Title: Dark Photon Superradiance

Speakers: Nils Peter Siemonsen

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 27, 2025 - 11:00 AM

URL: https://pirsa.org/25030088

Abstract:

Gravitational and electromagnetic signatures of black hole superradiance are a unique probe of ultralight particles that are weakly-coupled to ordinary matter. Through the kinetic mixing with the Standard Model photon, a dark photon superradiance cloud sources a rotating visible electromagnetic field. I will describe how this leads to the production of a turbulent pair plasma, characterized by efficient magnetic reconnection, which radiates large-luminosity high-energy electromagnetic emissions. This enables multi-messenger search strategies to probe unconstrained regions of parameter space.

Dark Photon Superradiance

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March 27, 2025

Princeton gravity Initiative

Q: How can we probe fundamental physics using astrophysical systems?

Why?

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

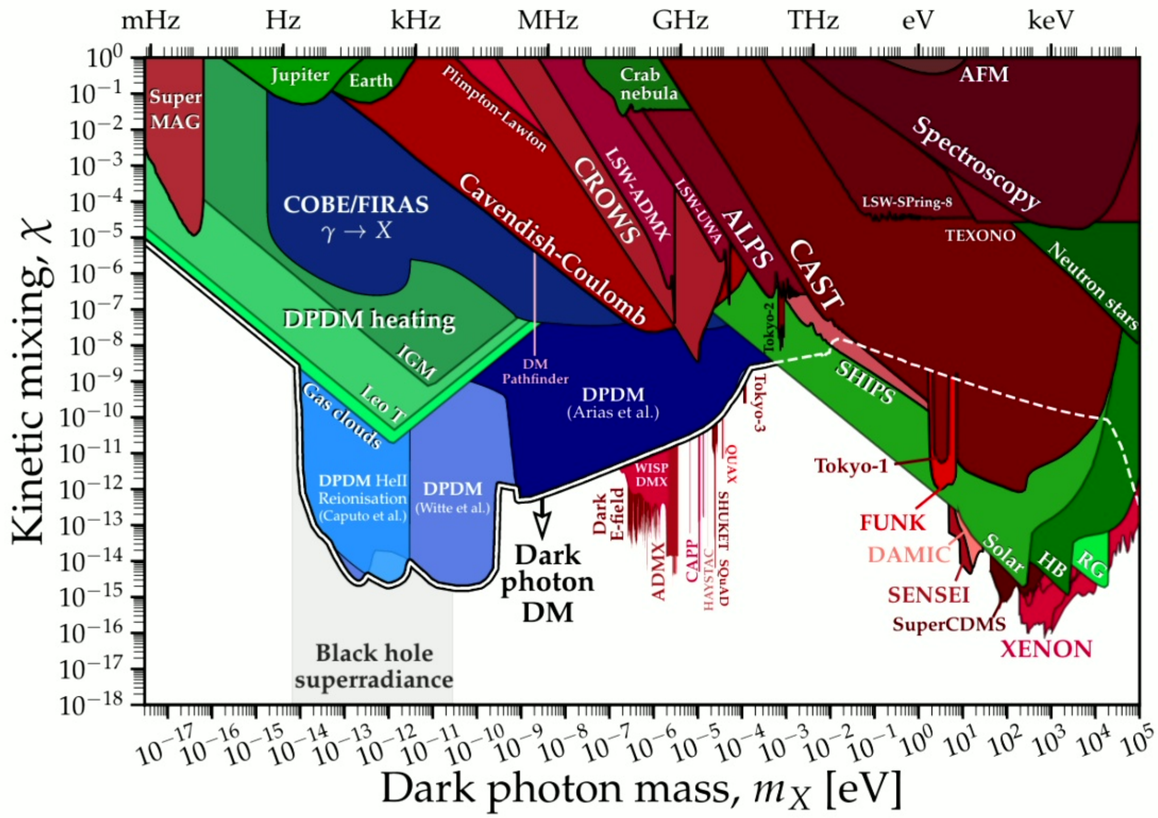
Candidates:

