

New Horizons for Psi

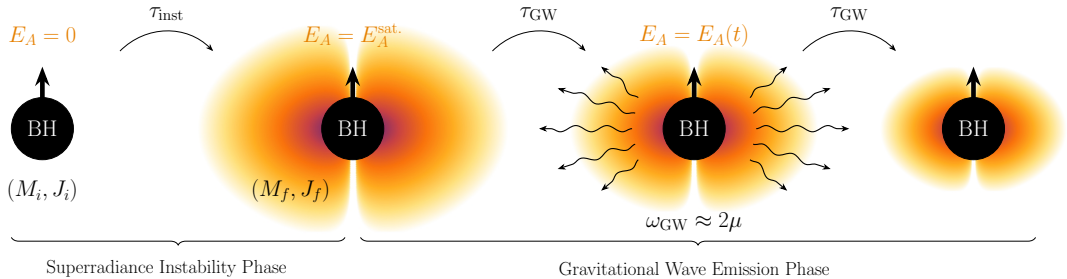
Black hole superradiance and beyond

Nils Siemonsen

Princeton Gravity Initiative

August 27, 2026





[Tsukada+ (incl. **NS**), 2020]

Numbers for vector boson:

- Instability most efficient if $m_V \sim 10^{-12} \text{ eV} \left(\frac{10M_\odot}{M_{\text{BH}}} \right)$
- Instability timescales: $\tau_{\text{inst}} \sim 1 \text{ min} \left(\frac{M_{\text{BH}}}{10M_\odot} \right)$
- Gravitational wave timescales: $\tau_{\text{GW}} \sim 33 \text{ days} \left(\frac{M_{\text{BH}}}{10M_\odot} \right)$
- Cloud frequency: $f \sim 320 \text{ Hz} \left(\frac{10M_\odot}{M_{\text{BH}}} \right)$

$\Rightarrow$ Black hole spindown & gravitational wave emission

Follow-up searches

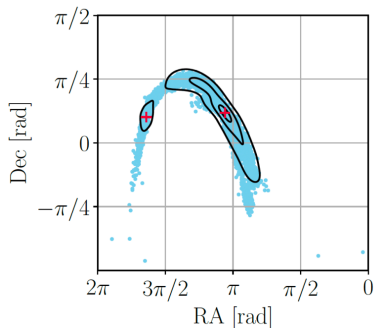
Constraints from follow-up searches [Arvanitaki, Baryakhtar, Isi, Sun, Brito, ...]

1. detect binary black hole
 2. measure remnant's mass, spin, and sky position
 3. follow sky position up with quasi-continuous waves search [Jones+ (incl. **NS**), 2023, 2024]
- ⇒ Absence of gravitational wave signal ⇒ Constraints on ultralight bosons

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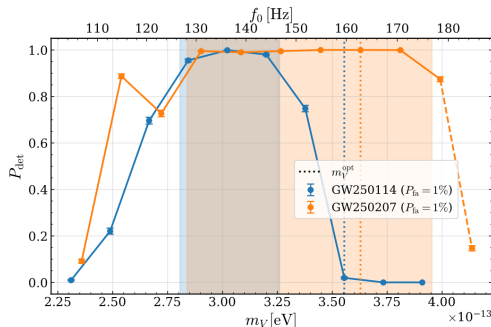
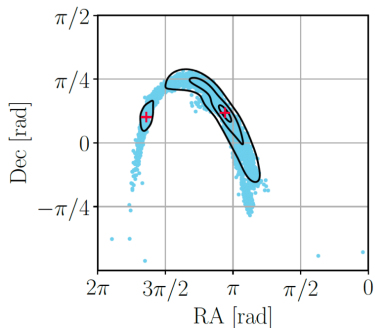


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[LVK (incl. **NS**), 2026]



Black hole spin measurements

Constraints from spin measurements:

1. detect binary black hole
2. measure constituent's spins
3. assumptions about spin evolution
4. map to constraints on boson masses

Place constraints using LVK O4+ data

[Aswathi+ (incl. **NS**), 2025]

