Title: Grad Student Seminar with Nils Siemonsen

Speakers: Nils Peter Siemonsen
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Abstract: Nils Siemonsen, Perimeter Institute & University of Waterloo

Dark Photon Superradiance

Gravitational and electromagnetic signatures of black hole superradiance are a unique probe of ultralight particles that are weakly-coupled to ordinary matter. Considering the lowest-order interactions one can write down for spin-1 dark photons, the kinetic mixing, a dark photon superradiance cloud sources a rotating visible electromagnetic field. A pair production cascade ensues in the superradiance cloud, resulting a turbulent plasma with strong electromagnetic emissions. The emission is expected to have a significant X-ray component and to potentially be periodic, with period set by the dark photon mass. The luminosity is comparable to the brightest X-ray sources in the Universe, allowing for searches at distances of up to hundreds of Mpc with existing telescopes. Therefore, multi-messenger search campaigns are sensitive to large parts of unexplored beyond the Standard Model parameter space.

Grad Student Seminar, Perimeter Institute

Dark Photon Superradiance

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May 1, 2023

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Be Part of (the) Equation

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Q: Can we detect beyond the Standard Model physics using astrophysical probes?

Why?

- Strong CP-problem, dark matter
- Low-energy limit of quantum gravity models

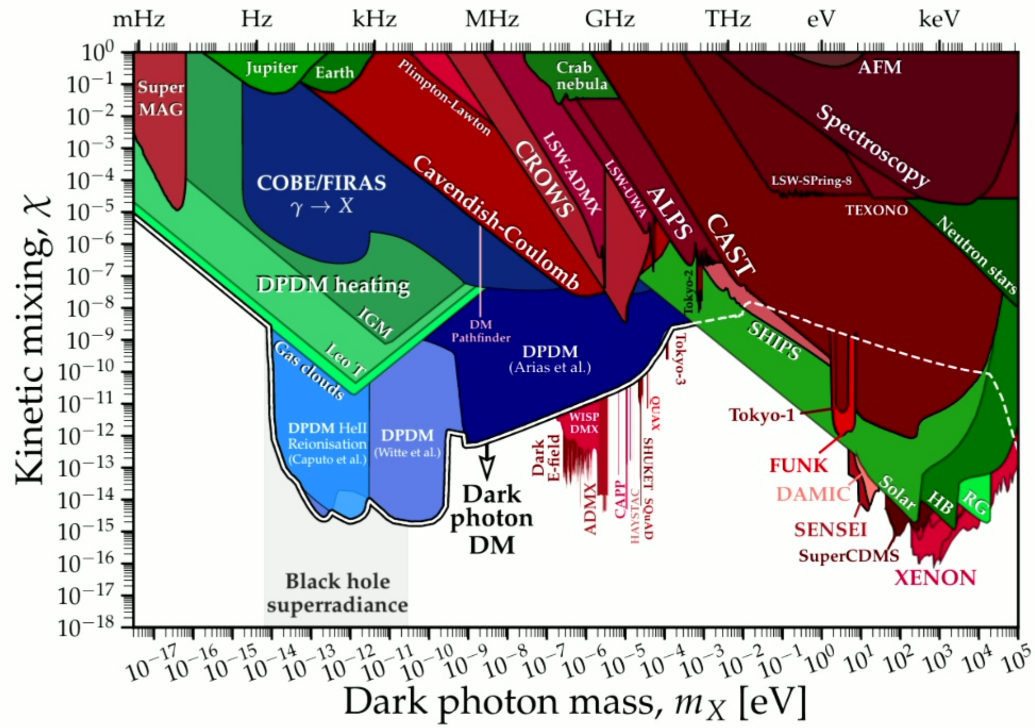
Candidates:

- Axion (spin-0)
- Dark photon (spin-1)

Couplings:

- Axion-photon
- Kinetic mixing

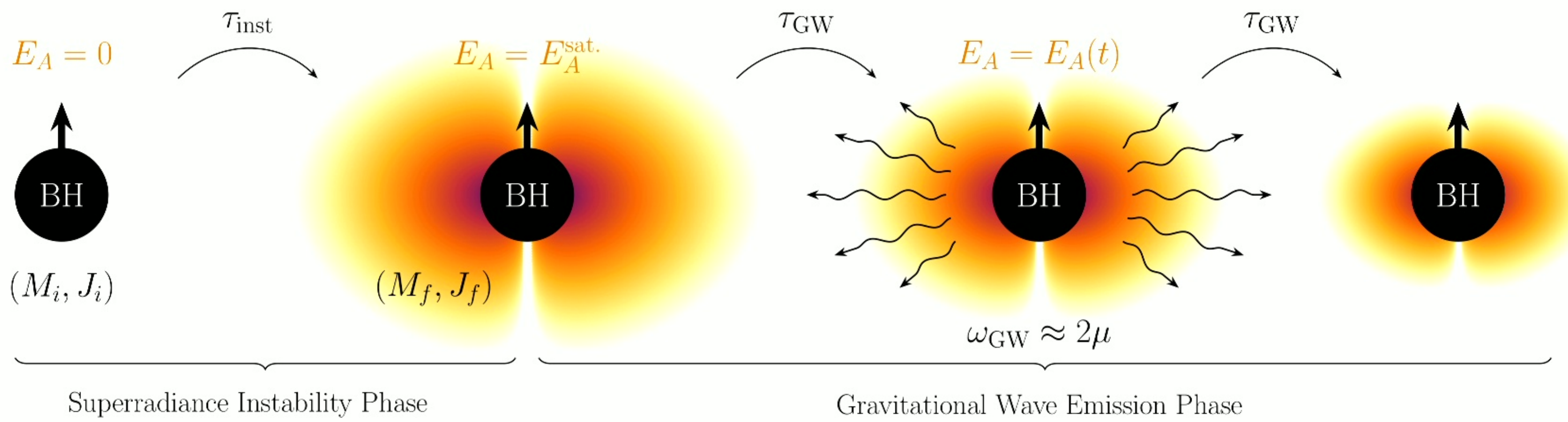
[Caputo et al., 2021]



Black hole Superradiance

- $\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\mu^2}{2}A'_\mu A'^\mu$
- Penrose, Zeldovich, ... $\Rightarrow$ Energy extraction from black hole
- Massive fields [Detweiler, 1980] $\Rightarrow$ $A'_\mu \sim e^{t/\tau_{\rm SR}}$
- Timescales [Baryakhtar et al, 2017]: $\tau_{\rm SR} \sim 1$ min $(\frac{M_{\rm BH}}{10M_\odot})$
- Instability most efficient if $\mu \sim 10^{-12}{\rm eV}(\frac{10M_\odot}{M_{\rm BH}})$
- Quantum fluctuations seed instability
- Cloud mass [East, 2018]: $M_c \lesssim 10\%\ M_{\rm BH}$

Black hole Superradiance



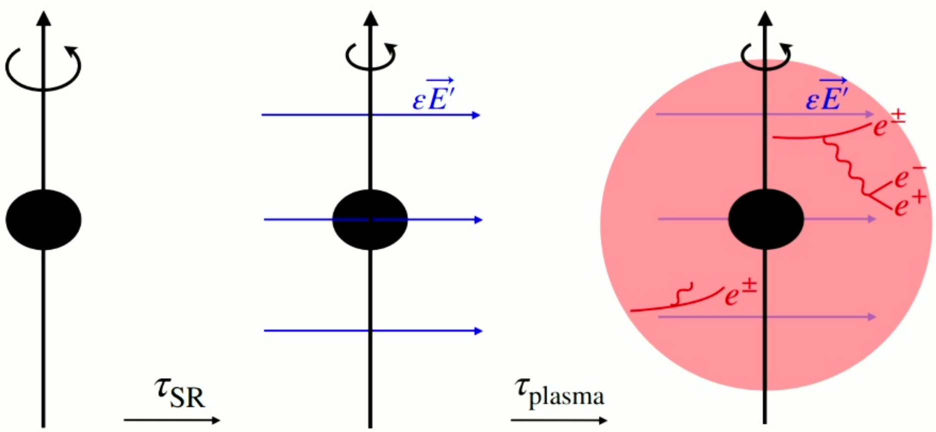
- Gravitational wave timescales [NS & East, 2019]: $\tau_{\rm GW} \sim 33$ days $\left(\frac{M_{\rm BH}}{10 M_\odot}\right)$
- Cloud frequency: $\mu \sim 320$ Hz $\left(\frac{10 M_\odot}{M_{\rm BH}}\right)$