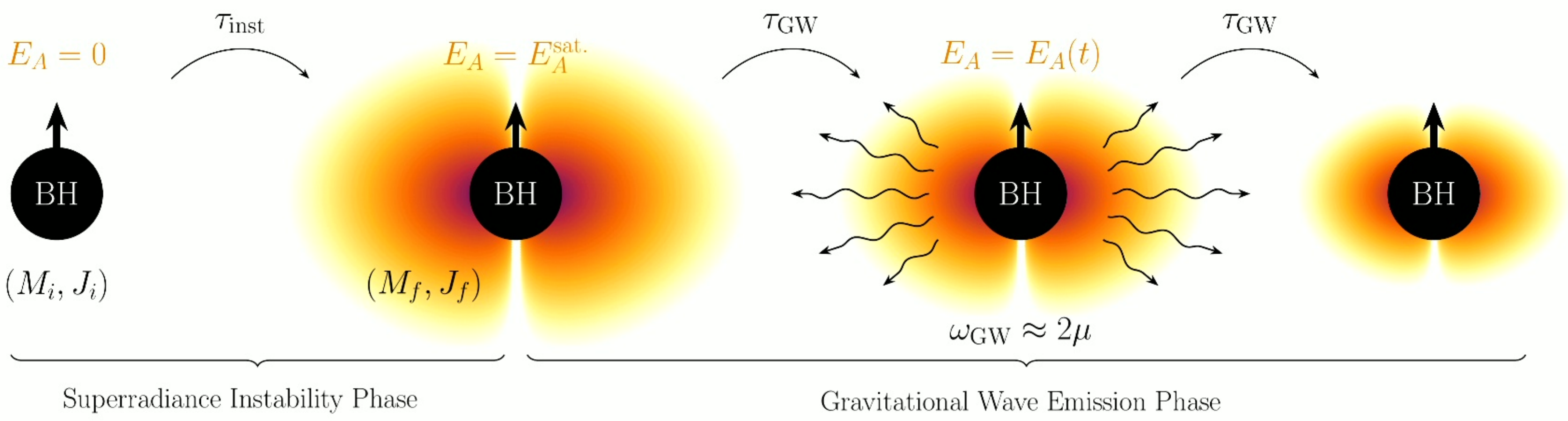
- Axion (spin-0)
- Dark photon (spin-1)

Couplings:

- Axion-photon
- Kinetic mixing

[Caputo et al., 2021]





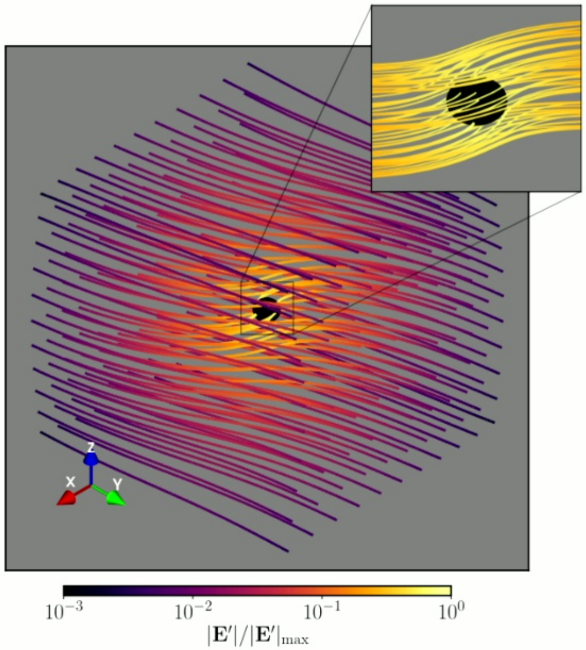
- Instability timescales: $\tau_{\rm inst} \sim 2 \text{ min} \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^7$
- Gravitational wave timescales: $\tau_{\rm GW} \sim 33 \text{ days} \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{11}$
- Cloud frequency: $\mu \sim 320 \text{ Hz} \left(\frac{10 M_\odot}{M_{\rm BH}}\right)\left(\frac{\alpha}{0.1}\right)$
- Cloud size: $a_{\rm Bohr} \sim 100 \left(\frac{G M_{\rm BH}}{c^2}\right)\left(\frac{0.1}{\alpha}\right)^2$

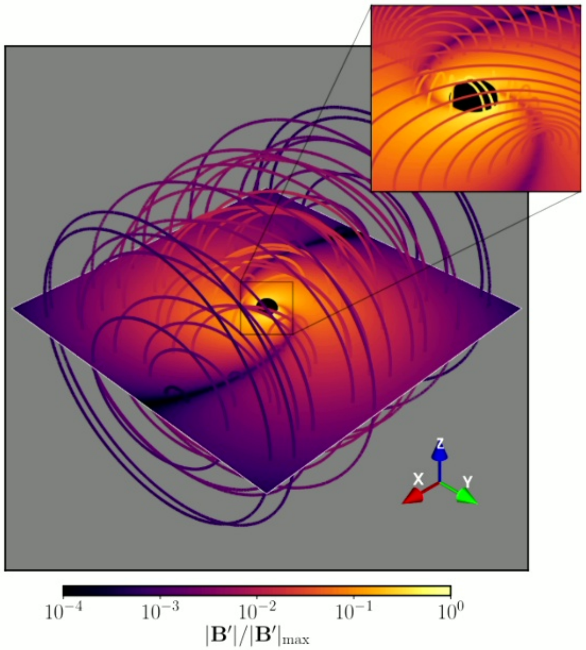
Dark Photon Superradiance

NS, Mondino, Egaña-Ugrinovic, Huang, Baryakhtar, East

Dark photon dynamics:

- Kinetic mixing $\varepsilon \Rightarrow$ visible electromagnetic field
- Large electric fields: $E \sim 10^{13}$ V/m
- Pair production cascade fills dark photon cloud





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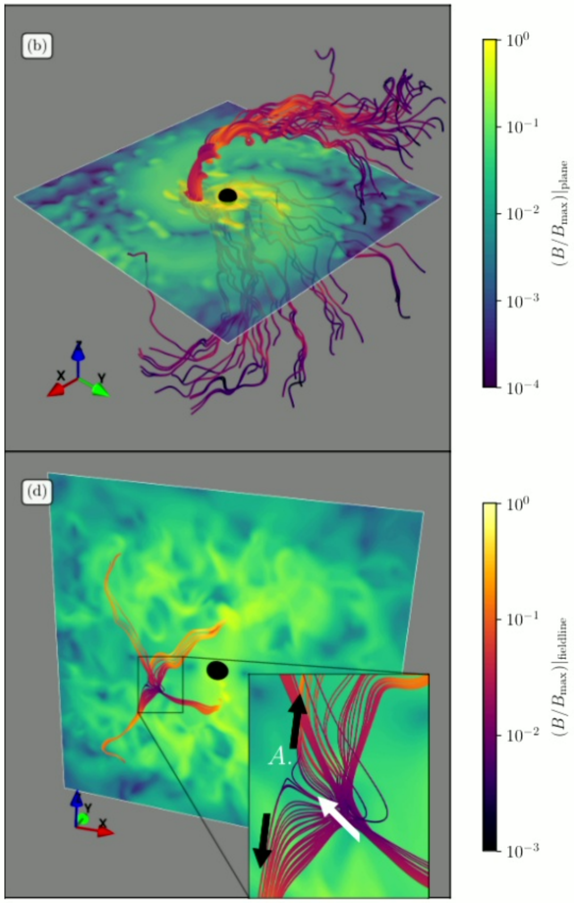
Endstate of cascade:

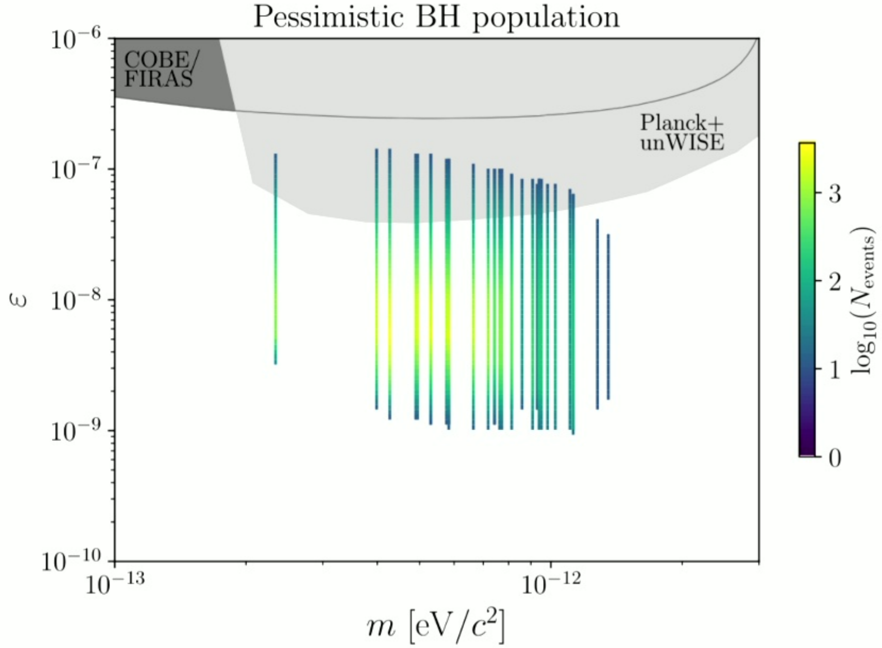
- Turbulent (almost) force-free plasma
- Largely magnetically dominated: $|\mathbf{B}| > |\mathbf{E}|$
- Efficient magnetic reconnection in bulk of cloud
- Strong dissipation: $P_{\rm diss} \gg P_{\rm Poynting}$
- Power output: $L \lesssim 10^{43}$ erg/s
- Some evidence for periodicity $\Rightarrow$ "fake pulsar"
- $|\mathbf{B}| \lesssim 10^{8}$ Gauss $\Rightarrow$ X-ray & γ-ray