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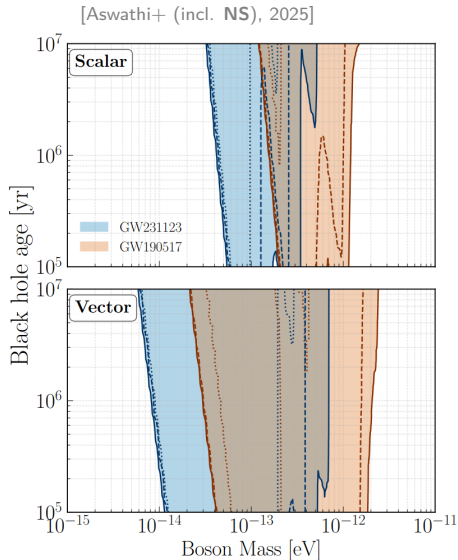
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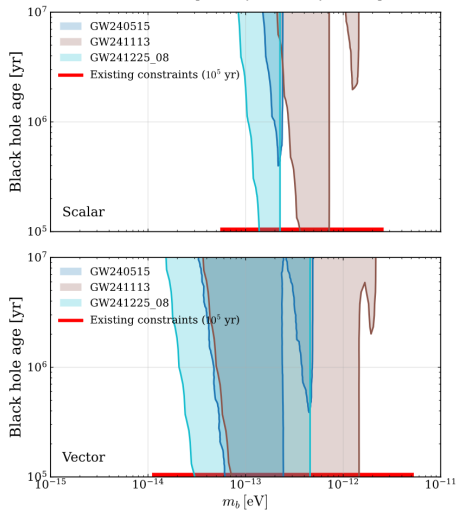
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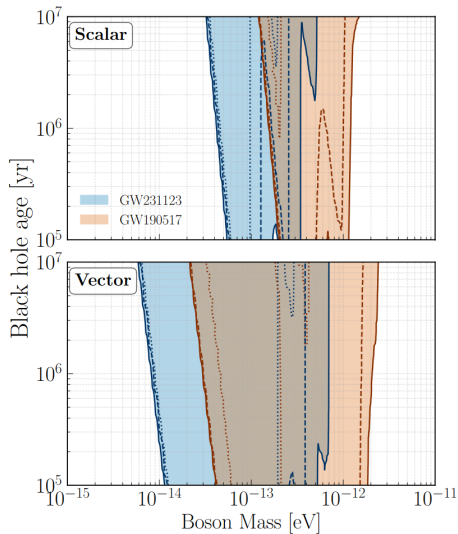


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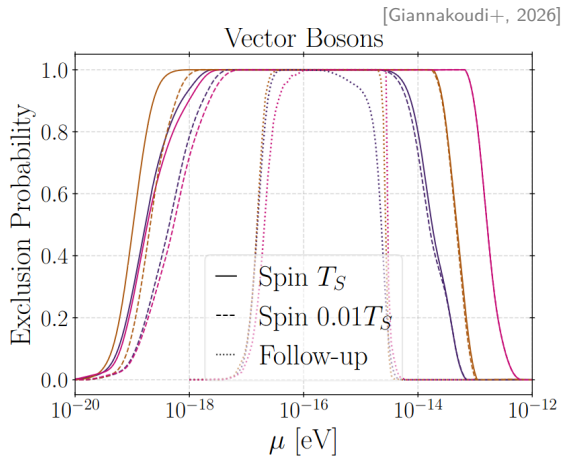
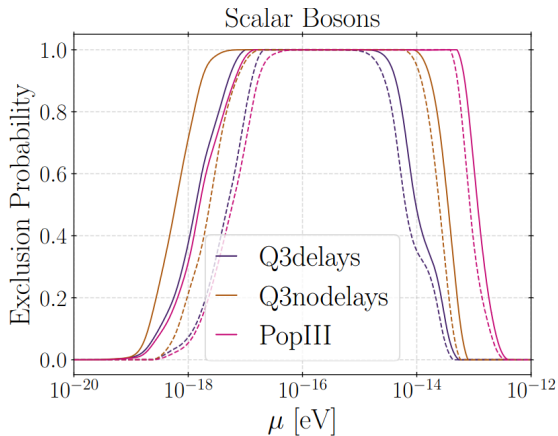


[Aswathi+ (incl. NS), 2025]



Future prospects

Prospects of mHz GW detectors, assuming population of SMBHs [Brito+, 2017]



Conclusion

LVK data:

Ruled out ≈ 3 order of magnitude of vector, and ≈ 2 order of magnitude of scalar masses

Space-based detectors:

“Rule out the rest”

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Space-based detectors:

“Rule out the rest”

Are we done here?