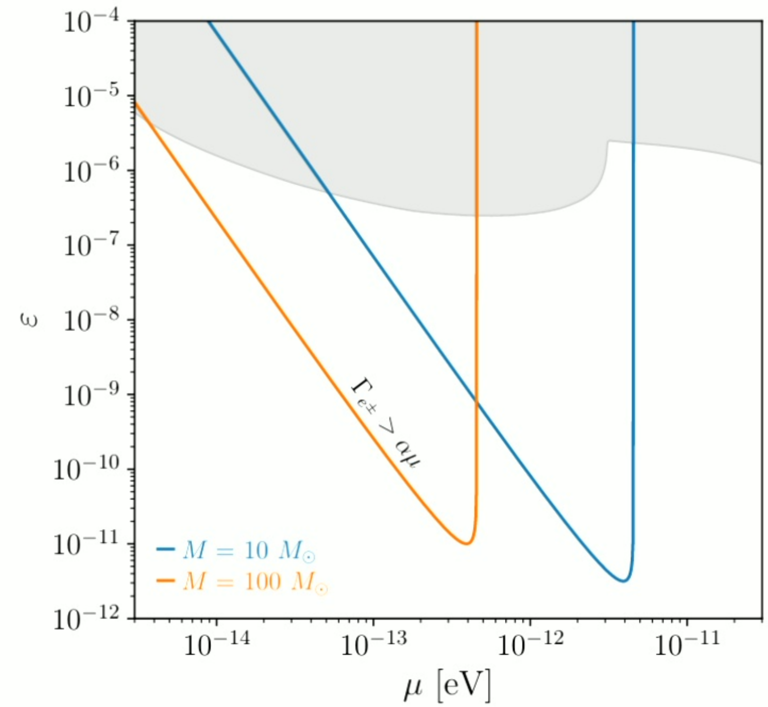
$\Rightarrow$ Black hole spindown & gravitational wave emission

- Superradiance as “axion detector” [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell,...]

- $\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\mu^2}{2}A'_\mu A'^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + I_\mu(A^\mu + \varepsilon A'^\mu)$
- Large electric fields $A'_\mu \to \varepsilon \mathbf{E}' \;\Rightarrow\; \gamma_e \sim 10^{12}$
- Synchrotron emission $\;\Rightarrow e^\pm$-creation

$\Rightarrow$ Pair production cascade with rate $\Gamma_{e^\pm}$





Simulations:

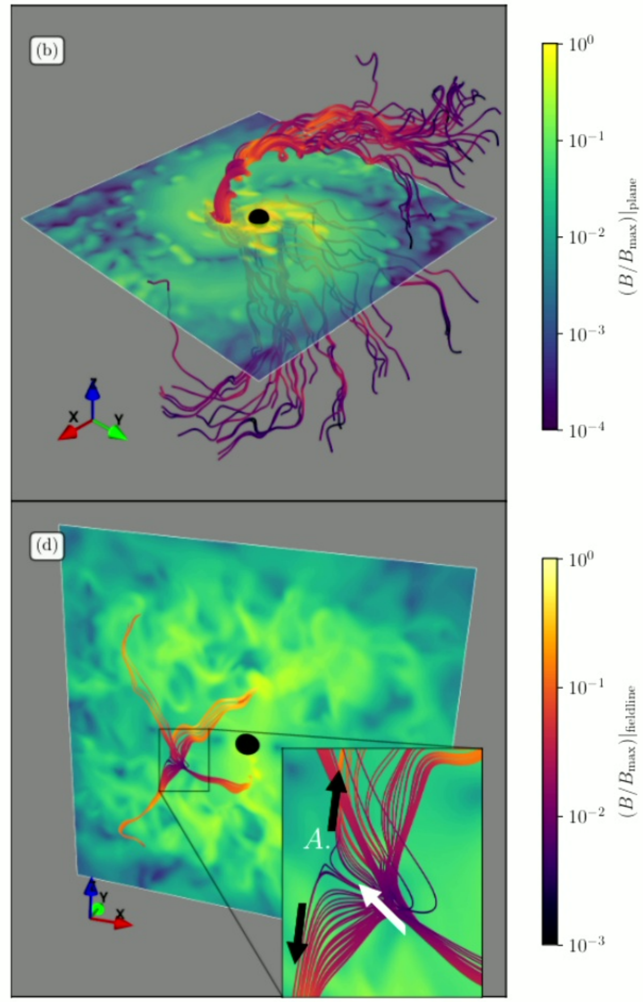
- Maxwell equations + Dark Photon sources
- 3D evolution on Kerr background
- Plasma modeling: "Resistive force-free" methods

Endstate of pair cascade:

- Turbulent plasma state
- Largely magnetically dominated: $|\mathbf{B}| > |\mathbf{E}|$
- Efficient magnetic reconnection in bulk of cloud
- Strong dissipation: $P_{\rm diss} \gg P_{\rm EM}$
- Luminosity: $L \lesssim 10^{43}$ erg/s
- Some evidence for periodicity
- $|\mathbf{B}| \lesssim 10^{8}$ Gauss $\Rightarrow$ X-ray & γ-ray

$\Rightarrow$ Electromagnetic signatures

[NS et al., 2022]

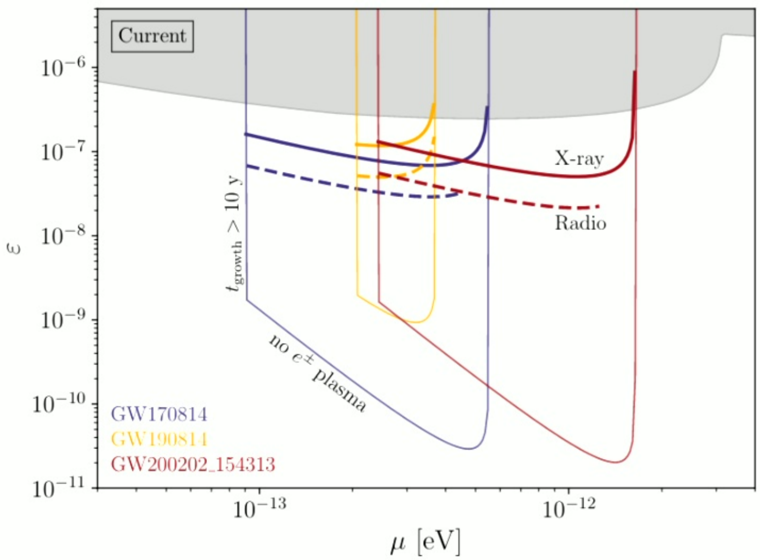


Observational prospects

Electromagnetic signatures:

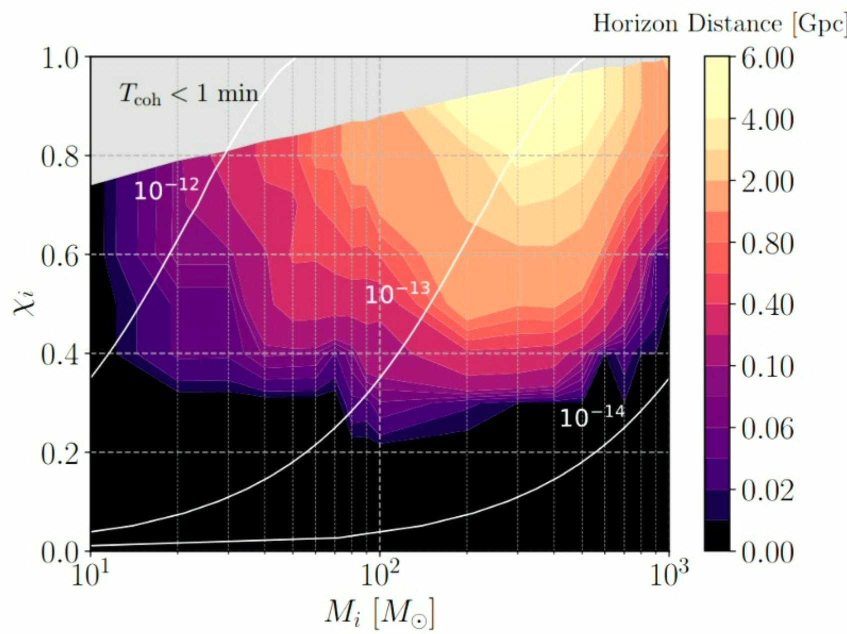
[NS et al., 2022]

- Follow up LVK binary black holes
- CHIME (radio), Swift/Fermi (X, γ-ray)



Gravitational waves:

- Various methods (SGWB, all-sky, directed)
- Follow-up searches [Jones et al., 2023]:



Conclusion

1. Dark photon superradiance results in electromagnetic/gravitational signatures
2. Current & future observation campaigns are sensitive to these signatures
3. Synergy potential for particle physics, relativity & astrophysics

Outlook:

- Candidate events in the LVK O4 to follow up (in EM & GW)
- Other relevant signatures around supermassive black holes