$\Rightarrow$ High-energy electromagnetic signatures

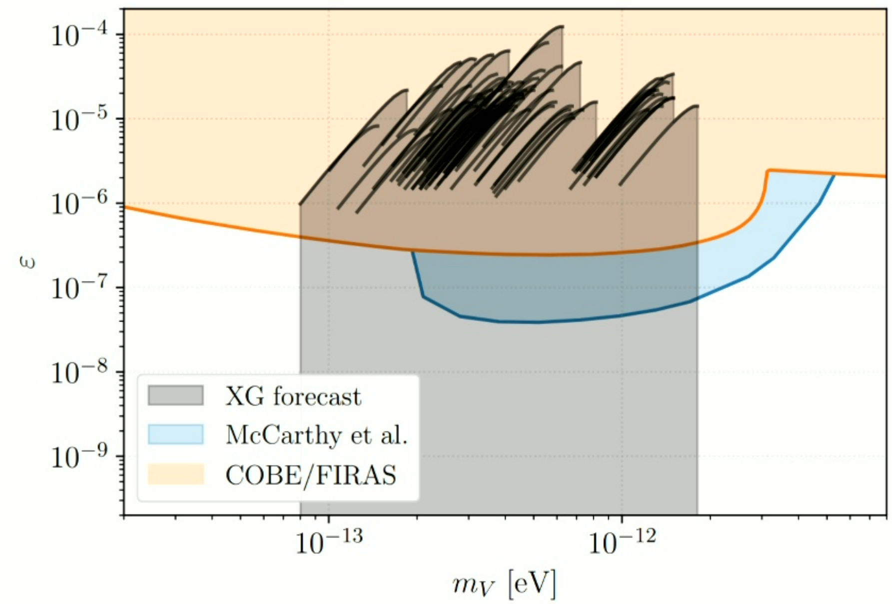


Observational prospects
Solar-mass black holes

[Mirasola, Mondino et al. (incl. **NS**), 2025]



[Jones et al. (incl. **NS**), 2024]

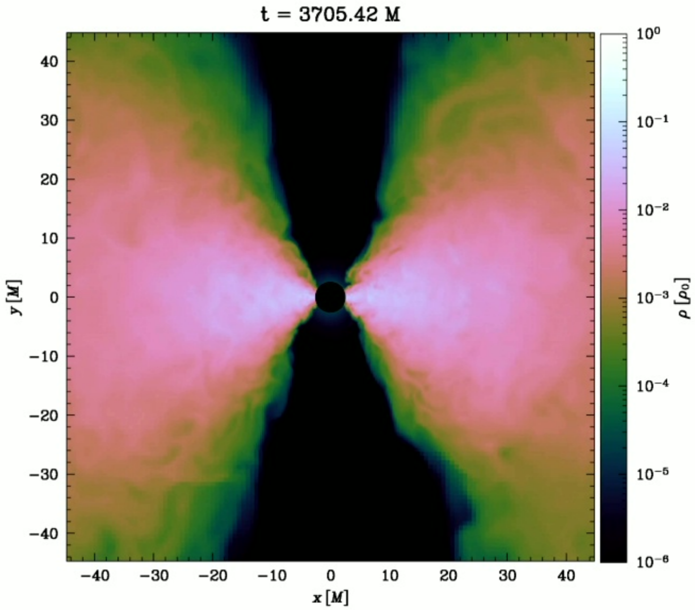


What about accretion?
Combi, Huang, Wong & **NS**, *in prep.*

Modified GRMHD: $\nabla_\mu T^{\mu\nu} = \varepsilon f^\nu_{\mathrm{DP}}$

Accretion states:

- Very small $\varepsilon \Rightarrow$ same as before
- Small – intermediate $\varepsilon \Rightarrow$ jet is perturbed
- Intermediate – large $\varepsilon \Rightarrow$ jet is destroyed
- Large $\varepsilon \Rightarrow$ accretion affected