To get the most out of superradiance, we need to understand

Among others: couplings to the Standard Model and self-interactions

Higg-Abelian superradiance

- Vector field obtains its mass through a Higgs mechanism with

$$\mathcal{L} = -\frac{1}{4}F^2 - \frac{1}{2}|D\Phi|^2 - \frac{\lambda}{4}(|\Phi|^2 - v^2)^2, \quad D_\mu = \nabla_\mu - igA_\mu.$$

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- Most important effects from presence of Higgs field

1. Additional radiation channel for $\alpha \lesssim 0.1$ can saturate instability [Jones+ (incl. NS), 2024]

$$\rho_A \lesssim 8 \times 10^{-5} \frac{\mu^2}{\alpha \Delta a_*} \frac{M_c^{\text{sat}}}{M_{\text{BH}}}.$$

2. “Stringy bosonova” for $\alpha \gtrsim 0.1$ can halt instability [East, 2022]

$$\rho_A \lesssim 32 \alpha^4 \mu^2 \frac{M_c^{\text{sat.}}}{M_{\text{BH}}}.$$

⇒ Map constraints on massive vector into constraints on Higgs mechanism

Dark Photon Superradiance

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

Plasma production:

- Kinetic mixing ε : $\mathcal{L} \supset \varepsilon F'_{\mu\nu} F^{\mu\nu}$
 $\Rightarrow$ “Dark” Lorentz force
 - Synchrotron emission $\Rightarrow e^\pm$ -creation
 - Pair production cascade
- $\Rightarrow$ Formation of pair plasma

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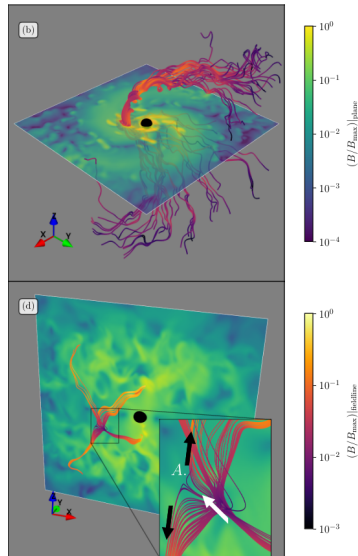
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Plasma properties:

- Power output:

$$L \approx 4 \times 10^{43} \text{ erg/s} \left(\frac{\varepsilon}{10^{-6}} \right)^2 \left(\frac{\alpha}{0.1} \right)^2 \left(\frac{\Delta a_*}{0.1} \right)$$

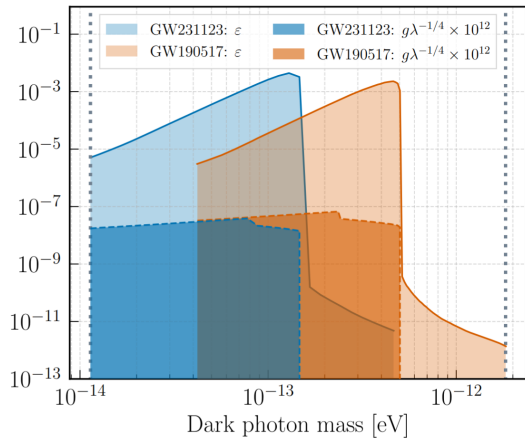
- $\Rightarrow$ Superradiance is impacted for large ε , small α
- Plasma heating and magnetic reconnection
- $\Rightarrow$ High-energy electromagnetic signatures



