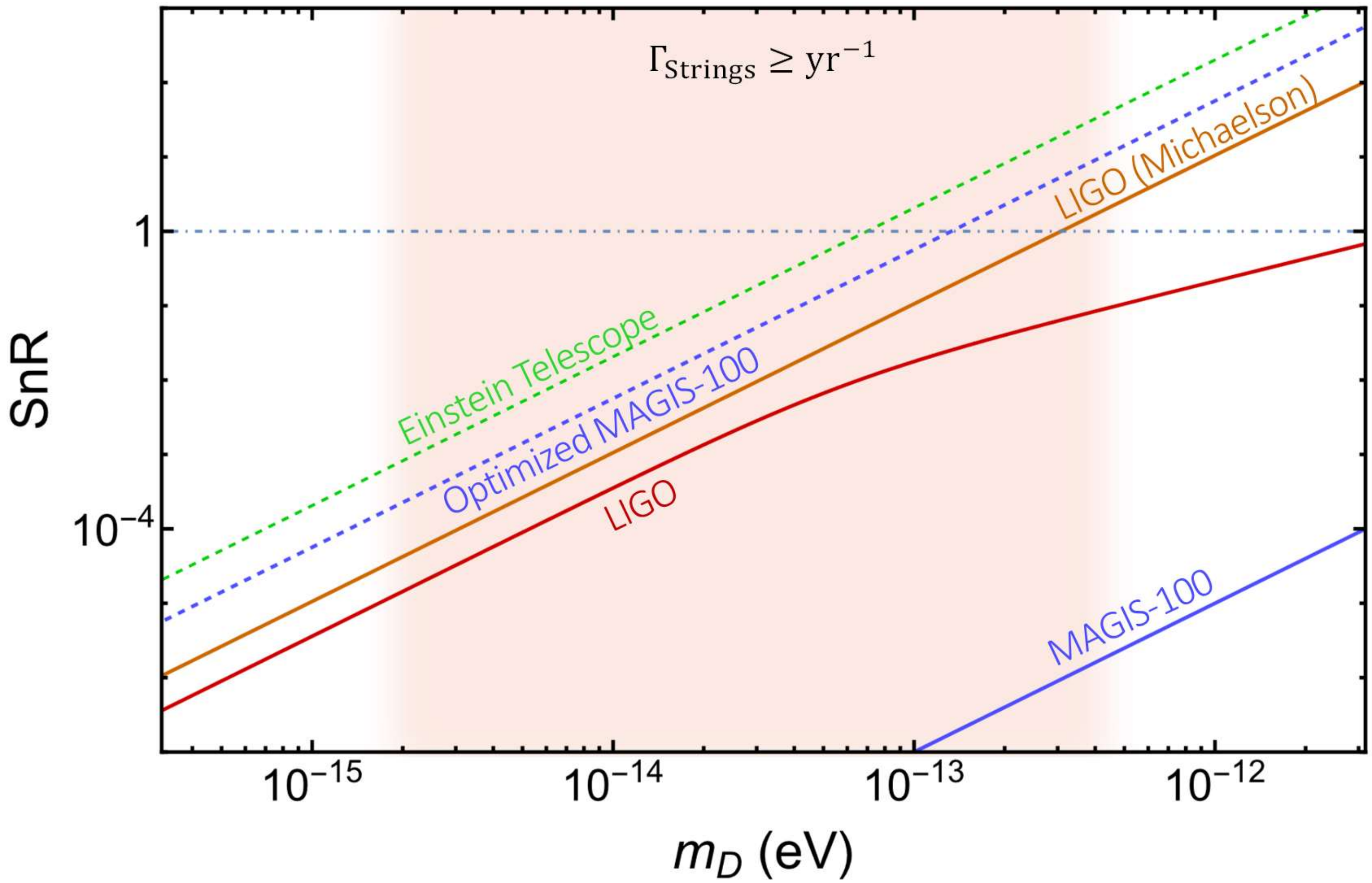

Ongoing Directions

- More precise computations for signals at MAGIS and LIGO
- Signal at LISA

Thanks

- Anson Hook, Junwu Huang, and Dawid Brzeminski
- University of Maryland, MCFP, Perimeter Institute, and NSF
- University of Pittsburgh, Pheno 2023

Back-Ups

Summing Over Black Holes

In our galaxy, there are multiple blackholes that are "alive" and can be estimated based on black hole formation rate $R_{BH} \approx 0.009 \text{ yr}^{-1}$.

$$N_{BH} = R_{BH} \min(\tau_{BH}, \text{Age of Milky Way}) \qquad \Gamma_{Tot}(M, a_*, r, g_D, m_D, \lambda) = N_{BH} N_{Expected}\, \Gamma_{Burst}$$

Average or distributions for:

- Black hole mass: $P(M) = M_0^{-1} e^{-(M-M_{min})/M_0}$ $\qquad M_{min} = 4.1\, M_\odot, \quad M_0 = 7.9\, M_\odot$
- Black hole spin: Optimistic Distribution, 80% above $a_* > .9$
- Black hole distance: Proportional to stellar distribution