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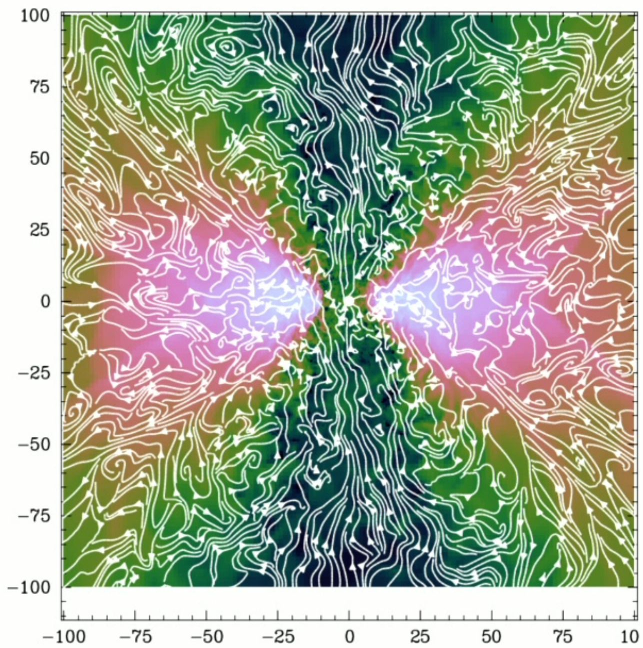

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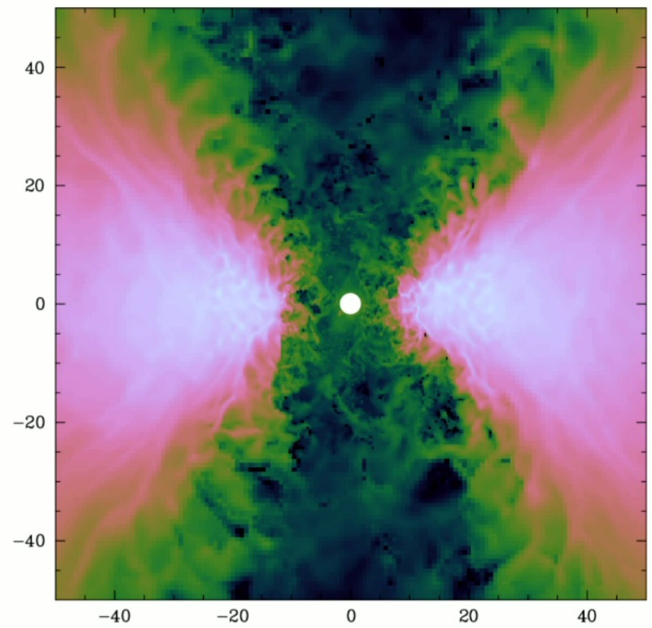

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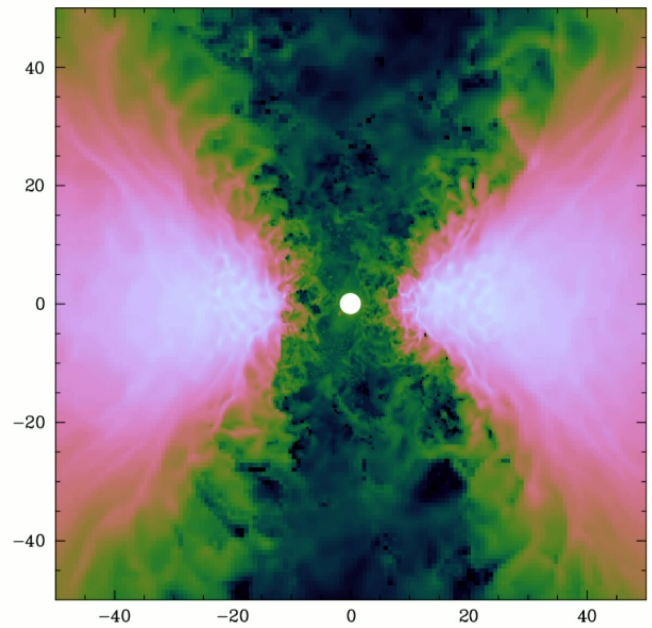

Observational implications:

- Independent spin measurements + AGN/X-rays $\Rightarrow$ strong constraint!
- EHT probes unexplored regions of parameter space
- Subtle effects (perturbed jets/disk modes) $\Rightarrow$ need population information

Conclusion

1. Black hole superradiance efficiently probes dark photon parameter space
2. Case for multi-messenger searches (solar-mass and supermassive black holes)
3. Future: PIC simulation of plasma, EHT observations