Spin measurements

GW231123 & GW190517

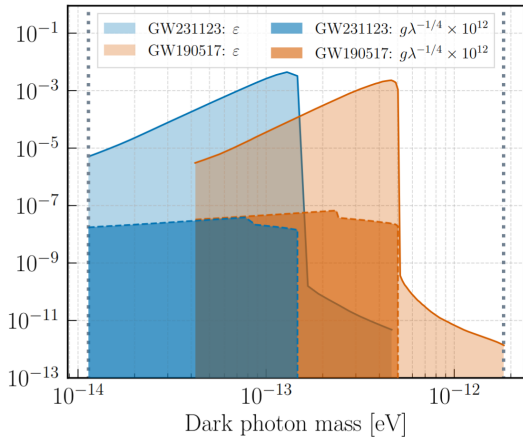
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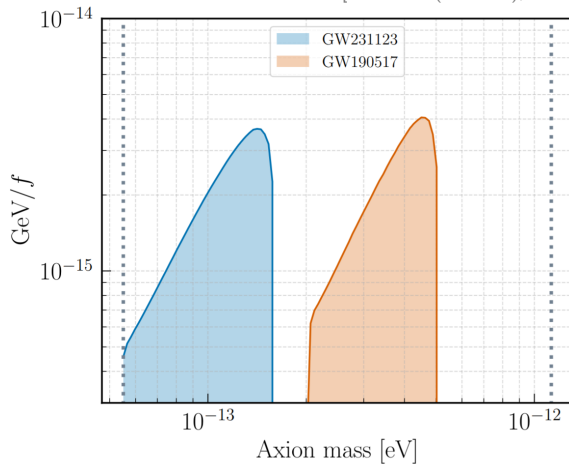
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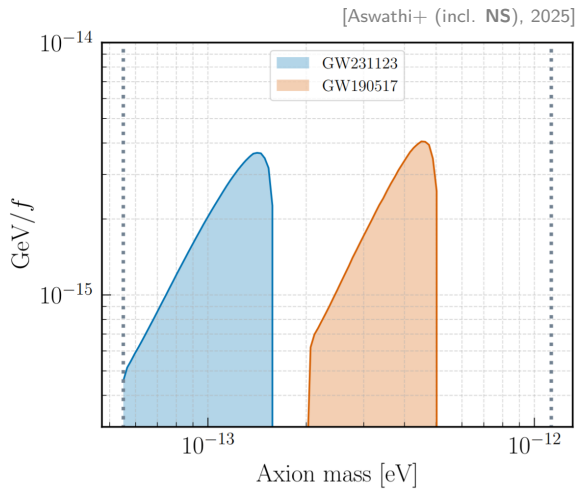
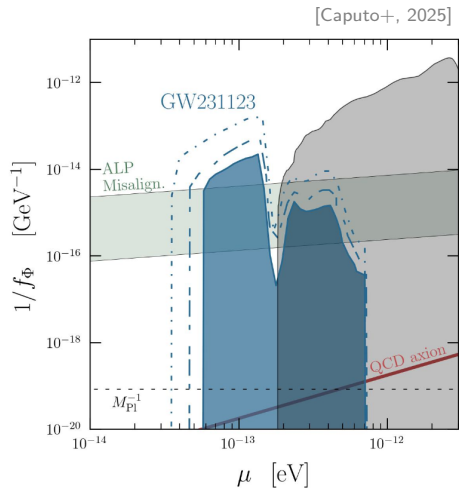


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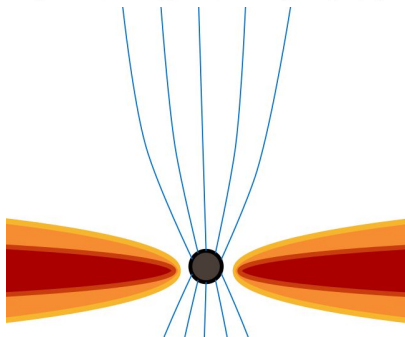
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Dark photon cloud coupling to an accretion disk through kinetic mixing ε

[Combi, Wong, **NS**, Huang, in prep.]



Dark photon cloud coupling to an accretion disk through kinetic mixing ε

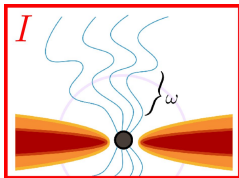
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$$\mathbf{f} = \varepsilon \mu^2 (\chi'_{\text{SR}} \times \mathbf{B}_{\text{disk}} + \chi'_{\text{SR}} \mathbf{E}_{\text{disk}})$$

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I: Periodically perturbed jet

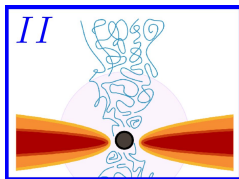
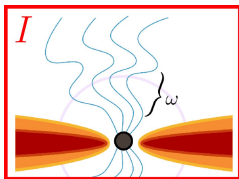


ε

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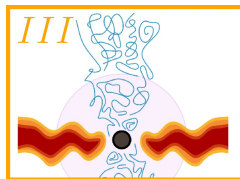
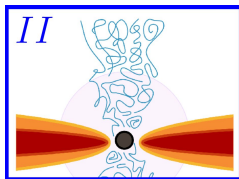
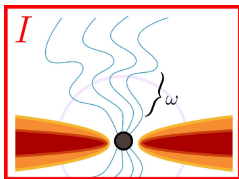
- I: Periodically perturbed jet
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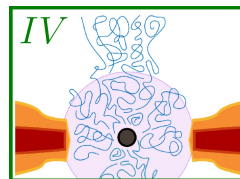
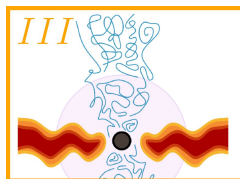
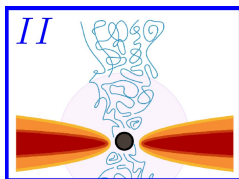
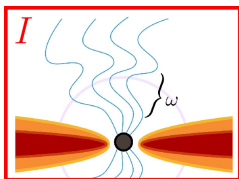
- I: Periodically perturbed jet
- II: Turbulent jet
- III: Periodically perturbed disk



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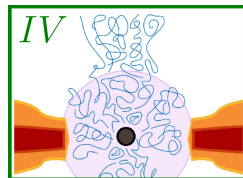
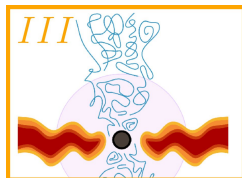
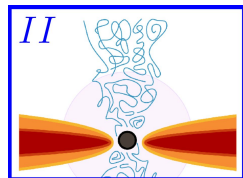
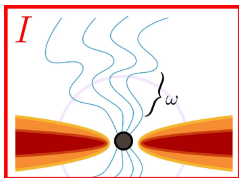
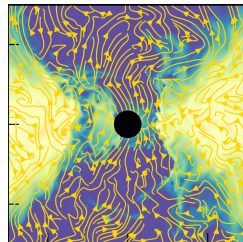
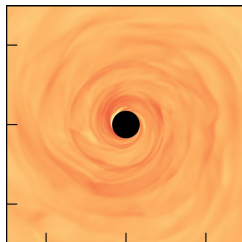
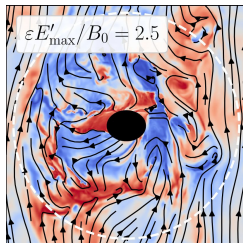
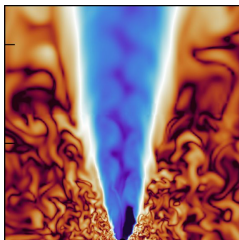


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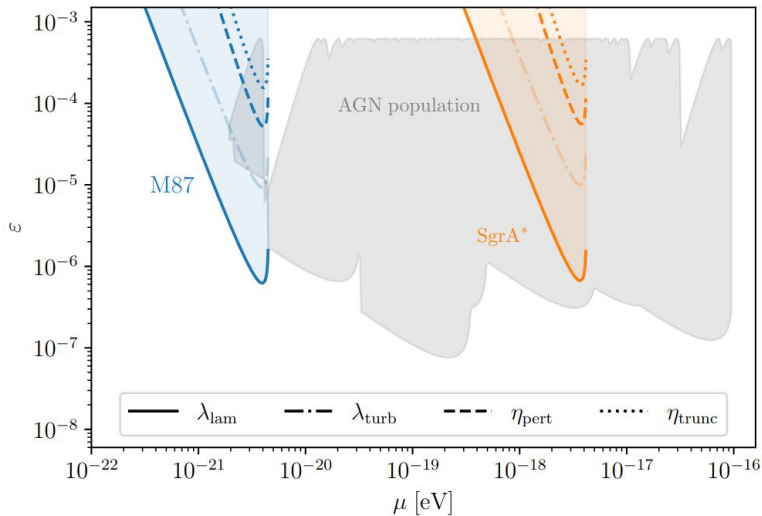


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Summary

1. Constraints on ultralight particles with LVK spin information

- Follow-up searches and BH spin measurements
- Constraints on ultralight scalar and vectors

2. Understanding impact of couplings allows to make the most of constraints

- Kinetic mixing and Higgs-Abelian superradiance
- Impact on accretion flow and EM observables